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Aquatic Sciences (2025) 87:66
https://doi.org/10.1007/s00027-025-01189-9

Aquatic Sciences

REVIEW

Threats and challenges for the conservation of marine molluscs in the southwestern Atlantic

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Received: 31 July 2024 / Accepted: 29 April 2025
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Abstract

The southwestern (SW) Atlantic is bordered by the coastlines of Brazil, Uruguay, and Argentina and is characterized by a great diversity of ecosystems, in which estuarine and marine molluscs are among the most representative invertebrates. The accelerating degradation of the environment due to human activity is resulting in the loss of species, leaving us insufficient time to comprehensively understand their morphology, ecological interactions, and the ecosystem services they provide. The aim of this manuscript is to review the conservation status of estuarine and marine molluscs in the SW Atlantic, identify the main threats and knowledge gaps, and indicate the challenges and prospects for their conservation. Physical degradation of environments, pollution, exotic species, and overexploitation of fishery resources are among the main non-climatic drivers threatening marine molluscs in the SW Atlantic. In addition, climate threats, such as rising temperatures and sea levels, and ocean acidification, create synergistic effects that are still not fully understood. Given this scenario, it is imperative to implement measures to mitigate this situation. These measures include strengthening management and governance to conserve habitats and control pollution and non-native species, with the aim of reducing ecosystem deterioration and establishing the foundations for monitoring environmental changes through long-term interdisciplinary projects. Additionally, there is a need to improve legislation aimed at regulating fishery practices. To achieve the effective conservation of estuarine and marine molluscs in the SW Atlantic, it is also essential to strengthen scientific dissemination projects and expand and support the training of researchers specialized in molluscs.

Keywords Biodiversity · South America · Anthropogenic impacts · Climate change · Environmental management

"La mer est le vaste réservoir de la nature".
Jules Verne, Vingt Mille Lieues sous les Mers.

Introduction

The concepts of the Anthropocene and the Great Acceleration show the clear interlinked nature of human socioeconomic activities, the planet's biophysical subsystems or processes, and the mid-twentieth century changes in the state and functioning of the Earth System (Steffen et al. 2015a). In this scenario, a set of frameworks and actions [e.g., the Convention on Biological Diversity of the United Nations Environment Programme, the 2030 Agenda, and their 17 Sustainable Development Goals, and the Decade of Ocean

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Published online: 26 May 2025

Science for Sustainable Development (2021–2030)] have been developed to help understand the risks associated with these changes and to provide guidance for Earth System Governance (Rockström et al. 2009; Steffen et al. 2015b; United Nations 2024a, b).

The vast richness of biota and the associated knowledge gaps in marine biomes make their conservation a great challenge. The species extinction curve is increasing exponentially [Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019; Obura et al. 2023], causing the scientific community to start thinking outside the box, looking for new methods and solutions to bend the curve and to safeguard ecosystems. Studies have already shown the impacts of anthropogenic stressors acting simultaneously on marine populations (e.g., marine pollution, habitat degradation, overfishing, the introduction of non-native species, and climate-change related stressors) (Poloczanska et al. 2013; Pecl et al. 2017; Cooley et al. 2022; Costello et al. 2022).

Molluscs are crucial components of the ecological balance of marine fauna, performing different functions in trophic niches and influencing the biodiversity of coastal and oceanic ecosystems (Gofas and Zenetos 2003). More than 50,000 species of marine molluscs are found throughout the world's oceans (Bouchet et al. 2023), on the ocean bottom or in the water column, from the intertidal to the deep sea, from the poles to the tropical latitudes, and this number is still considered an underestimate (Appeltans et al. 2012). Bouchet et al. (2016) suggested that ca. 150,000 species of marine molluscs remain to be described. Although marine species face significant threats, there are few and, in some cases, controversial, examples of extinction of marine molluscs (e.g., *Lottia edmitchelli*, *Cerithideopsis fuscata*, and *Littoraria flammea*) (Cowie et al. 2022; del Monte-Luna et al. 2023). Nonetheless, there are reasons to suspect that many marine extinctions have been generally overlooked and that several marine species are undoubtedly on the path to risk and extinction (Cowie et al. 2022), probably before being described. Currently, based on the categories and criteria established by the International Union for Conservation of Nature, 36 species of marine molluscs are classified as follows: Critically Endangered (14 species), Endangered (ten species), and Vulnerable (12 species). The low number of species evaluated is probably due to the scarcity of long-term studies that include population and reproductive data, which are more difficult to obtain for these groups compared to other animal groups.

The southwestern (SW) Atlantic, which is bordered by the coastlines of Brazil, Uruguay and Argentina, is characterized by a great diversity of ecosystems (Fig. 1). In its tropical area, there is a heterogeneous reef system, which includes the Great Amazon Reef System, the Brazilian semi-arid coast, and the Eastern Brazilian Reef System (Leão et al. 2003; Banha et al. 2022; Carneiro et al. 2022). This tropical area is also characterized by the presence of four oceanic islands/archipelagos (the Rocas Atoll, the Fernando de Noronha Archipelago, the São Pedro and São Paulo Archipelago, and the Trindade and Martin Vaz Archipelago) and a variety of ecosystems, including mangrove forests, seagrass beds, rhodolith beds, sandy beaches, rocky shores, and estuaries (Dominguez 2006; Mohriak 2020). The subtropical region is defined by vast sandy beaches interposed with rocky coastlines, with many bays and inlets (Dominguez 2006). The temperate zone features equally extensive sandy shores and, although it lacks or rarely has rocky cliffs, it has an extensive shelf composed of a mosaic of sediments and outcrops (Ab'Saber 2005; Parker et al. 1999). The cold region is characterized by wide tidal flats and high rocky cliffs among gravel and sand beaches (Coronato et al. 2008; Mateucci 2012). The deep-sea area of the SW Atlantic includes a variety of geomorphological features, such as sedimented plains, slopes, plateaus, canyons, seamounts, guyots and methane seeps, which host a great diversity of ecosystems, including those of deep-sea corals (Violante et al. 2017; De Leo et al. 2020; Burone et al. 2021; Carvalho et al. 2023).

Estuarine and marine molluscs in the SW Atlantic remain under-researched with respect to their ecology and species inventories, including basic population, reproductive, and trophic data, with some outstanding ecosystems in particular being poorly studied (e.g., reefs at the mouth of the Amazon River, rhodolith beds, and deep-sea communities); there is also an alarming lack of long-term studies on these organisms (Oliveira and Absalão, 2009; Horta et al. 2016; Corrêa et al. 2018; Santos et al. 2021; Gaurisas and Bernardino 2023). However, there has been a marked increase in malacological studies in the SW Atlantic in recent decades. Machado et al. (2023) compiled a list of 2525 valid species occurring along the Brazilian coast, which represent 71% of all Brazilian molluscs. Over 500 marine and estuarine mollusc species have been reported from Uruguay (Scarabino 2004; Scarabino et al. 2015) and, for the Argentine coast, Bigatti and Signorelli (2018) reported 862 valid molluscan species (approximately 30% of the marine invertebrate fauna recorded in this area).

Estimating and understanding the mollusc biodiversity of the extensive western Atlantic area require more research. The intrinsically high richness and morphological variation of Mollusca, along with the difficulty of collecting and/or finding some groups in situ, and the low number of specialists and scarce funding for biodiversity studies, bring great challenges for this field of taxonomic, systematic, and ecological research (Norman and Huchberg 2005; Leite and Mather 2008; Todt 2013; Lima et al. 2017; Campagnari and Geiger 2018; O'Brien et al. 2021; Santos and Carbayo 2021). In the last decade, studies have

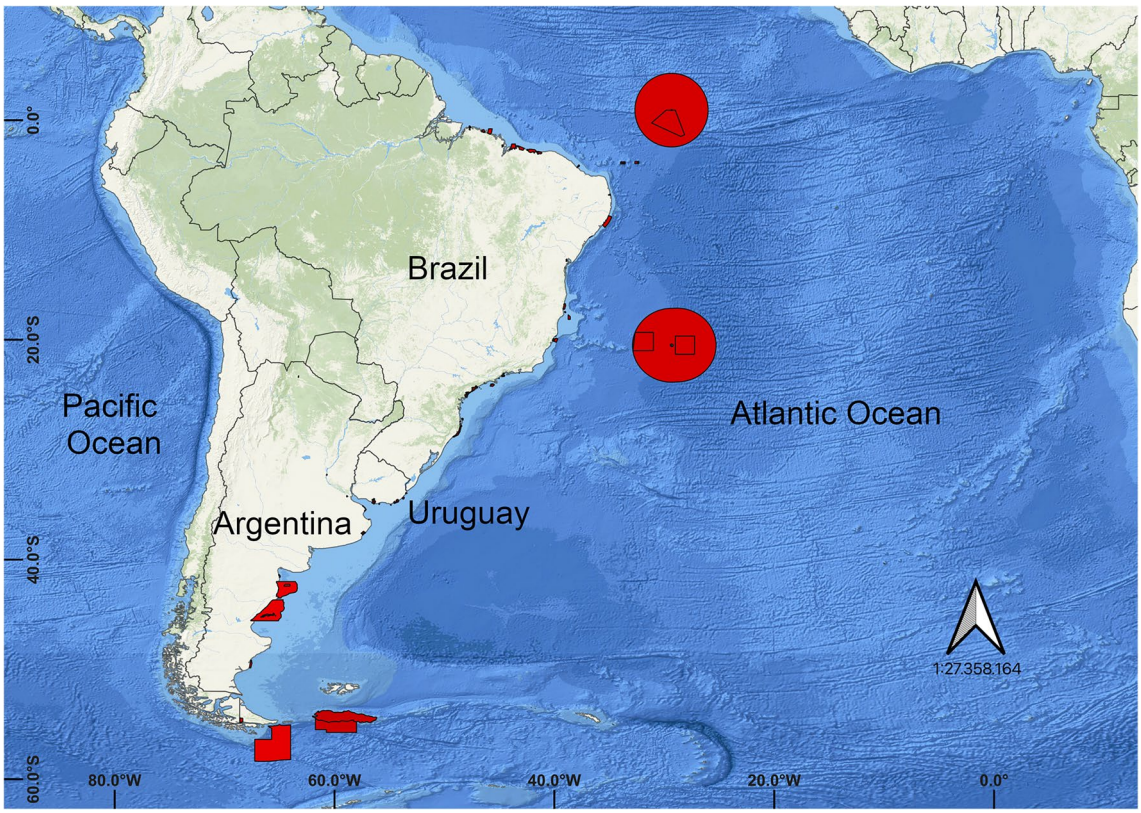


Fig. 1 The studied countries (Brazil, Uruguay, and Argentina) in the southwestern (SW) Atlantic Ocean, with their respective marine protected areas (MPAs) highlighted in *red*. Map created in QGIS using data from the Ministry of Environment and Climate Change (Brazil), the Ministry of Environment (Uruguay) and the Ministry of Defense (Argentina)

