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Coastal subtropical Southern American shallow lakes as unique ecosystems for monitoring anthropogenic induced ecosystem changes

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Abstract

The South American Coastal Shallow Subtropical Lakes (SA-CSSL) represent the largest continuous coastal shallow-lake system of its kind globally — a 1,000 km belt of over 100 wind-exposed polymictic lakes and lagoons - mostly freshwater due to high precipitation, groundwater inputs and large catchments — arrayed along southern Brazil into eastern Uruguay. The SA-CSSL lakes formed during the Quaternary as barrier–lagoon systems - lagoons impounded behind coastal sand barriers, a unique and peculiar feature in the context of shallow lakes. Despite their regional and global relevance, subtropical shallow lakes remain under-represented in limnology, making SA-CSSL a critical research target that goes beyond temperate-dominated research. The region spans strong climatic and anthropogenic gradients and is directly influenced by the El Niño Southern Oscillation (ENSO), creating a natural laboratory for comparative and replicated studies on ecosystem processes, biodiversity and resilience. Here, we synthesise the current knowledge on the system's origin, structure, functioning and pressures and formulate a forward-looking plan for coordinated research and monitoring. Drawing on the strategic outcome from a 2025 workshop in Brazil, we delineate four representative aquatic subsystems with historical monitoring and active projects — the Tramandaí River System, Patos Lagoon System, Mangueira–Mirim System and Uruguayan Lagoon System — as sentinels for integrated observation and research. Key anthropogenic and climatic stressors comprehensively documented include eutrophication, urban and agricultural runoff and emerging contaminants (e.g. pharmaceuticals, pesticides, microplastics), alongside rapid landscape change and more frequently occurring extreme weather events due to climate change. We further outline priority research topics that leverage the system's scale and gradients: (i) pollutant and "novel entity" surveillance combining analytical chemistry with microbial and molecular biomarkers; (ii) biodiversity and community-assembly studies across ecotones and salinity transitions; (iii) remote-sensing–enabled lake modelling and early-warning indicators; (iv) designs for extreme inflow events; and (v) transboundary governance cases. To align local action with global needs, we align a monitoring framework with planetary boundaries, propose indicators and highlight data-infrastructure needs. We position SA-CSSL as a globally unique large-scale model for subtropical shallow lakes and a collaborative nexus for testing ecological theory and managing freshwater under accelerating climate and societal change.

Keywords

coastal shallow lakes, subtropical freshwater, anthropogenic impact monitoring

Introduction

Spanning ca. 1,000 km of the south-eastern coastline of South America, the coastal lakes belt of southern Brazil and eastern Uruguay forms one of the most extensive continuous systems of its kind, here referred to as Southern American Coastal Shallow Subtropical

Lakes (SA-CSSL). In the Brazilian zone alone, the coastal plain that encompasses the SA-CSSL covers an area of approximately 37,000 km², nearly 40% of which is occupied by lakes and lagoons. With the Atlantic Ocean as an eastern boundary, it includes the Patos-Mirim complex — recognised as the most extensive coastal lagoon system globally — and a series of interconnected and isolated lakes that span five degrees of latitude from 30°S to 35°S, placing the region just south of the Tropic of Capricorn and spanning almost complete subtropical climate zone down to the temperate zone of the Southern Hemisphere (Fig. 1, Oliveira et al. 2019).

