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Facing oceanographic, fisheries, and governance hotspots: Scientific evidence and policy implications from the southwest South Atlantic Ocean

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ABSTRACT

The southwest South Atlantic Ocean (SWAO) is a highly dynamic region where subtropical and subantarctic waters converge, making it one of the world's most productive marine areas. The SWAO is also one of the world's most intense marine hotspots, with rising sea surface temperatures and climate-induced shifts in species distribution posing significant challenges. This paper investigates long-term trends in key fishery resources exploited by Brazil, Uruguay, and Argentina over the past 70 years, focusing on the transboundary and straddling stocks that dominate the region's catch statistics. Key strengths identified include the use of diverse stock assessment methods, the implementation of effective management measures, and the establishment of collaborative governance systems, all of which have contributed to fostering sustainable fisheries. However, the study highlights the need for adaptive management strategies due to the impacts of climate change, including the tropicalization of species and shifts in fish abundance. Governance challenges are exacerbated by weak coordination among countries and the absence of robust and inclusive international agreements, particularly for managing straddling stocks in international waters. The paper emphasizes the need for an international governance framework aligned with ecological, social, and institutional scales aiming to ensure sustainable fisheries amid climate-induced changes. Recommendations include the development of dynamic and adaptive management approaches, enhanced monitoring systems, and stronger regional cooperation to address the shared challenges in the SWAO. The interplay between climate, biodiversity, and fisheries management and governance is essential for establishing resilient social-ecological systems in this region.

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1. Introduction

Fisheries are complex social-ecological systems shaped by the intricate interplay of proximate and distal drivers that operate across a wide range of spatial and temporal scales [64,104]. Proximate drivers include local factors such as fishing practices, community dynamics, and environmental conditions, which directly impact fish populations and ecosystem health, as well as the people that depend on them. In contrast, distal drivers include broader influences like global warming, governance, economic policies, and global market demands, which can indirectly affect fisheries by altering ecosystem conditions, resource availability, and seafood supply chains.

The compounding effects of proximate and distal drivers create a dynamic and often unpredictable environment, complicating fishery management and highlighting the need for a comprehensive understanding of both local and global influences. This multiple exposure to drivers [29,80] has led to social-ecological collapses of some small-scale [30,138] and industrial [113] fisheries. Addressing these challenges requires integrated approaches that consider the multifaceted nature of fisheries, promoting sustainability through adaptive management and collaborative governance frameworks that are responsive to changing conditions [124].

Governance and climate change are two major drivers currently impacting the sustainability of fisheries. Their interactions are especially critical for fisheries targeting stocks that span across national jurisdictions. Such stocks can span two or more Exclusive Economic Zones (EEZs) as transboundary stocks, or occur both within and beyond the EEZs of coastal states in the case of straddling stocks [58]. These stocks are often subject to large-scale variations in oceanographic and climate-induced factors, as well as differences in institutional arrangements and management systems between countries. Several straddling stocks intensively exploited by multinational fleets constitute open-access systems in international waters, further complicating sustainability efforts. Transboundary and straddling stocks are of special relevance for management and governance purposes, as they require specific additional efforts to accommodate management measures and plans at larger spatial scales, where coordination among neighboring countries becomes critical. Indeed, effective regional approaches depend on strong political will and coordinated actions to develop better fisheries management for transboundary and straddling fish stocks [58]. Unfortunately, there is often a misalignment between institutional arrangements and management measures with the spatial scales of stock distribution, and ecological and fishing processes. The lack of coordination between countries, often unwilling to collaborate due to conflicting geopolitical interests, has severely hindered the establishment of precautionary fishing strategies and the implementation of robust management plans, becoming a major obstacle to achieving fisheries sustainability [54,119,120,124]. The management challenges arising from the transboundary and straddling nature of these resources are further compounded by the inherent uncertainty in stock assessment models for commercial species, particularly when these models are based on data limited to national segments of the stocks [35].