been conducted on lesser-known groups, such as Scaphopoda (Souza et al. 2013, 2020), Polyplacophora (Urteaga 2011; Güller et al. 2015; Jardim et al. 2022), Aplacophora (Ivanov and Scheltema 2008; Passos et al. 2019, 2021, 2022), and mesophotic and deep-water molluscs (Gleadall et al. 2010; Guerra et al. 2011; Signorelli and Pastorino 2015; Pastorino and Sánchez 2016; Signorelli and Crespo 2017; Siegwald et al. 2020; Barroso et al. 2021; Souza et al. 2021; Pacheco et al. 2022; Sánchez and Pastorino 2020). Advances in molecular methodologies have also sought to shed light on potential species complexes and the description of new species (Leite et al. 2008c, 2021; Claremont et al. 2011; Padula et al. 2014; De Biasi et al. 2016; Sales et al. 2019; Avendaño et al. 2020; Fernandes et al. 2021a; Jesus et al. 2021a; Dornellas et al. 2022; García-Méndez et al. 2022).

The objective of this review is to analyze aspects of estuarine and marine molluscs in shallow and deep habitats of the SW Atlantic (5 °N to 58 °S), focusing on the main threats, measures and ongoing management, challenges, and prospects for achieving their effective biodiversity conservation.

Threats to conservation

Marine biodiversity is threatened by several hazards, which can be classified as primary non-climate drivers (e.g., habitat loss, sea pollution, economic extractive activities, and non-native species) and climate-induced drivers (e.g., a long-term increase in sea surface temperature, acidification, the El Niño Southern Oscillation, and marine heat waves) (Cooley et al. 2022).

These two main types of threats interact with each other at local or regional scales, resulting in effects that can be synergistic, antagonistic or additive (He and Silliman 2019). Regarding the estuarine and marine mollusc species of the SW Atlantic, studies have indicated a set of local and regional impacts, including physical habitat degradation, marine pollution, fisheries/shell harvesting, non-indigenous species, increase in seawater temperature, and ocean acidification, as the main ones (see Fig. 2 and sections below).

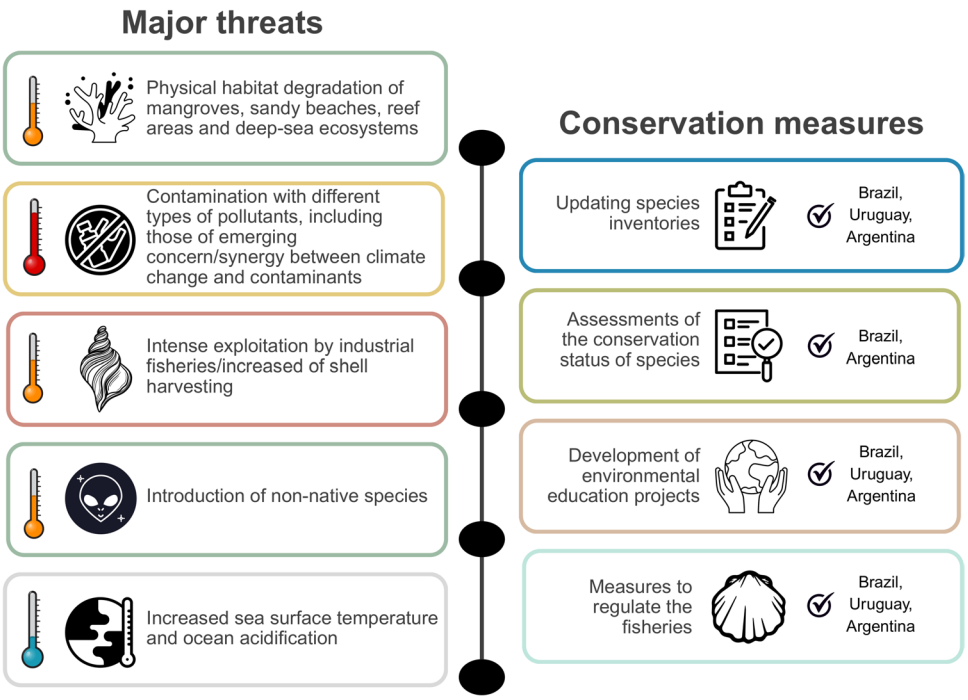


Fig. 2 Main threats to estuarine and marine mollusc species of the SW Atlantic Ocean, and some management measures that could help to safeguard their biodiversity. The number of studies related to threats is indicated by colored thermometers (*red* high number of studies, *orange* reasonable number of studies, *blue* low number of studies), and countries where conservation measures have already been implemented are indicated by a *check mark*

Primary non-climate drivers

Physical habitat degradation

The tropical and subtropical areas of the SW Atlantic are home to four of the ecosystems most heavily affected by human activities: sandy beaches, estuaries, mangroves, and coral reefs. The rapid growth of urbanization, fisheries, and tourism activities in Brazil, Uruguay, and Argentina in recent decades, together with the lack of controlled planning for natural coastal resources, has led to the construction of ports and coastal defenses (e.g., harbors and jetties) (Marcomini and López 2006). These structures, together with vehicular and ship traffic, the cultivation of seaweed, crustaceans and molluscs, and the extraction of sea salt, affect the morphodynamics of sandy beaches and estuaries, directly influencing communities of benthic and coastal molluscs (Amaral et al. 2016; Santos and Maia 2021; Corte et al. 2023), such as the bivalves *Amarilladesma mactroides*, *Brachidontes rodriguezii*, and *Donax hanleyanus* (Bom and Colling 2022; Elias et al. 2022). Estuarine areas have historically been favorable sites for human settlement and, more recently, have undergone intense urbanization, with many estuaries suffering from high levels of urban effluents, resulting in eutrophication and declining environmental quality (Barletta et al. 2019). In turn, the deforestation of mangroves areas, caused by shrimp farming, can influence shell morphology, size, and density of the gastropods *Littoraria angulifera* and *Melampus coffea* (Tanaka and Maia 2006; Maia and Tanaka 2007; Maia and Coutinho 2013; Araújo and Maia 2021).

With regard to reef areas, the biodiversity of the Great Amazon Reef System, of which still little is known (it is estimated that less than 5% of the reef area has been researched so far), is currently threatened by large-scale oil and gas exploration (Francini-Filho et al. 2018; Banha et al. 2022; Instituto Internacional Arayara 2023). So far, only a preliminary list of molluscs from this region has been published, which was obtained from bottom trawling (a current threat to this ecosystem) and cephalopod surveys using samples from red snapper stomachs (Sales et al. 2019; Santos et al. 2021). The physical destruction of areas of coral reef may also affect the population of the octopus *Callistoctopus furvus* in Bahia State (northeastern Brazil), where the highest density of this species occurs (Jesus et al. 2021a, b).

Deep-sea ecosystems are also threatened by anthropogenic stressors, especially mining activities. The economic and political pressures to exploit the seafloor run at a faster pace than scientific investigations (Sigwart et al. 2017; Rabone et al. 2023). Currently, the Rio Grande Rise, a large oceanic plateau located in the Economic Exclusive Zone (EEZ) of Brazil, is considered a target area for deep-sea mining (Praxedes et al. 2019). The diversity of molluscs of this region is still little known, and what is known is mainly based on empty shells (Pimenta et al. 2018; Fernandes et al. 2021b) and preliminary surveys (T.S. Leite, personal communication). In the Argentine Sea, resource exploitation initiatives have intensified in recent years, including planned mining activities (M.G. Palomo, personal communication) and the significant expansion of hydrocarbon exploration and extraction—particularly shale gas and oil—in the North

Argentine Basin, prompted by a series of government resolutions issued in 2018 (Socrate et al. 2024).

Marine pollution

Table 1 summarizes the studies carried out in the SW Atlantic, most of which investigated the bioaccumulation of metals and contamination with persistent organic pollutants (e.g., polychlorinated biphenyls, petroleum hydrocarbons and polyaromatic hydrocarbons, butyltin and organochlorine pesticides]. Despite the high number of publications on pollutant accumulation, and especially the occurrence of imposex (masculinization of females exposed to organotins such as tributyltin, which has been consistently associated with zones of high marine traffic), there are still few studies that have assessed the biological effects of environmental pollutants through biomarker detection (e.g., oxidative stress, shell structure and composition and histological alterations) (see Table 1).