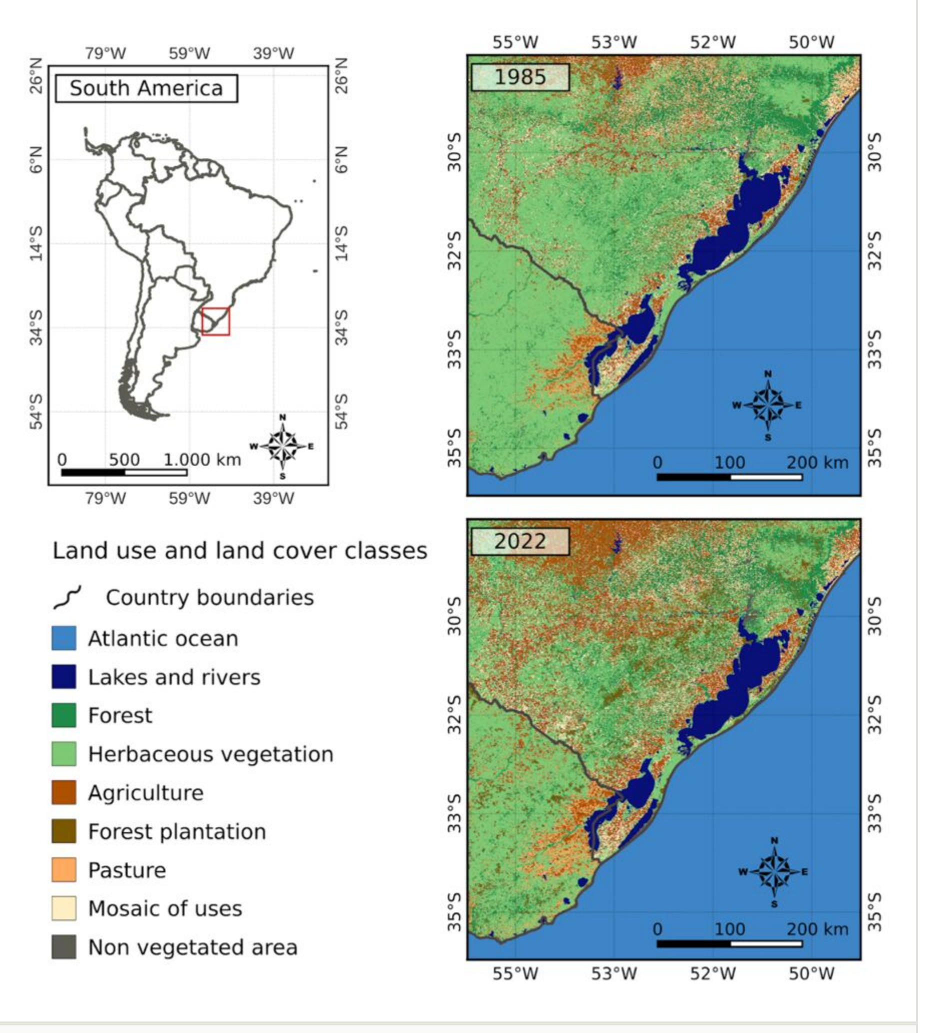

Figure 1.

Location of the SA-CSSL with use and land-cover classes and its change from 1985 to 2022.

The SA-CSSL represent a unique habitat with more than 100 lakes (Schäfer et al. 2014) of similar geological origin that were originally part of the Pampa grassland biome

(Ellwanger et al. 2025). The SA-CSSL are almost entirely within the passive-margin sedimentary Pelotas Basin, which extends from Santa Marta Cape (Santa Catarina State, Brazil) to La Coronilla (Uruguay) (Barboza et al. 2021). They originated in the Quaternary (Pleistocene and Holocene) after four major events of marine transgressions from ~ 400 ka to ~ 5 ka, which formed many barrier-lagoon systems (García-Rodríguez et al. 2001, Bracco et al. 2005, Inda et al. 2016, Barboza et al. 2021). Palaeolimnological records, based on the Uruguayan lagoons Rocha and Negra, show that past climate oscillations, including transitions between wet and dry phases, produced marked shifts in trophic status, salinity and community structure over millennial scales (García-Rodríguez et al. 2001, Bracco et al. 2005). Due to the strong action of winds, mainly along the northeast-southwest axis, the lakes became elongated and exhibited strong segmentation, resulting in variable degrees of age, connectivity, shapes and degrees of isolation from the Atlantic Ocean (Lanzer 2005, Guimarães et al. 2014, Barboza et al. 2021). These lakes are polymictic, with wind as a major driver of continuous water column mixing year-round. Notably, besides brackish lagoons in both Uruguay and Brazil, this region hosts large freshwater bodies near the ocean - a rare occurrence on sedimentary coasts, where brackish or saline lakes and lagoons are ubiquitous. This freshwater status is sustained by high precipitation rates, stable freshwater aquifers beneath the coastal barrier (Souza et al. 2021) and a massive input of freshwater from major drainage catchments, such as the Guaíba system (Fernandes et al. 2001).

Anthropogenic influences are very strong in this region (Fig. 1, Bueno et al. 2021, Bueno et al. 2025, Ellwanger et al. 2025) and clearly affect these coastal ecosystems, with lakes spanning oligotrophic to hypereutrophic conditions due to substantial urban wastewater and agricultural runoff. More recently, extreme climate events have also triggered abrupt ecological changes in several lakes, with effects such as reduced water levels, macrophyte proliferation and eutrophication episodes - particularly in systems with restricted marine connectivity and/or high anthropogenic pressure (Inda et al. 2016). These findings highlight the sensitivity of SA-CSSL to both natural climatic variability and additive effects under ongoing climate change and human activity.

The global relevance of the SA-CSSL

Despite its geographic breadth, the SA-CSSL remain under-represented in global limnological and ecosystem research. While scientific engagement in the region has grown significantly in recent decades, this system remains poorly integrated into the global understanding of subtropical freshwater ecosystems. Compared with temperate and boreal regions, few places with shallow subtropical lakes have been studied at scale – most notably Lake Taihu in China. Located near the East China Sea coast, Lake Taihu is often used as a reference for understanding eutrophication, hydrodynamics and algal blooms in shallow subtropical environments (Hu et al. 2015, Zhang et al. 2015, Zhang et al. 2016). Other study sites include subtropical lakes in Florida (USA; e.g. Lake Okeechobee and Lake George) and, more rarely, study sites in South Australia and KwaZulu-Natal (South Africa) in the Southern Hemisphere (Whitfield et al. 2017, Dang et al. 2023, Keneally et al. 2026). Despite being the only large-scale subtropical lake network in the world along a climatic and environmental gradient, the SA-CSSL are often missing from cross-system analyses. The spatial and environmental gradients of over 100 lakes are ideal for studying broad-scale ecological patterns and offer a robust basis for experimental design disentangling interactions between land use, hydrology, biodiversity and climate variability.