Climate change is a critical driver of fisheries social-ecological systems, with substantial evidence showing its global impact [5]. Climate-driven shifting stocks and decrease in catch rates and revenues are major threats to both current and future fisheries [9,107,114]. Pinsky et al. [114] projected that many of the world's EEZs will likely receive one to five new climate-driven transboundary stocks by the end of the XXI century. However, other studies suggest that the overall maximum fish catch potential in EEZs is expected to decrease due to climate change [5,6]. The regional reshuffling of commercial stocks and shifts in fish abundance will require significant human adaptations across geopolitical boundaries, along with the adoption of dynamic and adaptive management frameworks.

The Southwest Atlantic Ocean, designated by FAO as Major Fishing Area 41 (Fig. 1; [39]), is one of the world's most productive marine regions, known for its rich biodiversity and abundant fish stocks which supply food and livelihoods to millions of people [8]. This productivity

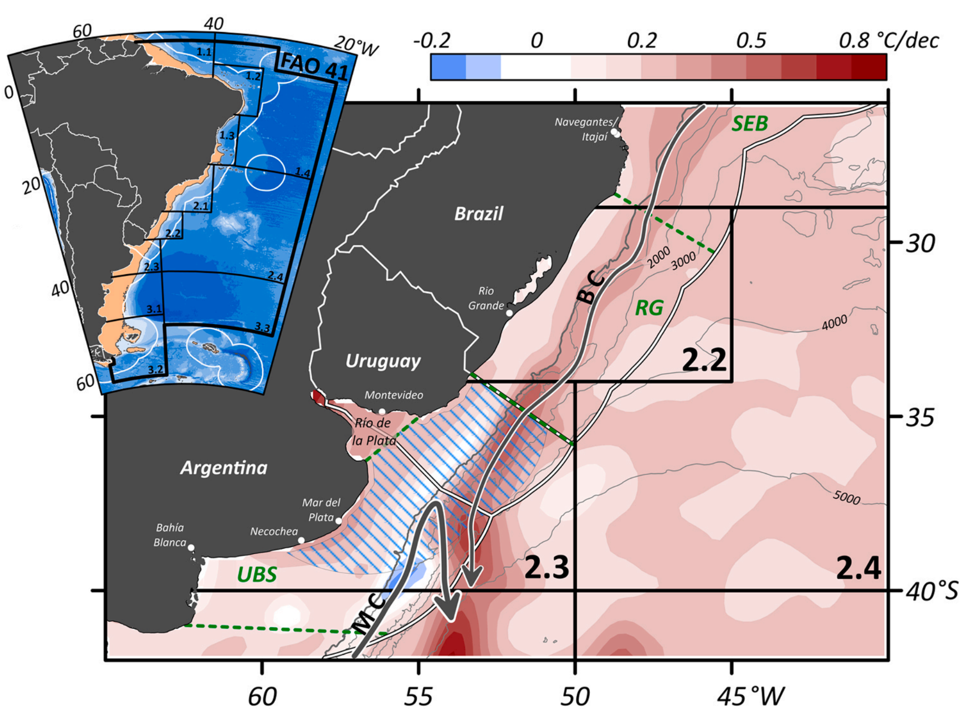

Fig. 1. Study area (SWAO: subregions 2.2, 2.3, and 2.4) within the FAO Major Fishing Area 41 (inset). The background colors in the main panel show the long-term sea surface temperature trends in °C/decade. Also shown are the major ocean currents (dark gray, BC: Brazil Current, MC: Malvinas Current), the limits of the Exclusive Economic Zones (EEZs) of Argentina, Brazil, and Uruguay (white line), the Argentine-Uruguayan Common Fishing Zone (AUCFZ, light blue hatching), and the major landing ports. Limits of the Marine Ecoregions (e.g., [135]) Southeastern Brazil (SEB), Rio Grande (RG), Río de la Plata, and Uruguay-Buenos Aires Shelf (UBS) are shown by dark green dashed lines. Inset: bottom topography (background colors) and EEZs (white line).

makes it a focal point for intense fishing pressure from national and international fleets. The fisheries sector supports a diverse range of activities, involving 27,000 active vessels, of which 18,000 are non-motorized, and includes both artisanal and industrial operations. It provides employment to approximately 3 million people, with 1 million engaged in the primary sector and 2 million in the secondary sector, including nearly 1.25 million women. Long-term average reported catches amount to around 2 million tons per year, generating an economic value exceeding 5.5 billion USD annually ([40] and unpublished data). The high demand for commercially valuable species has led to intense fishing activity, threatening the sustainability of fish populations and posing significant challenges to the health of marine ecosystems [29,40].