Regarding contaminants of emerging concern (e.g., pharmaceuticals, cosmetics, endocrine disruptors, biocides, and plastics), research is still scarce (Table 1). Some studies have already shown the presence of microplastics in edible species and in marine protected areas (MPAs) of the SW Atlantic (Nunes et al. 2023a), and preliminary data indicate that depuration can be an alternative method for the mitigation of microplastics contamination in oysters (Christo et al. 2021). However, the biological effects of ingesting molluscs contaminated with microplastics is still a knowledge gap. Other types of interaction with marine debris have been observed in cephalopods (which use it as a shelter) and bivalves (which use it as a means of transport over a long distance, also known as "rafting") in the SW Atlantic (see Table 1). There is a need for further studies on these interactions, especially concerning the plastics and contaminants of the debris (Freitas et al. 2023).

Besides responses at the individual level, the effects of coastal pollution, with the increasing runoff of contaminated water, have led to the loss of seaweed biodiversity in estuarine and marine areas in the SW Atlantic. This loss affects trophic webs, causing shifts in benthic populations and assemblages (Scherner et al. 2013; de Oliveira Soares et al. 2016; Martinez et al. 2022). For instance, reductions in macroalgal cover have been associated with decreased functional diversity in mollusc assemblages, likely due to a loss of structural complexity and habitat heterogeneity (Floyd et al. 2020).

Fisheries/shell harvesting

Molluscs from the SW Atlantic have been subjected to intense exploitation by subsistence, recreational, small-scale and/or industrial fisheries (Table 2). Among cephalopods, the industrial fishery of shortfin squid, *Illex argentinus*, historically represents between 10 and 30% of the total catches in this area (FAO 2022), while other squid species are caught in different types of fisheries. Regarding octopods, some species are targets of industrial (e.g., *Octopus americanus*, which is the most important one) or recreational/artisanal fisheries (e.g., *Octopus insularis*, *Octopus tehuelchus*, and *Enteroctopus megalocyathus*) (Table 2). In Brazil and Argentina, octopus catches reported in the national fishing statistics do not include catches by artisanal fishing nor the identification of the octopus species. The records correspond only to landings of octopus bycatch, or of octopus pot fishery (in the case of Brazil). Some species were tested in aquaculture trials in Brazil and Argentina, but none achieved commercial scale status (Bastos et al. 2018, 2020; Berrueta et al. 2020; Braga et al. 2021, 2022). As octopuses have never been commercially farmed before, there are no laws regulating this practice or the octopuses' welfare (Andrade et al. 2023).

Bivalve species are also targets of industrial, small-scale and artisanal fisheries, being important sources of food and income for traditional communities of the SW Atlantic (Table 2). An industrial fishery developed targets for the Patagonian scallop *Zygochlamys patagonica*, which has been exploited in Argentine waters since 1996 (Morsan et al. 2017). In the 1970s and 1980s, the scallop *Euvola ziczac* was also a target of industrial fishing (with drags and bottom trawls) off the Brazilian southern and south coasts, but overfishing led to the collapse of the fishery and a drastic decrease in the abundance of this species, from which it has still not recovered (Pezzuto and Borzone 2004). In Brazil, over-exploitation (sometimes acting together with other anthropogenic stressors, such as habitat modification) of natural beds or aggregations are also observed in respect of stocks harvested by artisanal fisheries, e.g., *Perna perna*, *Mytella* spp. and *Crassostrea* spp. (Henriques et al. 2004; Oliveira et al. 2005; Pereira et al. 2001, 2003; Carranza et al. 2011). Population declines are also observed in the yellow clam *Amarilladesma mactroides*, artisanally harvested in Uruguay, and recreationally in Argentina. In Argentina, a decrease in the population of this species has been reported for the beaches of the northeastern coast (Olivier and Penchaszadeh 1968; Dadon et al. 2001). In Uruguay, a marked decline in the populations of *A. mactroides* was the result of overfishing between 1980 and 1985 (this species has been commercially exploited since the 1960s) (Defeo et al. 2021), and it was decimated by climate-driven mass mortalities throughout its distribution range during the 1990s (see also the section "Climate-induced drivers").

Gastropod catches in the SW Atlantic are associated with bycatch in industrial demersal fish fisheries, directed "boom and bust" fisheries, scuba-diving harvesting, baited traps, and subsistence intertidal hand-gathering by traditional

Table 1 Observed impacts of pollution, a primary non-climate driver, on estuarine and marine molluscs of the southwestern (SW) Atlantic Ocean

Observed impacts	Affected species	References[d]
Bioaccumulation of metals	Bivalves (*Anomalocardia flexuosa*, *Aulacomya atra*, *Brachidontes rodriguezii*, *Dallocardia muricata*, *Iphigenia brasiliensis*, *Mytilus* sp., *Perna perna*, and *Phacoides pectinatus*) Gastropods (*Adelomelon ancilla*, *Buccinanops cochlidium*, *Buccinastrum deforme*, *Nacella magellanica*, *Odontocymbiola magellanica*, *Pachycymbiola brasiliana*, *Tegula patagonica*, and *Trophon geversianus*)	1–18
Contamination with persistent organic pollutants	Bivalves (*Ardeamya petitiana*, *Aulacomya atra*, *Brachidontes rodriguezii*, *Mytilus* sp., *Perna perna*, and *Tagelus* sp.) Gastropods (*Buccinastrum deforme* and *Siphonaria lessonii*)	18–28
Oxidative stress due to accumulation of pollutants	Bivalves (*Aulacomya atra*, *Brachidontes rodriguezii*, *Mytilus* sp., and *Perna perna*) Gastropods (*Nacella magellanica* and *Siphonaria lessonii*)	4, 7–10, 14, 18, 24
Shell structure and composition alterations due to accumulation of pollutants	Gastropods (*Buccinastrum deforme*, *Bostrycapulus odites*, *Lottia subrugosa*, *Odontocymbiola magellanica*, *Siphonaria lessonii*, and *Stramonita brasiliensis*)	29–35
Histological alterations due to accumulation of pollutants	Bivalve (*Brachidontes rodriguezii*) Gastropod (*Siphonaria lessonii*)	33, 36
Imposex[a]	Gastropods (*Adelomelon ancilla, Adelomelon beckii*, *Bostrycapulus odites*, *Buccinanops cochlidium*, *Buccinastrum deforme, Buccinanops monilifer*, *Conasprella jaspidea*, *Hastula cinerea*, *Leucozonia nassa*, *Monoplex parthenopeus*, *Odontocymbiola magellanica*, *Olivancillaria deshayesiana*, *Olivancillaria vesica*, *Olivella minuta*, *Pachycymbiola brasiliana*, *Pachycymbiola ferussacii, Pareuthria fuscata*, *Phrontis vibex, Prunum martini*, *Pugilina tupiniquim*, *Stramonita brasiliensis*, *Stramonita rustica*, *Thaisella coronata*, *Trophon geversianus*, *Voluta ebraea*, and *Xymenopsis muriciformis*)	2, 37–69
Accumulation of tributyltin (TBT) in individuals and egg capsules	Gastropod (*Pachycymbiola brasiliana*)	2, 70
Contamination with emerging pollutants (e.g., pharmaceuticals, cosmetics, endocrine disruptors, and biocides)	Bivalve (*Perna perna*)	18, 71–75
Accumulation of microplastics[b]	Bivalves (*Amarilladesma mactroides*, *Aulacomya atra*, *Brachidontes rodriguezii*, *Crassostrea tulipa*, *Limnoperna fortunei*, *Magallana gigas*, *Mytella guyanensis, Mytella strigata*, *Mytilus* sp., *Perna perna*, and *Tivela mactroides*) Gastropods (*Aplysia brasiliana* and *Nacella magellanica*) Cephalopods (*Abralia veranyi* and *Vampyroteuthis infernalis*)	76–90
Use of marine debris as a shelter	Cephalopods (*Octopus tehuelchus* and *Paroctopus cthulu*[c])	91–95
Use of marine debris as a means of transport (rafting)	Bivalves (*Isognomon bicolor* and *Pinctada imbricata*) Gastropod (*Petaloconchus varians*)	96–99

[a]Masculinization of females exposed to organotins such as tributyltin, a specific kind of contamination with organic pollutants

[b]A specific kind of emerging pollutant

[c]A new species documented only on marine debris, which also used it to brood its eggs