According to global and regional climate models, all scenarios of human CO_2 emissions – from the most optimistic to the most pessimistic – predicted a 15% increase in precipitation in southern Brazil between 2011 and 2040, with similar trends expected for the following decades (2041-2070 and 2071-2100) (Secretaria de Assuntos Estratégicos da Presidência da República 2015). Moreover, since the SA-CSSL are directly impacted by the El Niño Southern Oscillation (ENSO), they can be used to understand and predict its effects on freshwater ecosystems in the Southern Hemisphere (for more specific information on local climate and effects, see Suppl. material 1). In recent years, episodic flooding has become more frequent, with one of the most devastating flooding events in Brazilian history taking place in May 2024, in Rio Grande do Sul State (Pillar and Overbeck 2024, Agencia Nacional de Águas e Saneamento Básico 2025). This flooding affected 478 out of the State's 497 municipalities and impacted 2.4 million people. The flooding began in the central region of the State, an area characterised by river valleys, where some municipalities recorded over 200 mm of rainfall in just 24 hours and more than 500 mm over a 10-day span (de Oliveira Andrades-Filho et al. 2025, Ellwanger et al. 2025, Simoes-Sousa et al. 2025, Clarke et al. 2026). The rivers in these areas drain into the Guaíba Lake, which surrounds the State’s capital, Porto Alegre and registered a dramatic rise in water levels to a historic level of 5.37 metres - well above the 3-metre flood stage, causing widespread flooding. Since Guaíba Lake connects to the Patos Lagoon, the inundation extended throughout the SA-CSSL region, with slow drainage and floodwaters persisting for over a month. The ecological impacts of this historical flooding on affected watersheds are yet to be explored and launch a timely opportunity to evaluate the resilience and recovery of subtropical shallow lake ecosystems under increasingly frequent extreme rainfall and flooding events.

Over the last decades, the scientific activity and interest in SA-CSSL has grown considerably and current research highlights the involvement of scientists with contemporary and pressing topics. To position SA-CSSL within an international research context and to address these emerging topics, we held a workshop in Porto Alegre, Brazil, in April 2025 with 20 participants to discuss research and opportunities related to microbial ecology of these ecosystems. Participants of the workshop included nine researchers, eight graduate students and three undergraduate students involved in SA-CSSL studies from the partner universities of Brazil, Uruguay and Germany. Key goals included synthesising current research, evaluating SA-CSSL’s past and future importance globally and developing a conceptual framework for future studies and long-term monitoring. The workshop focused on fundamental limnological and ecological processes, while emphasising the key role of plankton and microbial communities. As a first step, we compiled data from past monitoring activities and ecological assessments and aligned them with ongoing research projects that address contemporary environmental and climate change challenges (Suppl. material 1- Supplementary Table 1). The resulting discussions emphasised the value of SA-CSSL, not only as a unique regional system, but also as a globally significant model for understanding freshwater responses to global change. This point is underscored by the striking under-representation of subtropical lakes in global models. For example, in a study of 8,000 lakes used to infer CO_2 emissions, over 98% were from non-tropical regions (Raymond et al. 2013). Filling this gap with SA-CSSL data can reduce bias in global carbon budgets and emission projections. Future research directions that link coastal lakes to major global change domains were also discussed (Richardson et al. 2023). Finally, the workshop was also designed to consolidate regional knowledge and helped propel international scientific engagement by attracting researchers with diverse expertise and experience - including those working primarily on temperate lake systems - into collaborative efforts focused on subtropical coastal lakes.

SA-CSSL Subsystems

Based on geographic proximity to each other and/or watershed membership as well as scientific attention, we have identified four representative subsystems within the SA-CSSL that are both ecologically rich and sufficiently studied to support integrated research and monitoring efforts. The four selected subsystems are: The Tramandaí River System (TRS), the Patos Lagoon System (PLS), the Mangueira-Mirim System (MMS) and the Uruguayan Lagoon System (ULS). These four units reflect the biogeographic, climatic and anthropogenic gradients present across the SA-CSSL and offer a structured way to monitor environmental change across space and time. They extend from the southernmost state of Brazil, Rio Grande do Sul, to north of Uruguay (Fig. 2).

The Tramandaí River System (TRS) is located in the northern coast of Rio Grande do Sul State, an ecotone between two main biomes in Brazil: the Atlantic Forest biome to the north and the Pampas grasslands to the south. The TRS comprises around 40 lakes within a single watershed (Tramandaí River Watershed), with the majority presenting some level of connectivity (Cruz Weiss et al. 2013). The TRS covers an area of about 2,700 km^2 and 115 km of coastline, supporting a population of over 265,143 inhabitants — 90% of which are in urban areas (SEMA RS 2021a). This region exhibits the highest demographic growth in the Rio Grande do Sul State (1.5-1.8% year^{-1}, nearly three times higher than the State's average) (Secretaria de Planejamento, Governança e Gestão 2024). Of the 20 fastest-growing municipalities in Rio Grande do Sul, seven are located within the TRS, with some showing population increases of around 25% between 2010 and 2017, accompanied by drastic land-use changes. Additionally, the 20 municipalities on the northern coast of Rio Grande do Sul faced an 85% increase in their urban areas between 2000 and 2010, implying that anthropogenic pressures have increased steadily in the last decades. The lakes in the TRS face several major environmental threats, including eutrophication from the disposal of untreated wastewater, sewage and agricultural runoff; water withdrawal for irrigation; and the spread of invasive species (Lanzer 2005, Castro and Mello 2013, Castro and Rocha 2016, Schäfer et al. 2017).