Within Area 41, we refer to as southwest South Atlantic Ocean (SWAO) the region extending from Cabo Santa Marta (28°S) to Bahia Blanca (41°S), encompassing FAO subareas 2.1, 2.2, and 2.3, along the coasts of Brazil, Uruguay, and Argentina (Fig. 1, see also [39]). The region hosts a broad variety of fisheries targeting fish and invertebrates of high economic value, which have supported the development of a large fishing sector in the three countries [53,101]. The SWAO is located at the transition between subtropical and subantarctic waters [116], characterized by sharp atmospheric and oceanic contrasts, and is particularly sensitive to climatic variations [42]. The region undergoes large seasonal and interannual fluctuations driven by variability of local wind patterns, continental discharges, and energetic boundary currents flowing along the continental slope [91,117]. In addition, the SWAO is largely immersed in one of the major ocean-warming hotspots worldwide, where sea surface temperature (SST) trends are much larger than the global average [65]. Long-term changes in oceanographic conditions may account for the recent shift from cold-water to warm-water species (i.e., tropicalization), as inferred using the mean temperature of the catch as a proxy, in both Southern Brazilian [108] and Uruguayan waters [51]. There is also empirical evidence of tropicalization in the region, with a relationship between SST and the occurrence of tropical fish species (e.g., [16,79,95]). The main species exploited in the SWAO transcend the political boundaries of the three countries, highlighting the growing need for a regional approach that integrates knowledge and capabilities to achieve more robust and institutionally consistent management at appropriate scales of analysis [53].

The transitional oceanographic conditions, the presence of one of the most prominent marine warming hotspots worldwide, and the multiple national responsibilities, make the SWAO a particularly challenging region for fisheries management and governance. This paper evaluates long-term trends over the past 70 years in the main fishery resources exploited by Brazil, Uruguay, and Argentina, with a focus on both the entire Southwest Atlantic Ocean and the SWAO in particular. It explores the historical factors driving changes in the region's fisheries and analyzes the strengths, weaknesses, and challenges in existing management and governance frameworks. Additionally, it examines the prevailing institutional framework and proposes guidelines for improvement in light of current and potential climate change impacts.

2. Physical Oceanography

2.1. Main environmental characteristics

The study region (SWAO) encompasses the continental shelf of eastern South America and neighboring oceans between ~28°S and ~41°S. It includes the shelf of southern Brazil, Uruguay, and northern Argentina, corresponding to subareas 2.2, 2.3, and 2.4 within FAO Major Fishing Area 41 ([39]; see inset in Fig. 1). The SWAO includes three ecoregions, all situated within the Warm Temperate Southwestern Atlantic Province [135]: (1) Rio Grande (RG); (2) Río de la Plata (RdlP); and (3) Uruguay-Buenos Aires Shelf (UBS). These ecoregions are similar to the FAO subareas 41.2.2 (Rio Grande) and 41.2.3 (Platense), where several fishery stocks of relevance to the SWAO are distributed and exploited (see Section 3).

Following the ecological definition of Province [135], the boundaries of the Warm Temperate Southwestern Atlantic Province are defined by specific hydrographic features (currents, upwellings) or geochemical influences (nutrient supply and salinity). In the three ecoregions that comprise the SWAO, the convergence of distinct water masses over the continental shelf and the adjacent deep ocean, together with the continental runoff and the variable wind patterns, create a complex and highly dynamic oceanographic setting. The northern portion of the shelf is characterized by southward flowing subtropical shelf waters, while the southern shelf is dominated by northward flowing cold-fresh subantarctic shelf waters [116]. The open ocean domain is characterized by intense western boundary currents: the southward flowing Brazil Current (BC) and northward flowing Malvinas Current (MC). The boundary currents collide near 38°S and veer offshore, creating intense mixing between subtropical and subantarctic waters, referred to as the Brazil/Malvinas Confluence (BMC, [56]). Our study is focused on the region south of 28°S, including the central and southern ecoregions of the Warm Temperate Southwestern Atlantic Province (RG, RdlP, and UBS), which are under the influence of the RdlP discharge.