[d]1—Gil et al. 2006; 2—Cledón et al. 2006; 3—Giarratano and Amin 2010; 4—Comoglio et al. 2011; 5—Conti et al. 2011; 6—Conti et al. 2019; 7—Duarte et al. 2011; 8—Giarratano et al. 2011; 9—Giarratano et al. 2014; 10—Di Salvatore et al. 2013; 11—Buzzi et al. 2017; 12—Primost et al. 2017; 13—Bigatti et al. 2018; 14—Ruiz et al. 2018; 15—Barbosa et al. 2019; 16—Cledón et al. 2021; 17—Francioni et al. 2004; 18—Santos et al. 2022; 19—Massara Paletto et al. 2008; 20—Arias et al. 2010; 21—Commendatore et al. 2015; 22—Oliva et al. 2015; 23—Laitano et al. 2016; 24—Laitano and Fernández-Gimenez 2016; 25—Primost et al. 2018; 26—Francioni et al. 2005; 27—Francioni et al. 2007a; 28—Francioni et al. 2007b; 29—Laitano et al. 2013; 30—Márquez et al. 2011; 31—Márquez et al. 2017; 32—Harayashiki et al. 2021; 33—Landro et al. 2021; 34—Gouveia et al. 2022a; 35—Gouveia et al. 2022b; 36—Arrighetti et al. 2019; 37—Castro et al. 2000; 38—Penchaszadeh et al. 2001; 39—Fernandez et al. 2002; 40—Camilo et al. 2004; 41—Castro et al. 2004; 42—Bigatti and Penchaszadeh 2005; 43—Castro et al. 2005a; 44—Castro et al. 2005b; 45—Castro et al. 2007a; 46—Castro et al. 2007b; 47—Castro et al. 2007c; 48—Queiroz et al. 2007; 49—Castro et al. 2008; 50—Meirelles et al. 2008; 51—Bigatti et al. 2009; 52—Cardoso et al. 2009; 53—Teso and Penchaszadeh 2009; 54—Averbuj and Penchaszadeh 2010; 55—Arrighetti and Penchaszadeh 2010; 56—Gomes 2010; 57—Lima-Verde et al. 2010; 58—Azevedo et al. 2012; 59—Castro et al. 2012; 60—Teso et al. 2012; 61—Rossato et al. 2014; 62—Petracco et al. 2015; 63—Primost et al. 2015; 64—Rossato et al. 2016; 65—Averbuj et al. 2018b; 66—Maciel et al. 2018; 67—Rodrigues et al. 2020; 68—Ribeiro-Brasil et al. 2021; 69—Santos and Maia 2023; 70—Goldberg et al. 2004; 71—Fontes et al. 2018; 72—Cortez et al. 2018; 73—Cortez et al. 2019; 74—Ortega et al. 2019; 75—Fonseca et al. 2020; 76—Santana et al. 2016; 77—Fernández Severini et al. 2019; 78—Pazos et al. 2020; 79—Pérez et al. 2020; 80—Ríos et al. 2020; 81—Ojeda et al. 2021; 82—Truchet et al. 2021; 83—Vieira et al. 2021; 84—Christo et al. 2021; 85—Staichak et al. 2021; 86—Costa et al. 2022; 87—Ferreira et al. 2022; 88—Nunes et al. 2023b; 89—Ribeiro et al. 2023; 90—Schuab et al. 2023; 91—Alves and Haimovici 2011; 92—Storero et al. 2013; 93—Leite et al. 2021; 94—Freitas et al. 2022; 95—Freitas et al. 2023; 96—Breves et al. 2014; 97—Marques and Breves 2014; 98—Póvoa et al. 2021; 99—Breves and Skinner 2014

communities (Table 2). While the utilization of molluscs as a food source is relatively common along the Uruguayan and Argentine coasts, it is not common in Brazil (athough some Brazilian traditional communities collect them specially for subsistence) (Table 2). The most popular use of gastropods in Brazil is for ornamental purposes, and demand for their shells is intense due to an increase in tourism (Dias et al. 2011; Mota et al. 2020). Large-scale shell collecting for reasons other than food was included among the possible, yet to be proven, causes for the local extinction of *Olivancillaria contortuplicata* in Barra del Chuy and La Coronilla (Uruguay) (Scarabino 2004). Along the SW Atlantic coast, gastropods are consumed without official records on their landings.

Non-indigenous species

In recent decades, reviews and new records of non-indigenous molluscan species in the SW Atlantic have been published (Pastorino et al. 2000; Orensanz et al. 2002; Carranza et al. 2010; Spotorno-Oliveira et al. 2018, 2020; Cavaleiro et al. 2019; Gernet et al. 2019; Messano et al. 2019; Amaral et al. 2020; Darrigran et al. 2020, 2025; Schwindt et al. 2020; Teixeira and Creed 2020; Lima and Passos 2021; Soares et al. 2022; dos Santos et al. 2023; Pedro et al. 2023). According to these studies, the non-indigenous molluscan species detected up to now in the SW Atlantic are the gastropods *Eualetes tulipa*, *Indothais lacera*, and *Nassarius foveolatus* (Brazil), *Pleurobranchaea maculata* (Argentina) and *Rapana venosa* (Brazil, Uruguay, and Argentina), and the bivalves *Leiosolenus aristatus, Mytilopsis* cf. *sallei, Mytilopsis leucophaeata*, *Perna viridis* and *Saccostrea cucullata* (Brazil), *Isognomon bicolor* (Brazil and Uruguay), *Magallana gigas* and *Talonostrea talonata* (Brazil and Argentina).

So far, few impacts on native molluscs have been reported (Carranza et al. 2023). Studies with *I. bicolor* have already shown high densities of this species on intertidal rocky shores along the Brazilian coast that have caused changes in the food habits of the gastropod *Stramonita* sp. (which previously preyed on *P. perna*) (López et al. 2010), with the potential to modify the composition and abundance of the local macrofauna community (Domaneschi and Martins 2002; Fernandes et al. 2004; Breves-Ramos et al. 2010; Martinez 2012; Dias et al. 2013). Living specimens of *I. bicolor* were also found in floating debris washed up on the coast of Uruguay, providing evidence that this species can be dispersed by rafting (Breves et al. 2014). *Perna viridis*, a native species of the Indo-Pacific Ocean, was recently recorded off the southeastern Brazilian coast (Messano et al. 2019; dos Santos et al. 2023). There is no record of impacts of this species on native communities, contrary to observations documented for the Caribbean and North America (Dias et al. 2018). Regarding non-indigenous oyster species, impacts of *S. cucullata* (which is native to the Indo-Pacific) on Brazilian benthic communities have yet to be observed, despite their sympatry with native oyster species along the southeastern and southern coasts of Brazil (Amaral et al. 2020). On the other hand, the introduced Pacific oyster *M. gigas* now forms extensive beds on stretches of rocky shores of the Argentine coast, altering the structure of intertidal ecosystems (Mendez et al. 2015; Horta et al. 2022). It has also been found that *T. talonata* may outcompete *Crassostrea tulipa*, and is thus considered a nuisance species for oyster culture (Cavaleiro et al. 2019). *Leisolenus aristatus* caused damage to the shells of cultured scallop *Nodipecten nodosus* in a marine farm in Brazil, including severe scarring, other deformations, and even death (Simone and Gonçalvez 2006).

Among non-indigenous gastropods, the predatory activities of *R. venosa* and *I. lacera* may be affecting the ecological properties of their habitat, such as mussel coverage on rocky bottoms (Carranza et al. 2010; Spotorno-Oliveira et al. 2020; Pedro et al. 2023). However, no studies have quantified the extent of this presumably significant environmental impact. The presence of high densities of the sea slug *P. maculata* on the Argentine coast, where it appears to have become successfully established, may also endanger native species, adversely impacting the local biodiversity and posing potential health risks for humans (due to the possible presence of neurotoxins), particularly in tourist hot spots such as north Patagonian gulfs (Bökenhans et al. 2019, 2022; Battini et al. 2021).

Two species previously registered as non-indigenous on the Brazilian coast, the bivalve *Perna perna* and the nudibranch *Bulbaeolidia alba*, do not have this status confirmed herein (Teixeira and Creed 2020; Darrigran et al. 2020). The former was classified as cryptogenic due to divergences in the results of studies carried out on the origin of this species (Teixeira and Creed 2020; Calazans et al. 2021). The latter, in turn, is not considered cosmopolitan but a complex of species (Carmona et al. 2017), and the Brazilian specimens are possibly of the species *Bulbaeolidia oasis*, originally described from Cuba.

The introduction of non-indigenous species of other taxa to the SW Atlantic and their influence on the molluscan community must also be considered. For example, the green crab *Carcinus maenas* from Europe, which has established non-indigenous populations in Argentina, is a potential invader in southern Brazil (Young and Elliott 2019). This invasive crab has already been observed preying on native molluscan species including the mussel *Perumytilus purpuratus* (one of the main structuring species that affords shelter), and the gastropods *Buccinastrum deforme* (in one of the most important nearshore marine gastropod fisheries of Patagonia) and *Tegula patagonica* (Cordone et al. 2022; Márquez et al. 2024). The invasion of the lionfish *Pterois volitans* into northeastern Brazil (Maggioni et al. 2023) could also affect

Table 2 Mollusc fisheries in the SW Atlantic Ocean

Class	Species	Local	Capture methods	References[c]
Cephalopoda (squids)	*Illex argentinus*	From southern Brazil and Uruguay to Islas Malvinas (Argentina)	Target of industrial jigging and trawl fisheries; bycatch of bottom trawlers hake fisheries (in the upper slope and continental shelf); bycatch by bottom trawling (on the outer continental slope); bycatch of gillnet fishing directed towards monkfish	1–7
	Doryteuthis pleii	Southeastern Brazil	Bycatch of shrimp fisheries; target of small-scale fisheries; artisanal hand-jigging fisheries	1, 2, 8, 9
	Doryteuthis sanpaulensis	Southeastern Brazil, Uruguay, northern Patagonian Shelf (Argentina)	Bycatch of coastal shrimp bottom trawling; artisanal hand-jigging fishery; artisanal fishing (bycatch of beach seine)	1, 2, 10–13
	Doryteuthis gahi	Patagonian Shelf and around the Islas Malvinas (Argentina)	Specialized bottom trawl fishery; artisanal fishing (bycatch of beach seine); bycatch of shrimp and prawn bottom trawling	5, 10, 12
	Doryteuthis surinamensis, *Eucleoteuthis luminosa*, *Histioteuthis corona*, *Hyaloteuthis pelagica*, *Lolliguncula brevis*, *Ommastrephes bartramii*, *Ornithoteuthis antillarum*, *Pholidoteuthis adami*, *Pickfordioteuthis pulchella*, *Sepioteuthis sepioidea*, *Sthenoteuthis pteropus*, *Thysanoteuthis rhombus*, *Todarodes filippovae*[a]	Brazilian coastal shallow or deep waters	Bycatch of trawling fisheries	1, 3, 14–16
	Martialia hyadesi	Southern Patagonia around Islas Malvinas and Georgias del Sur (Argentina)	Jigging over continental slope	5, 17, 18
	Moroteuthopsis ingens[a]	East of Islas Malvinas and international waters of Argentina	Bycatch of hake and squid trawlers on the continental shelf and upper slope	19, 20