Beyond the lakes, this coastal plain encompasses a diverse range of landscape features, including barriers, dunes and wetlands, making these areas attractive for tourist activities. As a result, these aquatic ecosystems have been intensively used for tourism and recreation (Lanzer et al. 2013, Schäfer 2013). Such touristic activities have led to waste accumulation, damage to local vegetation due to campsites, soil erosion caused by vehicle traffic and disturbance of wildlife due to noise pollution. During the summer season, the local population can increase up to 10-fold from incoming seasonal tourists, prompting the construction of numerous condominium developments for vacation homes (Matos and Gruber 2009). This seasonal influx significantly increases the demand for freshwater, while simultaneously overwhelming municipal sewage treatment infrastructure. For example, in Imbé Municipality, only 0.5% of domestic effluents are currently collected and treated (Ministério do Desenvolvimento Regional - Brasil 2024), underscoring the apparent mismatch between infrastructure capacity and peak population pressures. Importantly, these lakes serve a dual and conflicting purpose: they are both primary sources of urban drinking water for at least 17 municipalities and recipients of untreated or partially treated sewage.

The Patos Lagoon System (PLS) is centred around the Patos Lagoon, which is the world's largest choked lagoon. It is approximately 5 m deep with 250 km length, a width of 40 km and approximately 10^4 km^2 area (Kjerfve 1986). Along with Lakes Mirim and Mangueira, it is part of a 180.000 km^2 watershed in Rio Grande do Sul State (Martinbiancho et al. 2018). The estuarine area is approximately 10% of the lagoon, which connects to the Atlantic Ocean through a narrow channel (0.5-3 km wide, 20 km long, 14 m deep), characterised by brackish water (Asmus 1998). The estuarine plume, along with the La Plata River, is of significant relevance for the fertilisation of the continental shelf, rendering the Rio Grande do Sul coast one of the most productive fisheries in Brazil (Niencheski and Windom 1994, Ciotti et al. 1995, Nagy et al. 2002). Freshwater discharge through the estuary averages around 4,000 m^3s^{-1}, with considerably higher flows (up to 10,000 m^3s^{-1}) recorded during ENSO years (Seeliger 2001). The strong influence of ENSO on precipitation patterns has been shown to drive prolonged salinisation/desalinisation, which promote dramatic changes in suspended particulate matter (Távora et al. 2020) and alternating freshwater and brackish/marine communities of bacteria (They et al. 2015a), phytoplankton (Fujita and Odebrecht 2007) and fish (García-Rodríguez et al. 2001). The impacts of climate change and nutrient input on cyanobacterial blooms (Souza et al. 2018), as well as ecosystem services, have been under scrutiny in recent years (Asmus et al. 2019). The PLS ecological relevance is underscored by the RAMSAR site *Lagoa do Peixe* National Park (Ramsar Sites Information Service 1993). The brackish to saline Peixe Lagoon supports high concentrations of invertebrates and stands as an important wintering and staging area for migrant bird species (Instituto Socioambiental 2025). For this reason, since 1990, the Park is also a Western Hemisphere Shorebird Reserve Network Site (Western Hemisphere Shorebird Reserve Network (WHSRN) 2025). The PLS experiences significant anthropogenic pressure, primarily from major urban centres such as Porto Alegre, Pelotas and Rio Grande, which combined account for over two million inhabitants. These cities contribute to the discharge of untreated or partially treated sewage into the lagoon (Martins et al. 2007). The surrounding landscape is predominantly composed of agricultural fields, forming a mosaic with urban areas, silviculture plantations and remnant patches of native vegetation (Silva and Tagliani 2012).