The region is also characterized by significant continental freshwater discharges mainly from the RdlP (~35°S) and the Patos/Mirim Lagoon (PL, ~32°S), which discharge on average about 26,300 and 1100 $m^3 s^{-1}$, respectively [10,88]. The runoff represents a significant source of nutrients and impacts the vertical stratification [116] and the optical properties of the neighboring shelf [4,68]. The RdlP and PL create a low-salinity plume consisting of Plata Plume Water (PPW: salinity $<$ 33.5) spreading mostly northeastward along the coast of Argentina, Uruguay, and southern Brazil. Within the RdlP estuary, wind and discharge variations determine both the horizontal salinity distribution and vertical stratification [57,133]. The northeastward penetration of PPW over the continental shelf is strongly modulated by fluctuations of alongshore winds at synoptic, seasonal, and interannual time scales [117]. North of the RdlP estuary, the shelf circulation reverses from northeastward in austral fall-winter to southwestward in spring-summer. These seasonal reversals in the shelf circulation induce a northeastward extension of the PPW in austral fall-winter, and its southwestward retreat in spring-summer [98,116]. Thus, in summer, the PPW extends offshore and southward from the estuary [57]. Variations of the PPW driven by low-level winds can significantly influence the recruitment of commercially exploited species, and the spatiotemporal distribution and yields of coastal and shelf fishery stocks [42,72,73]. Substantial interannual variability is observed in the continental discharge of the RdlP [117] and PL [88]. For example, during the 1998 El Niño the RdlP average discharge exceeded 60,000 $m^3 s^{-1}$, while in 1978 it averaged 12,950 $m^3 s^{-1}$ [117]. These large discharge variations lead to substantial alterations of the shelf environment, which manifest as salinity, nutrient, and optical property variations primarily observed east of the RdlP mouth [91,118].

Both the shelf and adjacent deep oceans present distinct fronts, which are associated with high primary productivity [1,82,90,125]. The fronts are usually breeding grounds for species that lay planktonic eggs and larvae, and they offer suitable conditions for the development of early life stages of fishes and invertebrates. Adult fish migrate to these areas to take advantage of seasonal habitats [2]. Likewise, the region under the influence of the RdlP is characterized by high surface chlorophyll-*a* concentration [18,45], which is indicative of high phytoplankton abundance. Consequently, the study region hosts abundant pelagic and benthic populations, including commercially significant fishing species.

2.2. Oceanographic hotspot in the southwest South Atlantic

The SWAO forms one of the largest marine warming hotspots worldwide [65]. Several studies reported increased SST and/or bottom temperature along the path of the BC and the BMC since the early 2000s [42,43,123,143,145]. In contrast, the northernmost extent of the MC displays moderate cooling [44]. The southern portion of the outer-shelf region also presents a significant increase in surface chlorophyll-*a* concentration during the past two decades [31,44,89]. SST changes (displayed as background colors in Fig. 1) appear to be associated with changes in regional wind patterns, which may also have an impact on the distribution of PPW ([42], and references therein). Thus, there is solid evidence that the SWAO is sensitive to strong interannual variability and long-term changes associated with climate change.

3. Fisheries

3.1. Long-term trends

The FAO Major Fishing Area 41 supports highly productive fisheries that provide food and employment for millions of people, making them a critical component of the regional economy and food security [29,42,53]. Information spanning the past 70 years of landing data for Area 41 indicates a period of expansion and sustained growth in catches from 1950 to 1997, as has occurred globally [141], followed by a decline until 2004 (Fig. 2a). From then until 2021, there were interannual fluctuations of around 2 million tons per year, primarily driven by variations in catches of most important stocks. The Argentine shortfin squid (*Illex argentinus*) and the Argentine hake (*Merluccius hubbsi*) have accounted for 40 % of the total catches in Area 41 since 1950 (Table 1). Jigging and trawling are the main fishing methods employed for the Argentine shortfin squid, while trawling is the dominant fishing method used for Argentine hake.