Table 2 (continued)

Class	Species	Local	Capture methods	References[c]
Cephalopoda (octopus)	*Octopus americanus*	Southeastern and southern Brazil and Uruguay	Target of industrial pot fishery; bycatch of shrimp trawling; by artisanal fishers using harpoons during freediving (off rocky shores)	21, 22
	Octopus insularis	northeastern Brazil and Brazilian oceanic islands	Target of a commercial pot fishery; by artisanal fishers through freediving and with a hook walking on intertidal reefs (called "polvejamento")	23–27
	Eledone gaucha[a]	Southern Brazil	Bycatch of shrimp trawling and pot fishery	1–3, 21
	Eledone massyae[a]	Southeastern Brazil, coast of the Buenos Aires province and the northern part of Patagonia Shelf (Argentina)	Bycatch of fish, shrimp and prawn trawling fisheries	1, 28, 29, 30
	Callistoctopus furvus[a]	northeastern Brazil	Artisanal fishery through *polvejamento* (octopus fishing) (on shallow reefs)	26, 31
	Robsonella fontaniana[a]	Patagonian coast	Bycatch of octopus by artisanal fisheries	32
	Octopus tehuelchus	Patagonian coast, in Río Negro and Chubut (Argentina)	Use of hooks and traps in the intertidal and traps in shallow subtidal areas; bycatch in trawling fisheries; bycatch from trawl fishing for shrimp and fish	1, 33–37
	Enteroctopus megalocyathus	Patagonian coast, in Río Negro, Chubut and Santa Cruz provinces, and Beagle Channel (Argentina)	Use of hooks in the rocky intertidal and subtidal hard bottom areas (by diving in the subtidal); bycatch in trawling fisheries; bycatch in trap fishing for southern king crab zone	33, 38–41
Bivalvia	*Amarilladesma mactroides*	Uruguay and Argentina	Artisanal fishery	42, 43
	Donax hanleyanus	Argentina	Recreational	43
	Zygochlamys patagonica	Northern Atlantic Patagonian gulfs (Argentina)	Industrial trawling fisheries	44
	Aequipecten tehuelchus	Natural Protected Area Peninsula Valdés and the southern part of San Matías gulfs (Argentina)	Small-scale fisheries	45, 46
	Aulacomya atra, Eucallista purpurata, *Mytilus platensis*, *Panopea abbreviata*	Northern Atlantic Patagonian gulfs (Argentina)	Small-scale fisheries; harvested by divers (*P. abbreviata*)	12, 44, 47–50
	Anomalocardia flexuosa	Northeastern and southeastern Brazil	Artisanal fishery	51–57
	Euvola ziczac[b]	Southeastern and South Brazil (São Paulo, Paraná, and Santa Catarina States)	Industrial fishing with drags and bottom trawls	58

Table 2 (continued)

Class	Species	Local	Capture methods	References[c]
Gastropoda	*Adelomelon ancilla*, *Coronium acanthodes*, *Fusitriton magellanicus*, *Odontocymbiola magellanica*	Uruguay, Argentina	Bycatch in the industrial demersal fish fisheries	59–62
	Adelomelon beckii, *Pachycymbiola brasiliana*, *Tonna galea, Zidona dufresnii*	Uruguay, Argentina	Directed "boom and bust" fisheries	61, 63–69
	Buccinastrum deforme, Buccinanops cochlidium, Nacella magellanica, *Odontocymbiola magellanica*	Patagonian Atlantic coast (Argentina)	Scuba-diving harvesting, baited traps, intertidal hand-gathering	12, 61, 62, 70–72
	Strombus pugilis	Southeastern Brazil (Rio de Janeiro State)	Artisanal fishing by traditional communities	73

[a]Species caught in small numbers or accidentally

[b]Species for which the fishery collapsed due to overfishing

[c]1—Costa and Haimovici 1990; 2—Haimovici and Perez 1991; 3—Perez et al. 2004; 4—Perez et al. 2009; 5—Arkhipkin et al. 2015; 6—Brunetti et al. 1999; 7—Crespi-Abril et al. 2008; 8—Perez et al. 2002; 9—Judkins and Vecchione 2013; 10—Barón and Ré 2002; 11—Vidal et al. 2013; 12—Elías et al. 2011; 13—Braga et al. 2019; 14—Haimovici et al. 2007; 15—Boletim Estatístico da Pesca e Aquicultura 2011; 16—Rosa et al. 2013; 17—González and Rodhouse 1998; 18—Agnew et al. 2005; 19—Laptikhovsky et al. 2010; 20—Rosas-Luis et al. 2014; 21—Ávila-da-Silva et al. 2014; 22—Côrtes 2022; 23—Leite et al. 2008a; 24—Leite et al. 2008b; 25—Leite et al. 2009; 26—Haimovici et al. 2014; 27—Sauer et al. 2021; 28—Pérez and Haimovici 1991; 29—Ré and Taylor 1981; 30—Ré 1998b; 31—Jesus et al. 2022; 32—Ortiz and Ré, 2011; 33—Ré 1998a; 34—Narvarte et al. 2006; 35—Storero 2010; 36—Bocco et al. 2019; 37—Sánchez-Carnero et al. 2022; 38—Cinti et al. 2003; 39—Ortiz 2009; 40—Ortiz et al. 2011; 41—Ortiz and Ré 2019; 42—Olivier and Penchaszadeh 1968; 43—Dadon et al. 2001; 44—Morsan et al. 2017; 45—Orensanz et al. 2003; 46—Orensanz et al. 2007; 47—Morsan 2003; 48—Orensanz et al. 2006; 49—Narvarte et al. 2007; 50—Morsán et al. 2010; 51—Nishida et al. 2004; 52—Nishida et al. 2006; 53—Gil et al. 2007; 54—Botelho and Santos 2005; 55—Silva et al. 2007; 56—Pezzuto et al. 2010; 57—Nascimento et al. 2022; 58—Pezzuto and Borzone 2004; 59—Carranza 2006; 60—Carranza and Horta 2008; 61—Bigatti and Ciocco 2008; 62—Bigatti et al. 2015; 63—Arrighetti et al. 2011; 64—Riestra et al. 2000; 65—Giménez et al. 2005; 66—Defeo et al. 2011; 67—Marín et al. 2020; 68—Sánchez et al. 2012; 69—Navarro et al. 2019; 70—Nieto Vilela et al. 2019; 71—Cumplido and Bigatti 2020; 72—Cumplido et al. 2022; 73—Moscatelli 1987

the native molluscs there, including the *Octopus insularis* population, since they co-occur and could compete for prey (Leite et al. 2016; Peake et al. 2018).

Climate-induced drivers

Studies have been carried out on the impacts of climate change (increased sea surface temperature and ocean acidification) in the SW Atlantic, which stands out as one of the largest and most significant hot spots for ocean warming worldwide (Ortega et al. 2016; Franco et al. 2020; Gianelli et al. 2021).

Manipulative laboratory experiments conducted with estuarine littorinids (*Littoraria angulifera* and *Littoraria flava*) from the Brazilian coast showed an increase in mortality, weight loss, and changes in the behavior of snails due to an increase in water temperature (Maia and Troncoso 2022). In recent research on species from southern Brazil, Uruguay, and northern Argentina, the yellow clam *Amarilladesma mactroides* showed the greatest sensitivity to climate change among the molluscs evaluated, while the cephalopods *Illex argentinus* and *Doryteuthis sanpaulensis* were among the least sensitive (Gianelli et al. 2023). In the Nuevo Gulf (Argentina), mass mortalities of scorched mussels (*Brachidontes rodriguezii* and *Perumytilus purpuratus*), which were probably related to an anomaly in the sea surface temperature, where it increased by more than 1 °C, were detected in different sites where their coverage, which was close to 90% before the 2019 austral summer, was replaced by bare soil and algae (Mendez et al. 2021). Studies also showed that an increase of sea surface temperature may change the geographic distribution and ecological niche of cephalopod species of the SW Atlantic. For example, *Argonauta nodosus* and *Doryteuthis pleii* have undergone a distributional shift toward the poles (Vales et al. 2017; Martins and Juanicó 2018). In addition, species distribution models predict that *Octopus americanus* will experience a poleward expansion alongside a range contraction in lower Atlantic latitudes (Borges et al. 2022). Meanwhile, for *O. insularis*, niche space expansion from the tropical Atlantic to the temperate northern Atlantic and temperate South America waters is expected (Lima et al. 2020), and this species was recently reported off São Paulo State (Brazil), which means its distribution has expanded 5° south (Leite et al. 2024). Increasing sea temperatures are also affecting the distribution of species of the genus *Mytilus*, causing more heat-tolerant species to invade the areas of distribution of cold-water species, while the latter are migrating towards the poles (Beyer et al. 2017).