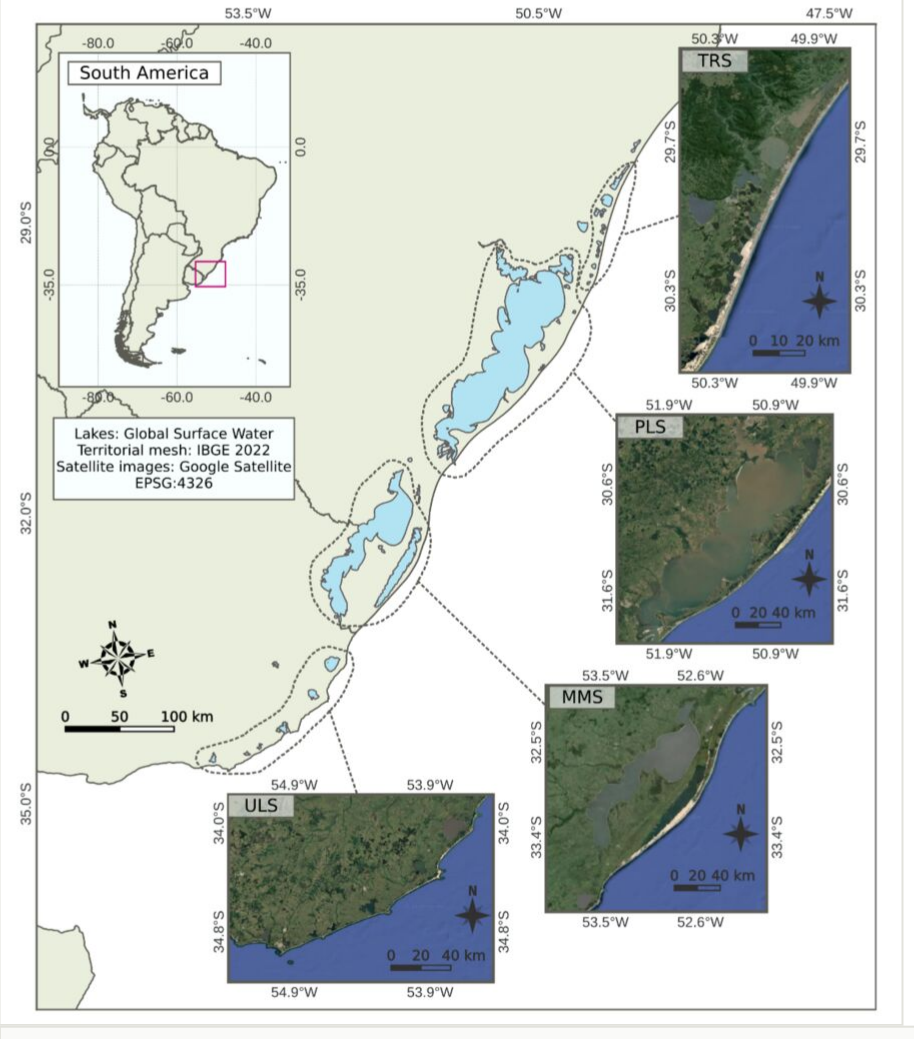

Figure 2.

Southern American coastal shallow subtropical lakes (SA-CSSL) system, with the four subsystems in detail: I - Tramandaí River System (TRS); II - Mangueira-Mirim System (MMS); III - Patos Lagoon System (PLS); IV - Uruguayan Lagoon System (ULS).

The Mangueira-Mirim system (MMS) is located on the southern coast of Rio Grande do Sul State within the Mirim-São Gonçalo Basin and comprises the two largest subtropical shallow lakes in Brazil, Mangueira and Mirim, which are part of the broader Taim Hydrological System (THS). The MMS covers an area 28,499 km² (SEMA RS 2025) and has a population of 771,728 inhabitants – 685,473 in urban areas and 86,255 in rural zones (SEMA RS 2021b). A central feature of THS is the Taim Wetland (32°32'3.48" S, 52°31'42.99" W and 32°50'10.41" S, 52°38'32.47" W), one of the few subtropical wetlands in Brazil. For this reason, a federal environmental protection area (Ecological Station of Taim) was established in 1978 (Villanueva et al. 2000) and stated as a RAMSAR site in 2017 (Ramsar Sites Information Service 2017). This system is of paramount ecological importance for its high biodiversity, serving as feeding-ground and site for reproduction and resting for many migratory birds and as habitat for a wide range of mammals, reptiles, fish, macrophytes and invertebrates (Marques 2013). Lake Mangueira is located on a narrow strip of land between the Atlantic Ocean and Lake Mirim. The lake is 90 km long and 3–10 km wide, covering a surface area of approximately 820 km^2, with a mean depth of 2.6 m and a maximum depth of 7 m. At both its northern and southern ends (Taim Wetland in the north), the lake interfaces with wetland areas rich in organic matter, primarily from macrophyte decomposition. The macrophytes are particularly present in the southern portion (Rodrigues et al. 2015) and shoreline processes, shaped by strong hydrodynamic forces, have created sandbars colonised by dense belts of these emergent plants. The lake's trophic status is generally oligotrophic, but episodic anthropogenic nutrient input occurs due to intensive rice cultivation in the watershed, particularly during spring and summer.

Lake Mirim is a large shallow subtropical lake located on the Brazil-Uruguay border, regulated by transboundary water governance agreements. The lake has a surface area of ca. 4,000 km^2, is 190 km long along its main axis and averages 40 km wide. The maximum depth is 10 m with a mean depth of 4.5 m. The Lake is connected to the larger Patos Lagoon through a natural channel (São Gonçalo), which is approximately 76 km long (Munar et al. 2019) and to Lake Mangueira via an artificial channel (Coradi et al. 2009, Oliveira et al. 2015). Both channels have water gates to control water flow, especially for the São Gonçalo channel to prevent saline water intrusion from the Patos Lagoon estuary. The Basin faces significant pressure from industry, livestock and agriculture, with a large portion of the water being used for rice fields irrigation (Oliveira et al. 2015). Untreated wastewater discharge further elevates phosphorus, increasing eutrophication risks (Coradi et al. 2009). Given the environment and economic relevance of Lake Mirim, a binational initiative for integrated water-resource management was implemented in 2022 through an agreement signed by Brazil's Ministry of Integration and Regional Development, Uruguay's Ministry of Environment and the Food and Agriculture Organisation of the United Nations (FAO). Supported by US $4.7 million in funding from the Global Environment Facility, the programme aims to strengthen institutions for sustainable water use, ecosystem preservation and climate-change adaptation. With nearly one million people directly dependent on the Lake's water and biodiversity, coordinated Brazil–Uruguay action is pivotal for regional development, environmental security and long-term socioeconomic stability in the MERCOSUL context (Ministério da Integração e do Desenvolvimento Regional 2024).