The aforementioned trends reflect the overall fisheries production in

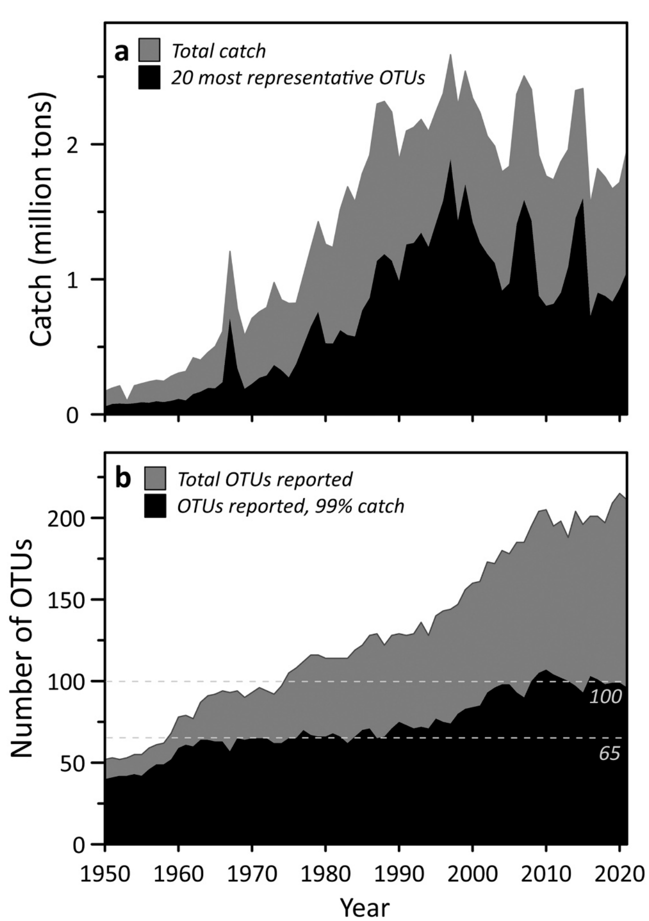

Fig. 2. Fishery production (a) and number of Operational Taxonomic Units (OTUs) (b) of fish, crustaceans, and mollusks exploited in FAO statistical Area 41 from 1950 to 2021. (a) Total catch (light grey) and landings for the 20 OTUs selected as the most representative in the SWAO (black). (b) Total number of OTUs (light grey) and number of OTUs representing 99 % of the catches (black). The dashed lines indicate two relatively stable periods in the number of OTUs reported in 99 % of the catches: ~ 65 OTUs between 1960 and 1985 and ~ 100 OTUs between 2005 and 2021. Source: FAO Global Fishery and Aquaculture Production Statistics v2023.1.2.

Table 1
Main Operational Taxonomic Units (OTUs) and their percent contribution to the total landings from FAO Area 41, aggregated from 1950 to 2021. Also listed are the major fishing ports where the OTUs are landed in the SWAO. BB: Bahía Blanca, NEC: Necochea, and MDP: Mar del Plata (Argentina); MVD: Montevideo, and LP: La Paloma (Uruguay); RG: Rio Grande, NVG: Navegantes, and ITJ: Itajaí (Brazil). * indicates species not included in FAO Global Fishery and Aquaculture Production Statistics v2023.1.2. nei: 'not elsewhere identified'. Additional information extracted from [53] is highlighted in bold.