Regarding the effects of ocean acidification, the manipulative laboratory experiments conducted by Maia and Troncoso (2022) also showed a decrease in shell size, resulting from the dissolution of the spire. Although there is no published information about the direct effects of ocean acidification on octopus species in the SW Atlantic, an indirect effect could be responsible for the reduction in the number of empty shells available as shelter to the smaller octopus species that have been found using marine debris as alternative dens (Iribarne 1990; Leite et al. 2021; Freitas et al. 2022).

A few studies only have documented the synergistic effects of primary non-climate and climate-induced drivers in the SW Atlantic. The collapse of *Nodipecten nodosus* sea farming in southern Brazil has been attributed to the negative effects of water pollution (high levels of nutrients and bacteria), combined with warming seawater (Thompson et al. 2023). Another consequence of these joint effects is the increase of frequency and duration of harmful algal blooms of marine coastal environments in recent decades, as a result of global climate change and anthropogenic eutrophication, which have negatively impacted *Amarilladesma mactroides* fishing activities, reducing fishers' revenues and leading to an increase in economic uncertainty (Gianelli et al. 2021). Mass mortality events of *A. mactroides* coincided with the onset of a climate shift (ocean warming) during the 1990s and early 2000s, occurring sequentially in a poleward direction from southern Brazil to Argentina as tropical waters moved poleward (Ortega et al. 2016 and references therein).

Oyster reefs and beds, which are dominant structures in estuaries around the globe, are another ecosystem threatened by multiple stressors and their synergistic effects (e.g., extensive harvesting of wild populations, dredging and trawling, introductions of non-native oysters, diseases, alterations of shorelines, changes in freshwater inflows, and increased loadings of sediments, nutrients, and toxins) (Beck et al. 2011). In a global analysis, oyster reef conditions in the SW Atlantic were categorized as "good" (less than 50% lost) or "fair" (50–89% lost), based on the percentage of the abundance compared to historical levels of abundance (Beck et al. 2011). Similar to oyster reefs, mussels also play a crucial role as ecosystem engineers, with their decline considered critical in the context of environmental change (Borthagaray and Carranza 2007; Carranza et al. 2009).

Conservation measures and management in progress

Some management measures have been undertaken in the SW Atlantic to safeguard mollusc diversity and maintain ecosystem health and services, such as the updating of species inventories, assessing the conservation status of species, developing environmental education projects, and undertaking measures to regulate fisheries (Fig. 2).

Biodiversity inventories

For the elaboration of public policies, decision-making, conservation plans, and effective management, it is indispensable to know how many valid taxa are represented in a study area and how vulnerable the species that are present are.

In Brazil, a group of more than 50 taxonomists maintains the list of mollusc species that is constantly updated as part of the Taxonomic Catalog of the Brazilian Fauna, a governmental open access database (http://fauna.jbrj.gov.br) (Machado et al. 2023). In Uruguay and Argentina, several studies, including recent oceanographic expeditions, have been conducted to improve knowledge on mollusc diversity and distribution in these regions (Pastorino and Chiesa 2014; Signorelli and Pastorino 2015; Zelaya 2015; Scarabino et al. 2015; Pastorino 2016b, 2016a, 2019; Pastorino and Sánchez 2016; Bigatti and Signorelli 2018; Di Luca and Pastorino 2018; Siegwald et al. 2020; Sánchez and Pastorino 2020; Pacheco et al. 2022, 2024; Cetra and Roche 2023; Sánchez et al. 2023, 2024, 2025).

Although the increasing number of studies undertaken in these areas enhances our knowledge about mollusc biodiversity there, the use of empty shells in taxonomic and biodiversity research hampers our understanding of the true diversity of extant species, as these assemblages could have been on the seafloor for centuries or millennia, and may represent rare extant or extinct taxa (Kowalewski et al. 2023). These factors must be taken into consideration in future studies.

Species conservation assessments

In the most recent Brazilian assessment, based on the categories and criteria established by the International Union for Conservation of Nature, four mollusc species were considered under threat (cephalopods were evaluated separately); of these, the three gastropods were classified as Vulnerable (*Petaloconchus myrakeenae*, *Macrostrombus costatus* and *Titanostrombus goliath*) and the bivalve as Endangered (*Euvola ziczac*) (ordinance ICMBio no. 148, 7 June 2022). The vermetid *P. myrakeenae*, categorized as Vulnerable, was recently proposed as a junior synonym for *Petaloconchus varians* (Breves et al. 2022), and therefore its conservation status should be reviewed. In relation to cephalopods, in the first Cephalopods Threatened Species Evaluation List for Brazil, published in 2024 (https://salve.icmbio.gov.br/#/), six species (three octopuses and three squids) were classified as Data Deficient and 40 species as Least Concern. The Argentine Malacological Association is set to publish the red book of molluscs from Argentina [*Libro Rojo de Moluscos Argentinos: Categorizacion de la Malacofauna segun su Estado de Conservacion*"] (in press), which will be the first assessment and compilation of vulnerable molluscs in the country.

Since there are still limited data on the diversity and ecology of many estuarine and marine mollusc species, the use of life history traits, such as body size and trophic position, can be a useful preliminary screening criterion for assessing a species' vulnerability to extinction. A recent study on benthic gastropods in the western Atlantic showed a negative association between large species and their trophic position, suggesting potential energy restriction and heightened vulnerability to environmental changes (Carranza and Arim 2023). These results indicate the importance of employing screening methods (such as the use of life history traits) prior to regional or global conservation assessments for mollusc species.

Environmental education projects

Environmental education can play a role in increasing public awareness about conservation, especially when conducted in collaboration with relevant environmental authorities. These educational initiatives usually have a localized influence and are associated with public universities or non-profit civil associations.

In Brazil, there are projects that are focused on an ecosystem [e.g., the Ecomangue project, (Instagram @_ecomangue; the Araçá Bay)] (Amaral et al. 2010, 2015) or a specific group [e.g., Projeto Cephalopoda (Instagram @projeto_cephalopoda)], which are developed through joint action by researchers and local communities. In Uruguay, the environmental education newsletter *Caracol Negro y sus Ovicápsulas* (Scarabino et al. 2020) has been particularly well received and used in a multitude of educational settings. Scarabino (2021) detailed ongoing or particularly interesting activities related to environmental-heritage education focused on molluscs from the country's eastern coast (Rocha). In Argentina, the non-profit entity ProyectoSub promotes ocean conservation, especially that of marine invertebrates and algae, using social networks and audiovisual technologies to encourage oceanic culture (https://www.proyectosub.org.ar/). There is also an educational program in Argentina focused on malacology, which contributes to the dissemination of knowledge about molluscs and promotes education in this field (Darrigran et al. 2014).

Management of molluscan fisheries

Molluscan fisheries in the SW Atlantic still lack effective regulatory measures designed to promote the conservation and management of these marine resources.

In Brazil, there is some federal and/or state legislation to regulate the artisanal fishery of the clam *Anomalocardia flexuosa* in some locations (Normative Instruction IBAMA no. 81, 28 December 2005), the artisanal fishery of *Octopus*

insularis in the Fernando de Noronha Archipelago (Leite et al. 2008a, b), the commercial octopus pot fishery in north and northeastern regions (Normative Instruction SEAP/PR no. 15, 19 June 2007), the pot fishery of *Octopus americanus* in the southern region (Normative Instruction SEAP/PR no. 26, of 19 December 2008 and Ordinance SAP/MAPA no. 452, of 18 November 2021), and the squid fishery in Rio de Janeiro (law no. 282–88 and Ordinance ICMBio no. 6, of 29 January 2014) and Santa Catarina (Ordinance SAQ no. 1/2024, of 9 February 2024) states. However, all of these measures are spatially restricted and fail to consider the geographic distribution of the target species. The management of *A. flexuosa*, for example, needs to take into account the structure of subpopulations (banks) at different levels of connectivity within a metapopulation, exploitation in specific banks, and the establishment of protected areas to maintain stocks (Rocha 2013). In the case of *O. insularis*, while the abundance of the Fernando de Noronha Archipelago population appears to be stable due an adequate management plan (Leite et al. 2008a, b), this species has also been artisanally harvested along the tropical Brazilian coast without regulation or monitoring, despite the high number of scientific publications on the species that can support appropriate legislation for its management (Leite et al. 2008a, 2016; Lima et al. 2014a, b). In turn, the change in the minimum depth allowed for capturing O. *americanus* (from 70 m to 35 m deep) (Ordinance SAP/MAPA nº. 452, of November 18, 2021) did not consider the ecology of the species, leading to the proposal of conservation measures, such as restricting industrial fishing near rocky shores (vital areas for juvenile growth and feeding) and maintaining artisanal freediving fishing for subsistence purposes (Côrtes 2022).

In Uruguay, there are also some management and conservation measures used to regulate fishing activity, such as the prohibition of the fishing of *Adelomelon beckii* and the establishment of minimum landing and commercialization sizes for *Mytilus platensis*, *Amarilladesma mactroides* and *Zidona dufresnii* (Resolution DINARA no. 213/018). In the case of *A. beckii*, the implementation of some specific fishing regulations have been recommended, such as the establishment of closed areas to guarantee the population's reproductive success, or the prohibition of the shell trade along the coast to definitively prevent landings of this species (Carranza et al. 2017). With regard to *A. mactroides*, authorization for its harvesting went through several phases, with the opening or closing of the season, based on the recovery of populations that presented episodes of mass mortality linked to harmful algal blooms and an increase in seawater temperature (Gianelli et al. 2021). These changes have significantly impacted the social-ecological system of the area, with the 14-year closure of its fishing in Uruguay resulting in economic losses and affecting the livelihoods of local communities (reviewed in Defeo et al. 2021). Despite the passage of time, clam populations have not recovered to their pre-mass mortality levels of abundance, indicating their high sensitivity to warming and limited adaptive capacity.