The Uruguayan Lagoon System (ULS) forms a chain of medium to large waterbodies aligned in parallel to the Atlantic coast (García-Rodríguez et al. 2004). This is the southernmost system of the SA-CSSL and is part of the Atlantic Coastal Basin, which covers an area of 9,266 km² and includes several key lagoons such as Negra, Castillos, Rocha, Garzón, Escondida, José Ignacio, Blanca, Diario and Sauce. Except for Negra Lagoon, the ULS is characterised by an intermittent connection to the Atlantic Ocean, mediated by a sand barrier which periodically separates them from the ocean (Conde et al. 2000, García-Rodríguez et al. 2001, Bracco et al. 2005, Conde et al. 2019). This contrasts with the coastal plain of Rio Grande do Sul State, where most of the lakes are separated from the Atlantic Ocean by a continuous coastal barrier. In the ULS, the connection to the ocean is often artificially forced by local municipalities to reduce flooding in mostly unplanned urbanisation (Rodríguez-Gallego et al. 2010, Conde and Chreties 2014, Carreira et al. 2025). Smaller shallow lakes, such as Escondida and Blanca, are permanently isolated from the ocean (Kruk et al. 2009) by mobile dune systems, currently fixed by exotic vegetation and highly urbanised. In other cases, such as Diario and Sauce, infrastructure construction (e.g. dams) prevents bidirectional interaction with La Plata River (Inda et al. 2016, González-Madina et al. 2022).

The ULS is embedded in diverse watershed contexts, from relatively pristine areas dominated by native grasslands to basins undergoing rapid land-use change due to agriculture, afforestation and urban expansion. The intensification of rice cultivation and the proliferation of forestry plantations results in nutrient export and sediment loads (Rodríguez-Gallego et al. 2017) and altered hydrodynamics and salinity regimes (Mazzeo et al. 2003, García-Rodríguez et al. 2004, Inda et al. 2016). The ULS has great social and economic importance, supporting essential ecosystem services that are intensely used by the population, such as drinking water supply (Crisci et al. 2017), the most important continental artisanal fisheries on the coast and growing ecotourism (Rodríguez-Gallego et al. 2017). A significant portion of these lagoons is legally protected under Uruguay's National System of Protected Areas (SNAP) and through international conservation instruments. The Bañados del Este y Franja Costera and the Rocha Lagoon are two Ramsar sites that include a mosaic of lagoons, wetlands (e.g. wetland of Arroyo Maldonado), dune fields and floodplains and is one of the largest protected wetland complexes in South America (Ramsar Sites Information Services 2001, Ramsar Sites Information Service 2015).

State of the Art

Over the last decade, the SA-CSSL have increasingly attracted the attention of government agencies, civil society organisations and local universities. Government institutions are involved in environmental monitoring, law enforcement, water resource management and environmental licensing, particularly in ecologically sensitive areas such as wetlands. Civil society organisations have played an important role in advocating for conservation policies and in pressuring governmental agencies against developments that may compromise the multiple uses of these waterbodies, especially water supply, recreation and fisheries. Local universities have been conducting key studies over the past decades, which covers a wide range of disciplines, such as limnology, ecology, environmental monitoring, geomorphology and hydrology (Fragoso et al. 2008, Alonso et al. 2009, They et al. 2010, Crossetti et al. 2014, Finkler Ferreira et al. 2018, Rocha 2020, Lemos et al. 2022). These studies targeted different biological compartments, such as seston, plankton, nekton, benthos, macrophytes and genetic markers, as well as physical-chemical processes and compounds. The body of research demonstrates that the SA-CSSL region already holds a robust and interdisciplinary scientific foundation, largely built through efforts by Brazilian and Uruguayan universities. Slowly but surely, SA-CSSL is also gaining international attention. To showcase the most recent activities within SA-CSSL, a representative list of current and ongoing studies in the region has been compiled (see Suppl. material 1 on key studies). This highlights SA-CSSL as a promising research arena and re-affirms the continued engagement of national and regional academic institutions, as well as international collaborators. Two of the most important topics are addressing anthropogenic impacts and deterministic structuring of plankton communities by abiotic and biotic factors. Further details on these topics are provided in the following sections.

Exemplary studies on anthropogenic impacts

The emergence of novel entities and pollutants in the SA-CSSL has, for some time, caught the attention of researchers. For example, microplastics in the waters of the TRS showed concentrations of 225-240 units 100 m^{-3} in two of the larger lakes, indicating medium pollution levels of Polyethylene Terephthalate (PET), Polyvinyl Chloride (PVC), Polypropylene (PP) and Polyethylene (PE) (Corrêa et al. 2021). The plastisphere itself hosts variable microbial communities where taxa of potential public health concern were detected in high abundance during summer (Menegotto-Silva 2025). Moreover, chemicals, such as heavy metals (Rocha 2020), pesticides and pharmaceuticals (Pagani et al. 2022) are currently under investigation for developing a catalogue of different pollutants relevant for the spread and emergence of antimicrobial resistance and pathogens (Leite et al. 2019, Quintana 2024). Such studies were recently extended to bacterioplankton, where the coastal lagoons have emerged as key sites for identifying bacterial markers that can serve as indicators of emerging contaminants. High-throughput sequencing and basin-scale chemical profiling in Rocha and Castillos lagoons revealed that bacterial assemblages are partially structured by gradients of emergent contaminants, including pharmaceuticals, pesticides and endocrine disruptors (Griffero et al. 2019, Griffero et al. 2024). Distinct microbial signatures consistently differentiated contamination levels across seasons and included known degraders of xenobiotics, as well as groups of pathogens and opportunistic pathogens (Griffero et al. 2024). These findings highlight the potential of bacterioplankton communities as sentinels of both diffuse and point-source pollution and as integrators of multiple stressors for bioindicator frameworks.