Operational taxonomic unit	FAO common name	Landings FAO Area 41 (%)	Major fishing ports		
			Argentina	Uruguay	Brazil
Merluccius hubbsi	Argentine hake	20.6	BB, MDP	MVD	RG, NVG, ITJ
Illex argentinus	Argentine shortfin squid	19.8	BB	MVD	RG, NVG, ITJ
Micropogonias furnieri	Whitemouth croaker	4.6	MDP	MVD	RG, NVG, ITJ
Engraulis anchoita	Argentine anchovy	1.3	MDP, NEC	**LP**	
Scomber colias	Atlantic chub mackerel	1.2	MDP		
Cynoscion guatucupa	Stripped weakfish	1.1	BB, MDP	MVD	RG, NVG, ITJ
Rajiformes	Rays, stingrays, mantas nei	1.0	BB, NEC, MDP		**RG**
Umbrina canosai	Argentine croaker	0.6	**BB, NEC, MDP**	**MVD**	RG, NVG, ITJ
Pomatomus saltatrix	Bluefish	0.5	**BB, NEC, MDP**		RG, NVG, ITJ
Pleuronectiformes	Flatfishes nei	0.4	NEC		
Mustelus schmitti	Narrownose smooth-hound	0.4	BB, NEC	**MVD**	RG, NVG, ITJ
Macrodon atricauda	King weakfish	0.3	**BB, NEC, MDP**	**MVD**	RG, NVG, ITJ
Percophis brasiliensis	Brazilian flathead	0.3	NEC		RG, NVG, ITJ
Urophycis brasiliensis	Brazilian codling	0.2	**BB, NEC, MDP**	**MVD**	RG, NVG, ITJ
Artemesia longinaris	Argentine stiletto shrimp	0.1	BB		RG, NVG, ITJ
Helicolenus dactylopterus	Blackbelly rosefish	0.1	BB	**MVD**	
Squatina guggenheim	Argentine angelshark	0.1	NEC	**MVD**	RG, NVG, ITJ
**Penaeus spp.*	Pink-shrimps	-		**MVD**	RG, NVG, ITJ
**Prionotus punctatus*	Atlantic searobins	-			RG, NVG, ITJ
**Urophycis mystacea*	Brazilian codling	-			RG, NVG, ITJ

the SWAO: 20 of the historically most exploited Operational Taxonomic Units (OTUs)[1] in the study region (Table 1), representing 6 % of the 285 OTUs registered in the FAO database, account for 53 % of the total landings in Area 41 (Fig. 2b). In FAO subareas 2.2, 2.3, and 2.4 (see Fig. 1 and Section 2.1 for details), landings deconstructed by country show several commonalities. In the ports of Rio Grande, Itajaí, and Navegantes (Brazil), most of the landings consist of demersal sciaenid species (mainly trawling), including whitemouth croaker (*Micropogonias furnieri*), Argentine croaker (*Umbrina canosai*), and stripped weakfish (*Cynoscion guatucupa*) (Table 1). Note that although Itajaí and Navegantes are located outside from the study area, most of the catch landings at these ports are fished within the SWAO. Uruguayan landings are characterized by the dominance of three demersal species (trawling): *M. hubbsi, M. furnieri*, and *C. guatucupa* (Table 1). In Argentina, the port of Mar del Plata accounts for most landings obtained in the RdlP and Buenos Aires shelf regions (92 %), which are primarily characterized by the prevalence of *M. hubbsi*, *Engraulis anchoita*, *M. furnieri*, *Rajiformes*, *C. guatucupa,* and *Scomber colias* (Table 1). Other relevant species in the remaining Argentine ports (Bahia Blanca and Necochea) are bony fish (*Pleuronectiformes*, *Percophis brasiliensis* and *Helicolenus dactylopterus*), cartilaginous fish (*Mustelus schmitti* and *Squatina guggenheim*), and *I. argentinus* and Argentine stiletto shrimp (*Artemesia longinaris*) (Table 1). Other species reported in northern Argentine fishing ports are mostly caught further south (i.e., outside the SWAO) and thus were not included in the analysis (see the Dataset Section in the Supplementary Material). The results detailed above reveal that most of the exploited resources in the SWAO are transboundary (Table 1).

A regional heatmap showing fishing effort exerted in 2022 in the SWAO, based on the Automatic Identification System (AIS) data from Global Fishing Watch (https://globalfishingwatch.org/map) showed that Argentina and Uruguay each accounted for slightly over 20 % of the fishing effort, while Brazilian vessels represented 31 %, and foreign vessels contributed 24 % (Fig. 3). Furthermore, areas of higher fishing intensity were observed in the RdlP, corresponding to the Argentine-Uruguayan Common Fishing Zone (AUCFZ) and on Brazilian coasts. The spatial distribution of fishing effort throughout the study area displays a notable data gap in the northern Uruguayan shelf (Fig. 3).