Argentina has also implemented measures to promote sustainable fisheries management, such as quotas and fishing seasons, but these are spatially restricted. The only octopus fishing management regulation (which is currently not applied), for example, is limited to Rio Negro province (northern Patagonia) and establishes rules for *O. tehuelchus* fishing (BO 4288, Resolution no. 025/2005). Regarding the shortfin squid, *Illex argentinus*, within the Argentine EEZ there are fishing management regulations that establish geographical and temporal limits (Consejo Federal Pesquero 2019, Resolution no. 14/2016). However, an important part of the *I. argentinus* life cycle occurs within the limits of the EEZ and in the adjacent international waters, where there is unregulated fishing by foreign overseas fleets. Overfishing in areas adjacent to the national EEZ is becoming a serious problem (FAO 2019), but the effects of the catches on the fished populations are not yet known (Brunetti et al. 2002; Arkhipkin et al. 2015). For *Doryteuthis gahi*, the Malvinas Islands fishery adopted management measures based on effort limitation (Arkhipkin et al. 2015). Regarding marine gastropod catches in North Atlantic Patagonia, a regulation (Regulation no. 199/2018 of the Secretary of Fisheries of Chubut Province) establishes a minimum harvestable size and fishing season for the species *Odontocymbiola magellanica, Adelomelon ancilla, Adelomelon beckii, Zidona dufresnii* (Volutidae), *Buccinastrum deforme, Buccinanops cochlidium* (Nassariidae), *Trophon geversianus* (Muricidae), *Tegula patagonica* (Trochidae), and *Nacella magellanica* (Patellidae) (Cumplido and Bigatti 2020; Cumplido et al. 2022). This was established prior to the massive exploitation of the resource, but only in Chubut Province, despite recommendations of specific fishery regulations for the entire coast of Argentina (Giménez et al. 2005; Arrighetti et al. 2011). With regard to the observed populational decline of *Amarilladesma mactroides*, the Buenos Aires Province Fisheries Directorate and the Municipality of Partido de la Costa have implemented measures prohibiting the extraction of this bivalve (Directive no. 956/96 of the Buenos Aires Province Fisheries Directorate, 1238/96, 1704/96, 1004/01).

Using scientific research together with traditional knowledge is also an important initiative in establishing effective regulatory conservation measures. An experiment with the artisanal pot fishery in northeastern Brazil was developed together with local fishers, who collaborated with the planning, developing and evaluation of the efficiency of pots in capturing *Octopus insularis* (Andrade 2016). Interviews with artisanal octopus fishers in several MPAs allowed the redescription and delimitation of the distribution area of the octopus *Callistoctopus furvus* (Jesus et al. 2021a, b, 2022). Ethnoecological research in the Coroa Vermelha

Environmental Protection Area (Brazil) demonstrated that fishers have knowledge about biological and ecological aspects of the octopuses that are compatible with scientific information about the species, and especially about its behavior and trophic ecology (Martins et al. 2011).

Most marine mollusc stocks that are commercially exploited in the warm-temperate SW Atlantic are fully exploited, overexploited, or depleted (Gianelli and Defeo 2017; Gianelli et al. 2023). In industrial fisheries developed in this area, sustainable management systems include onboard and port-based monitoring of catches, surveys and stock assessments, reference points, limited entry, rotational harvesting, and no-take areas (Defeo and Vasconcellos 2020). Considering that most sessile and sedentary mollusc species, and the typical way in which they are fished, have a strong and persistent spatial structure, spatially explicit management considerations should be of utmost priority for them (Defeo and Castilla 2005; Orensanz et al. 2005). For example, the distribution area of the Patagonian scallop is divided into management units, and the stock status of each unit is determined by a combination of biomass estimates and the proportion of harvestable scallops (Soria et al. 2016). Similar spatially explicit considerations have been implemented to manage other relevant commercial bivalve industrial fisheries in the SW Atlantic (Gutiérrez et al. 2011; Masello and Defeo 2016), and have also been considered a relevant management strategy in some small-scale fisheries in the region (Defeo and Castilla 2012; Orensanz et al. 2013).

Challenges and perspectives

Management of marine areas and fisheries

One of the greatest challenges for the effective conservation of marine species is understanding the dynamics of evolutionary and ecological processes in their environment. Consequently, a more nuanced evaluation of extinction risks is necessary, coupled with the implementation of measures for the effective mitigation of oceanic defaunation. The establishment of protected areas and precautionary management of ocean resources can contribute to achieving this objective (McCauley et al. 2015; del Monte-Luna et al. 2023). There are ongoing projects focused on creating new MPAs in the SW Atlantic. In Brazil, there are proposals to establish new MPAs along the coast that have different conservation priorities, and to create a protected area for benthic organisms, including *Octopus americanus*, in the southern region (Magris et al. 2021; Côrtes 2022). The government of Uruguay has made a commitment to increasing the protected marine area of the country to achieve a 30% target by 2030, which will be achieved by creating a network of well-connected and representative MPAs (Limongi et al. 2023). In Argentina, marine areas have increased significantly in the last 10 years, with the creation of the Namuncurá Banco Burwood and Yaganes MPAs. The criteria adopted in their creation were based on fisheries and touristic activities, with the aim of protecting economic resources and/or breeding sanctuaries, as well as the protection of marine mammals and birds (Fig. 3).

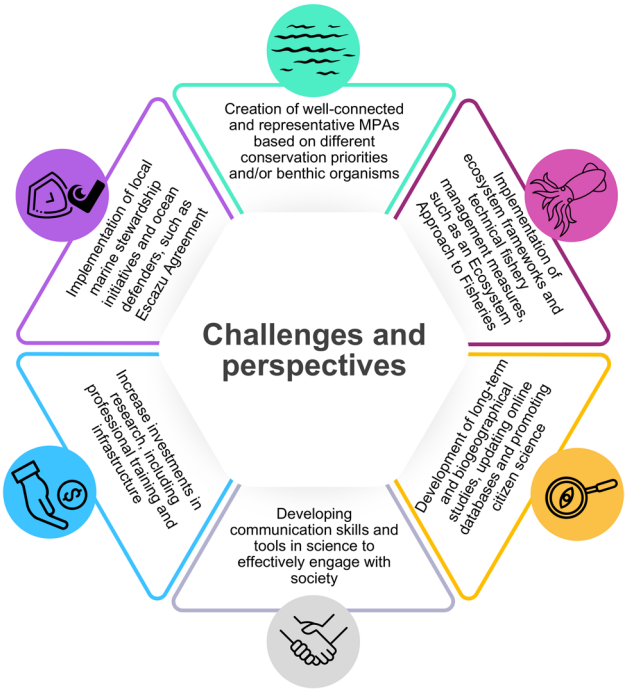


Fig. 3 Challenges and prospects for achieving the effective conservation of estuarine and marine mollusc species of the SW Atlantic Ocean

In the management of the molluscan resources in the SW Atlantic, the prevalence of open access regimes and the extensive accessibility of open coasts to unauthorized fishers and/or recreational harvesters have led to management failures. Additionally, distinct fisher idiosyncrasies among countries and the growing influence of external drivers, such as international trade and market globalization, governance, illegal fishing, and climate change, have emerged as major determinants in landings trends and stock statuses (Defeo and Vasconcellos 2020). Measures designed for the recovery of molluscan resources from such situations need to take into consideration spatially explicit management strategies and a set of biosocioeconomic indicators under a precautionary approach and solid governance schemes that must account for the full participation of fishers (Orensanz et al. 2013). Effective management strategies must take into account the fact that most molluscs are structured as metapopulations (Orensanz et al. 2005), implying that the spatial dimension

of processes related to both stages of the life cycle (i.e., dispersive larvae and benthic adults) must be considered when assessing and managing their stocks. Thus, assessment and management of these stocks require the identification of meaningful spatial scales to provide unbiased estimates of abundance and population structure, and to assess key spatial dimensions (population regulation mechanisms and processes, and the associated spatial dynamics of the harvesting process) (Orensanz et al. 2005; McLachlan and Defeo 2018). Moreover, the high sensitivity of certain exploited species and an increase in the representation of species with potential distribution changes due to climate change pose risks for future catches and benthic fisheries as a whole (Gianelli et al. 2023). Given this complex and concerning situation, comprehensive studies on the ecological impacts of the different external drivers acting jointly, or in isolation, are needed. Additionally, the development of long-term research programs that include the collection of scientific and traditional knowledge, along with participatory monitoring, control, and surveillance of management strategies, could provide a more optimistic perspective than the current one.

Weak governance and institutional instability also pose significant challenges to the sustainability of mollusc fisheries in the SW Atlantic, with important conservation implications. To ensure the long-term sustainability of fisheries, it is crucial to have sustained political commitment, state policies and high-level policy goals, as well as the implementation of ecosystem frameworks and technical management measures. Additionally, fishers themselves should be involved as stewards of their own activities. Incentive-based approaches that clearly define community and individual harvest or territorial rights should be implemented, alongside community-based data collection programs for research, monitoring, and effective oversight, to promote sustainable fisheries and better engage stakeholders in responsible fishing practices (Orensanz et al. 2013). An ecosystem approach to fisheries that includes co-management as a formal mode of governance is suggested to correct failures in fisheries (Gianelli et al. 2018). This approach may be applied, for example, to artisanal, small-scale molluscs fisheries, which are the most common form of exploitation on sandy beaches and rocky shores, and have important socioeconomic relevance in the SW Atlantic, providing food and employment and generating direct incomes for fisher communities and, in some cases, high export revenues for the countries concerned (Defeo et al. 2021). Therefore, management plans are needed to sustain fisheries over time and to contribute significantly to food security and adequate nutrition.