Exemplary studies on biodiversity and the structuring of communities

Across the SA-CSSL gradient, recent work spans fish ecology, microbial dynamics and system-scale monitoring. In parallel, lake-model development and assessments of anthropogenic impacts have advanced (Silva and Tagliani 2012, Lanzer et al. 2013, Schäfer 2013, Castro and Rocha 2016, Schäfer et al. 2017, Leite et al. 2019, Oliveira et al. 2019, Rocha 2020, Corrêa et al. 2021, Caballero et al. 2022, Quintana 2024, Menegotto-Silva 2025, Contreras Rojas et al. 2025). This also includes contemporary analysis of eDNA, for example, for fungal diversity, trace the dispersal of microorganisms from the terrestrial catchment and as a biomarker for high amounts of sewage-related eutrophication (Pagani et al. 2022, Pagani et al. 2023). Many analyses of microbial biogeography of bacterioplankton were conducted, with emphasis on spatial patterns of distribution of taxa and relative roles of local and environmental factors on beta diversity (They et al. 2010, Lima et al. 2016, They and Marques 2019, Lima et al. 2020, Ribeiro et al. 2024). The structuring role of macrophytes on microbial communities was also investigated. Areas densely colonised by these plants induce bacterial biomass, density, growth, respiration rates and diversity through competition for inorganic nutrients and release of allelochemicals (They et al. 2010, They et al. 2013a, They et al. 2013b, They et al. 2015b, They and Marques 2019). Moreover, many lakes are now covered by monitoring and modelling efforts using remote sensing-spectral indices (Munar et al. 2018, Cabezudo et al. 2025) applied to phytoplankton blooms and water skin temperature (Munar et al. 2019, Tavares et al. 2019, Tavares et al. 2024).

Perspectives and Recommendations

Building on the existing knowledge and considering the unique environmental and societal contexts of the SA-CSSL region, we propose a set of priority research directions arising from our first workshop discussions. This workshop was held in Porto Alegre (Rio Grande do Sul, Brazil) from 31 March to 4 April 2025. It was hosted by the Institute of Hydraulic Research at the Federal University of Rio Grande do Sul (UFRGS) and the School of Health and Life Sciences at the Pontifical Catholic University of Rio Grande do Sul (PUCRS). An invitation to participate in the workshop was sent to research groups involved with the SA-CSSL. Students and researchers could register free of charge by completing an online form, with places allocated on a first-come, first-served basis. Participants included professors, researchers and students from the partner universities of Brazil, Uruguay and Germany. Accommodation and travel costs for participants from outside Porto Alegre were covered by a Global Incentive Fund from the Technical University of Munich. The activities involved lectures from participant researchers and students and discussions aimed to outline the next steps of the SA-CSSL collaborative projects, joint articles to be published and main recommendations for SA-CSSL studies. The programme also included an additional day visit to the Center for Coastal, Limnological and Marine Studies (CECLIMAR) in Imbé, Rio Grande do Sul, held on 8 April 2025. This visit aimed to promote interaction between international participants and local students, as well as to provide an opportunity to visit some of the shallow coastal lakes. The recommendations and research lines presented below were collaboratively established during the manuscript preparation process and all authors contributed ideas through a shared online document.

These recommendations reflect both the scientific potential of the system and its relevance for addressing broader global challenges, such as climate change, biodiversity loss, water quality deterioration and land-use transformations.

Key Features of SA-CSSL and proposed research lines:

- Extensive coastal belt: over 100 shallow coastal lakes, with a high number and diversity of lakes (isolated vs. interconnected, small vs. large, freshwater vs. intermittently brackish). This provides strong environmental gradients that enable comparative, gradient and event-based studies of community assembly, ecosystem functioning and resilience;
- Wind-dominated hydrodynamics: wind plays a central role in generating permanently mixed lakes that provide rare conditions for year-round analysis free from the influence of stratification dynamics for research on nutrient resuspension and ecosystem functioning, ideal for studying dispersal patterns and drift of natural communities and health concerning entities, such as pathogenic bacteria and antibiotic resistance genes. Moreover, due to this usually weak thermal gradient, these lakes respond quickly to changes in atmospheric conditions that may be driven by climate variability;
- Transitional zones: interface of marine, freshwater and terrestrial ecosystems enables studies of ecotones, salinity gradients and cross-ecosystem species dispersal. The proximity of such a large freshwater system with a similar origin to the ocean is a rare global setup. This brings the opportunity to study, for example, adaptation, biome specialisation, invasive species boundaries and other transitional features;
- Anthropogenic pressure: landscapes range from residual patches of pristine reserves to heavily impacted urban and agricultural zones, enabling gradient studies on how land-use, eutrophication, resilience and mitigation strategies influence ecological patterns and critical environmental processes. Several decades of limnological, ecological and geomorphological research and existing infrastructure for ongoing and future monitoring programmes establish the baseline for the study of future impacts, granted by well-established local expertise;
- Climate-change studies: The SA-CSSL system is ideal to study and develop models for the effects of rising temperatures and shifting ENSO on eutrophication and algal blooms, as well as the impact of climate change on the structure and functioning using a short-latitude range approach. For instance, connectivity amongst lakes and between land and lakes increases after more frequent flood events, providing an ideal condition for studies of before-and-after control impact (BACI) with time replication. This is the case of the Patos Lagoon system, which receives runoff from some of the largest watersheds in southern Brazil - a major outlet for extreme precipitation events, that are becoming more frequent and intense due to climate change. These systems can serve as natural laboratories to investigate the cascading effects of extreme freshwater inflows and the fate of terrestrial runoff under extreme weather or to investigate the effect on invasive

species (e.g. the spread of invasive fish species, such as *African tilapia* (Tavares et al. 2024));