3.2. Exploring the underlying factors behind the long-term trends

Fisheries in the SWAO are increasingly targeting a broad array of species that have gained socioeconomic importance. The long-term analysis reveals a consistent upward trend in the number of OTUs reported by FAO landings for Area 41, increasing from 51 in the 1950s to 215 in 2020 (Fig. 2b). Considering 99 % of the landings, the reported OTUs were fewer than 50 in the 1950s, increased to 65 in the mid-1960s, and remained constant until the 1990s, when there was another rise, stabilizing around 100 since 2005 (Fig. 2b, black shaded area). This pattern has also been documented in the SWAO, and is linked to the development of new fisheries targeting underexploited stocks with high unit value and increasing international demand [13,55,70]. While this increase might be partly attributed to improved species identification capabilities, the evidence for diversification of landings over time remains robust. The above-described trends in the number of OTUs coincides with a diversification of fisheries in the AUCFZ observed in the 1990s, which was associated with declining landings and fishing yields of traditional demersal resources such as *M. hubbsi*, *M. furnieri* and *C. guatucupa* [49,69]. Demersal fisheries in southern Brazil have exhibited a similar multi-fleet, multispecies trend, with diversification initiated in the early 1980s due to biomass reductions in pink shrimp (*Penaeus* spp.) and sciaenid species, including *M. furnieri*, *U. canosai*, *C. guatucupa*, and *Macrodon atricauda* [61]. During the 1990s and 2000s, trawl, bottom gillnet, and deep-set longline fisheries were developed, targeting various fish and invertebrates [62,110,115]. Other fisheries were developed in mid-slope regions by an international fleet targeting deep-sea crabs (*Chaceon* spp.), shrimps (Family Aristeidae), monkfish (*Lophius gastrophysus*), and octopuses (*Octopus americanus*) using traps, pots, gillnets, deep-set longlines, and trawls [109].

Some fisheries in the SWAO have transitioned from small-scale operations to multi-fleet industrial fisheries with major fishing power. The Argentine anchovy *E. anchoita* and Atlantic chub mackerel *S. colias*, two pelagic fish species, serve as examples. *E. anchoita*, a key species in the ecosystem, is the most abundant resource in the SWAO, with an estimated biomass of 4.5 million ton across its distribution area [83], while *S. colias* presents an increasing abundance [14] and a recent expansion in its poleward distribution mainly associated with rising SST [42,106]. Both resources are being fished below their potential. They have been exploited in Argentina since the beginning of the 20th century by small vessels using purse seine nets operating from Mar del Plata and more recently by vessels of greater size, range, and endurance (coastal and offshore ice-chilling vessels), which use mid-water and bottom nets. These small vessels, which have historically caught mackerel with small purse seines in late spring and early summer, now account for a smaller share of the landings. Only 13 small-scale vessels targeting both species in Argentina remain operational [47]. *E. anchoita* is not fished in Uruguay and Brazil [12,83]. The recent poleward range expansion of *S. colias* could have significant socioeconomic benefits, including year-round access for the canning industry, job creation, and local economic growth in Argentina [106].

3.3. Assessment, management and governance: strengths, weaknesses and challenges

3.3.1. Strengths

Various enablers contribute to promoting sustainable fishing practices by providing redundancy and complementarity in the assessment, management, and institutional aspects of these social-ecological systems, including:

1) Diverse stock assessment methods integrate long-term fishery data. The majority of key stocks exploited in the study region are supported by extensive databases. These include both fishery-dependent data (e.g., CPUE), and independent data from stock surveys. The systematic collection of data over several decades has facilitated the use of dynamic stock assessment approaches that consider fishing effort and/or the age structure of the populations analyzed [55,60]. Ancillary information accumulated over time aids in estimating performance indicators for the ecological, social, economic, and institutional pillars of sustainability. In southern Brazil, data-limited methods have proven effective in assessing demersal stocks [17]. In small-scale fisheries, however, long-term fishery data are scarcely available, resulting in a disparity in the quality and quantity of information.

2) A wide range of management measures applied simultaneously, including harvest controls and catch and effort regulation (e.g., limited entry, global and individual quotas). For most of the OTUs landed in the study region (Table 1), various management measures have been implemented simultaneously, including total allowable catches, spatial restrictions on bottom trawling, individual size limits, and bans on shark finning [23,69,81]. The positive relationship between the number of management measures applied and fishery success suggests that the benefits of management actions are cumulative and recommended to achieve sustainability goals, as observed elsewhere [59,93]. For the northern Argentine hake stock, a spatially dynamic management tool is the protection of juveniles in the AUCFZ through no-fishing zones. These seasonally closed areas, implemented decades ago and still in use today, are determined annually based on surveys assessing juvenile abundance [81].