Long-term interdisciplinary monitoring programs

The development of long-term projects can help to establish new protected areas and manage species and their habitats. Although some seemingly reasonable initiatives have been developed in Brazil (Bernardino et al. 2016; Cordeiro et al. 2022), there is still a lack of long-term coordinated studies on molluscs from the SW Atlantic, which is a significant limitation for studying changes in these species and related marine ecosystems over time. For instance, little is known about the ecological impacts on molluscs of the mining dam collapse in 2015 (Matthews-Cascon et al. 2018) and the extensive oil spill in 2019 that affected Brazil's coastline (Viana et al. 2022; Soares and Rabelo 2023). There is also a lack of spatial and temporal trend data that show whether there are site differences and whether levels of pollution are increasing, decreasing, or are stable. The development of long-term monitoring programs that involve the collaboration of multiple countries, organizations and researchers is urgently needed and indispensable. Such programs should use standardized methods for data collection and analysis and involve new technologies, such as DNA sequencing and stable isotope analysis. Furthermore, the use of open access global geospatial datasets could help in delimiting target areas while simultaneously assessing the effects of land use changes (e.g., sediment runoff) in their vicinity (Delevaux and Stamoulis 2022).

Along with long-term monitoring programs, biogeographical studies should also be conducted to promote a better understanding of the biodiversity patterns of SW Atlantic molluscs. In recent years, efforts have been made to understand these diversity patterns in shallow (Barroso et al. 2016a; Cord et al. 2022; Oliveira et al. 2024) and deep waters (Teso et al. 2019; Pacheco et al. 2022), including those of oceanic islands (Hachich et al. 2015; Barroso et al. 2016b). Investigations using this approach can contribute to knowledge of species distribution patterns in different biogeographic areas of this region, and provide insights into the factors that influence benthic patterns on a global scale. Pending challenges in taxonomic and biogeographic research will be successfully addressed only if multinational collaborative initiatives are undertaken in a framework of integrative taxonomy (Scarabino et al. 2015).

Important tools to aid these studies are the on-line databases (WoRMS, MolluscaBase, Obis, GBIF, Malacolog, among others) that contribute to the updating of the taxonomic status and the current distribution range of species, showing and comparing the distribution ranges on a large scale and global level. Thus, the contribution of local and regional editors for the online databases is essential, to clarify the taxonomic status of mollusc species, as is the case with Project Cephalopoda and Lamece—UFSC (Brazil), which are working with photos and video databases

to identify octopus species (O'Brien et al. 2021). Another potential tool is to encourage citizen science efforts for the collection of data on mollusc populations, using platforms such as iNaturalist. This approach has been recognized as a complementary tool in alien species management and large-scale biodiversity conservation (Kelly et al. 2020). Citizen science initiatives can be an effective way of gathering large amounts of data over a long period of time, while also engaging society in reliable research.

Understanding the reproductive characteristics of a species is also a relevant tool that can assist in the creation of MPAs, the management of fisheries, long-term monitoring programs, and biogeographical studies, since the geographical distribution of species is affected, among other factors, by the type of larval development (Barroso et al. 2022). The reproductive characteristics of most mollusc species in the SW Atlantic, including those inhabiting adjacent deep-sea areas, are still little known. However, recent studies have expanded our understanding of deep-sea ecosystems in the area and allowed for the reassessment of species diversity (Pastorino and Scarabino 2008; Penchaszadeh et al. 2016, 2017, 2019, 2022; Averbuj et al. 2018a; Sánchez et al. 2018; Teso and Penchaszadeh 2019; Teso et al. 2019, 2020). These works revealed that the biodiversity and reproductive strategies of various taxa in these extreme conditions are more complex than previously thought. The knowledge gained from these studies is valuable for understanding life in the deep sea and can aid decision-making processes aimed at protecting marine biodiversity.

Major investment by research funding agencies that are disassociated from companies that aim to profit from the exploitation of living and non-living resources, as is the case in Brazil, is especially important for the operation of vessels to study mesophotic and deep-water molluscs. In Brazil, several projects have been developed through different types of cooperation, including between the Brazilian government and navy, research funding agencies and the state-owned Brazilian multinational corporation of the petroleum industry (Petrobras), in addition to partnerships with foreign institutions (see, for example, Absalão 2010; Perez et al. 2012; Veloso et al. 2017; Lavrado et al. 2017). In the case of Argentina, the Puerto Deseado research vessel, which was used in expeditions between 2009 and 2018, is currently out of service for researchers, while public policies to overcome this situation are not evident. An uneven capacity for sampling has also been the case in Uruguay, which mostly relies on international cooperation to achieve an understanding of its deep-sea biodiversity.

Another challenge that needs to be faced by researchers in South America concerns museums and scientific collections, which are fundamental resources for decision-makers (Johnson et al. 2023). Since the study of molluscs in the SW Atlantic began with the European and North American expeditions of the nineteenth century, most of the specimens collected were deposited in collections in the northern hemisphere. Despite the increase in the number of described species in the last years, many type specimens are housed in European or North American institutions, and access to these materials is often limited. The mismanagement of institutions has also led to the loss of important collections, such as the fire in 2018 at the National Museum of Rio de Janeiro (Zamudio et al. 2018), which housed one of the most important malacological collections in Brazil (Mega 2019). It is imperative that governments and civil society recognize species as heritage and appreciate them for their intrinsic value. Additionally, there is a need for increased investment in the training of taxonomists and other researchers specialized in the study of biodiversity, as well as the development of additional relevant infrastructure. Currently, the number of taxonomists dedicated to the study of marine molluscs is small (approximately 40 Brazilian, 14 Argentine and three Uruguayan researchers), when taking into consideration the vast area and diversity of ecosystems in the SW Atlantic.

Education and scientific dissemination

Effective conservation of marine molluscs requires a multi-faceted approach, including environmental education initiatives to raise public awareness on this issue. Interventions must be carried out in partnership with competent environmental agencies. This integrated and collaborative approach could foster the development of management and conservation strategies for the protection of molluscs and their ecosystems for future generations. The implementation of local marine stewardship initiatives and ocean defenders has been at the forefront of sustainability efforts, but still needs to receive recognition and support (Bennett et al. 2022). In this setting, the Escazu Agreement, developed in Latin America and adopted in March 2018, is the first international treaty in the world to include provisions on the rights of environmental defenders, providing full public access to information, decision-making, and legal protection and recourse concerning environmental matters (United Nations 2018). It also recognizes the right of current and future generations to a healthy environment and sustainable development. The Escazu agreement recognizes the primary role of civil society in securing environmental protection and consequently biodiversity conservation (McLachlan and Defeo 2023). Given their characteristics and socioecological significance across estuarine and marine ecosystems, molluscs possess the potential to be recognized and appreciated as pivotal components within these initiatives.

Conclusions

Despite the abundance of available information on estuarine and marine molluscs in the SW Atlantic, there remains a considerable way to go for their effective conservation. The numerous knowledge gaps highlight the necessity for effective public measures aimed at expanding financial and structural resources to attain the requisite knowledge and apply it more effectively in the establishment of environmental protection areas and for fishery stocks management. One of the pivotal considerations in forming these protected areas is to recognize benthic organisms as an essential component for the conservation of their entire ecosystem. Given the aforementioned, the following crucial measures can be outlined for the enhanced conservation of estuarine and marine molluscs in the SW Atlantic:

1. Strengthening management and governance to conserve habitats and control pollution and non-native species, with the aim of reducing the deterioration of ecosystem services provided by molluscs.
2. Establishing the necessary foundations for the monitoring of environmental changes—particularly those related to climate change and excessive human alterations that could lead to the loss of biodiversity in estuarine and marine ecosystems—through long-term interdisciplinary projects.
3. Expanding and supporting the training of researchers specializing in molluscs.
4. Increasing funding for scientific dissemination projects to increase society's awareness of the importance of molluscs.
5. Enhancing and improving legislation aimed at regulating mollusc fisheries.

Each of these measures requires a strategic approach and collaboration among various stakeholders, including governments, research institutions, local communities, and non-governmental organizations. Successful mollusc conservation depends on both the efficient implementation of short-term projects and investment in long-term solutions to address climate change and ecosystem degradation. Among the short-term projects, whose results could be observed within 2–3 years, are investments in researcher training, with an increase in capacity-building programs for taxonomists and greater funding for scientific dissemination. However, these measures will not be effective without long-term programs focused on integrated coastal zone management, which include partnerships between governments and local communities to regulate land use, pollution, and fishing and shellfish harvesting, as well as the establishment of environmental monitoring networks. Such projects are critically important for assessing real-time climatic and anthropogenic impacts and require planning, legislation, and continuous implementation.

Acknowledgements We are thankful to all of the researchers who have dedicated themselves to malacology. We are also thankful to Alexandre Dias Pimenta for contributing to the early stages of the manuscript, and Comisión Sectorial de Investigación Científica (CSIC Grupos 32).

Author contributions All of the authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by CXB, EPA and VT. The first draft of the manuscript was written by CXB and all of the authors commented on previous versions of the manuscript. All of the authors read and approved the final manuscript.

Funding FDP has received financial support from the São Paulo Research Foundation (FAPESP) (grant no. 2018/10313-0).

Data availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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