- Environmental and public health monitoring: the high pollution levels observed in many of the SA-CSSL sets an opportunity to identify microbial and molecular biomarkers of environmental and public health relevance (e.g. antimicrobial resistance genes, human pathogens, pollutants). These systems can serve as critical models for understanding how aquatic ecosystems respond to challenges posed by urbanisation, insufficient sanitation and climate-driven runoff events. While such conditions may differ from those typically found in the Global North, they provide complementary insights into pollution-related risks that are increasingly relevant worldwide and can be integrated into a Planetary Health framework;
- Fill the gaps: most limnological knowledge is based on temperate lakes from the Northern Hemisphere. These systems offer a contrasting context that can help test or challenge assumptions (e.g. on community diversity and assembly, biogeochemical cycling) and will fill the global knowledge gaps that will allow a broader generalisation of results;
- Transnational conservation and regulation framework: SA-CSSL shares lakes and watersheds (e.g. Lake Mirim) across national borders offer case studies in transboundary governance, conflict and cooperation.

The landscape of the SA-CSSL is undergoing rapid transformation (Fig. 1), driven by diverse and often competing demands, including agriculture, fishing, aquaculture, infrastructure expansion, water resource management, drinking water supply and wastewater discharge. These pressures reflect the complex socio-environmental challenges at the heart of global change and planetary health, where human activities increasingly reshape ecosystems with direct implications for biodiversity, water quality and public well-being. Consequently, a future monitoring programme of the SA-CSSL will also be instrumental in its capability to provide information to science and the public, internationally and regionally. We decided to exemplify future monitoring parameters by using the planetary boundary system as it offers a structured and policy-relevant way to organise key environmental pressures affecting SA-CSSL (Richardson et al. 2023). Freshwater systems are amongst the most affected ecosystems when exceeding each category of planetary boundaries. Therefore, we discussed the required indicators for monitoring the planetary boundaries using the SA-CSSL as a global model site. We compiled a table (Table 1) that summarises the indicators we can use to measure the boundaries and identify the type of research that is still needed to establish and develop sustainable monitoring for future monitoring programmes. Next to scientific methods and standardisation needs, we identified that, if we would like to address and involve stakeholders along the SA-CSSL gradient for accompanying the dynamic changes and for conservation efforts, we will need to establish a sustainable communication platform, for example, based on a GIS system that can intersect multiple datasets and illustrate these for stakeholders (Uchaikina et al. 2025). Additionally, there is a great potential to involve local inhabitants in environmental monitoring through citizen science, as applied succesfully in other lakes to monitor cyanobacterial harmful algal blooms (Matthews et al.

2021) and lake transparency across wide geographical ranges as in the Secchi Dip-In Project.

Table 1.

Future Monitoring of global change factors.

Global change factor	**Expected changes**	**Indicators**	**Research needs**
Changes in ENSO	Shifting precipitation patterns, frequency of heavy storm events	Catchment hydrological models	Resistance and resilience of SA-CSSL ecosystems
CO_2 emissions	SA-CSSL as coastal carbon sink system	Sedimentation, production and respiration measurements	Role of SA-CSSL as carbon sink/source
Novel Entities	Emerging contaminants (pesticides, pharmaceuticals, heavy metals, microplastics)	Chemical indicators (for classes of chemicals), microbiological indicators for monitoring effects	Thresholds for minimal selective concentrations; multifactorial effects
Biosphere Integrity	Invasive species (*Ceratium*, piranhas, tilapias), antimicrobial resistance	Turnover of microbial communities, eDNA monitoring, antibiotic resistance genes	Endemicity of SA-CSSL microbes, degree of functional redundancy and vulnerability
Land System Change	Wetland degradation, increased urban and agricultural pollution	Remote sensing, water chemistry, urban markers	Catchment models and source tracking
Freshwater Change	Saltwater intrusion, freshwater quality loss	Water chemistry, microbial markers, algal pigments, algal bloom detection by remote sensing	Water usage and reuse capacity; management by restoration and biomanipulation
Biogeochemical Flows	Eutrophication, algal blooms, cyanotoxins	Water chemistry, microbial markers, lake metabolism	Stability of trophic networks in SA-CSSL
Atmospheric Aerosol Loading	Wind-driven aerosol loading of lakes	eDNA analysis, particle analysis	Rate of deposition, monitoring of catchment processes

Conclusions

In summary, the SA-CSSL comprises several comparable model lake systems along a latitudinal gradient on the South American subtropical coast. The systems are directly subjected to the effects of climate change caused by the predicted higher variability of ENSO (Cai et al. 2021). Moreover, the SA-CSSL is a highly dynamic region with different anthropogenic changes that enable investigation of global change effects other than warming, i.e. change in land-use, increase in novel entities, eutrophication, loss of biodiversity and change in water resources. Considering the geography, SA-CSSL is a highly interesting site for research on investigating multiple factors linked to ecology and anthropogenic activities on aquatic ecosystems, which are representative of a subtropical ecosystem in the Southern Hemisphere and may serve as a future sentinel system for a changing world.

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Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary material

Suppl. material 1: Supplementary Information

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Data type: Text
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