Stock assessments in the AUCFZ are regularly conducted for *M. furnieri* and *C. guatucupa*, key coastal species in the SWAO targeted by

[1] Operational Taxonomic Units are preferred due to the uncertainty in taxonomic identification of species within certain taxa or groups.

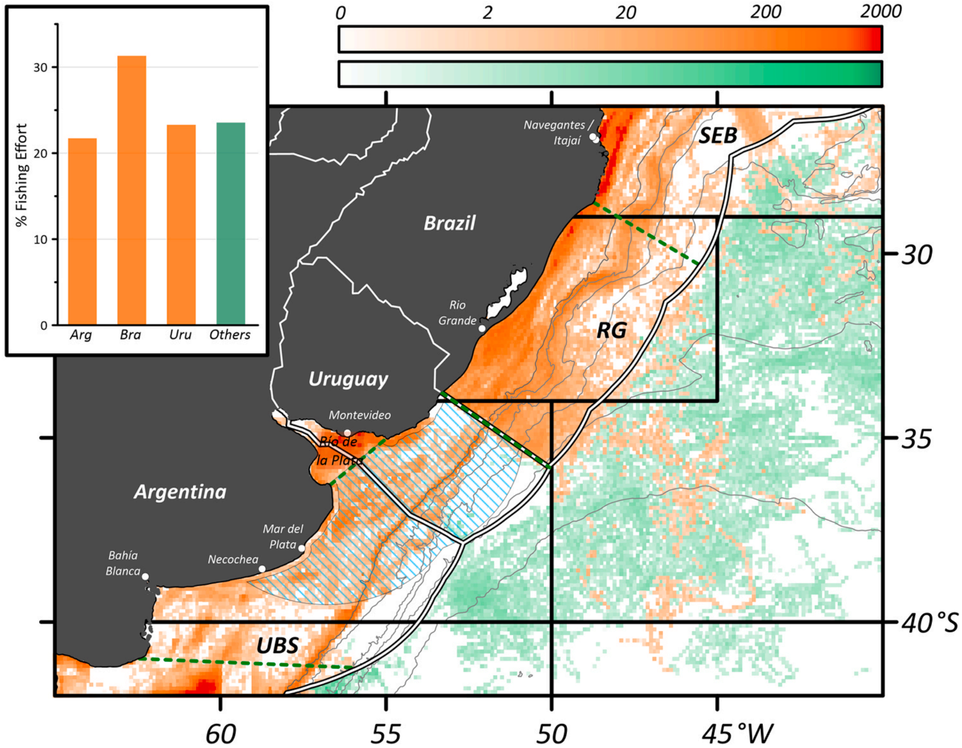

Fig. 3. Heat map showing the apparent fishing effort in hours during 2022 in the SWAO. Argentine (Arg), Brazilian (Bra), and Uruguayan (Uru) vessels are represented in orange, while vessels from other countries are shown in green (Others). The inset displays the relative fishing effort (%) achieved by Arg, Bra, Uru, and Others. The data collected from Global Fishing Watch (https://globalfishingwatch.org/map) covers all fleet types and fishing gear and depicts fishing effort distributed both along the continental shelf and offshore of the SWAO. Also shown are the limits of the Exclusive Economic Zones of Argentina, Brazil, and Uruguay (white line), the Argentine-Uruguayan Common Fishing Zone (AUCFZ, light blue hatching), and the major landing ports. Limits of the Southeastern Brazil (SEB), Rio Grande (RG), Río de la Plata, and Uruguay-Buenos Aires Shelf (UBS) ecoregions [135] are indicated by dark green dashed lines.

industrial fisheries across southern Brazil, Uruguay, and Argentina [53]. Management measures such as spatial closures, minimum landing sizes, and total allowable catches ensure sustainable fishing [28], though concerns persist for stocks in southern Brazil [63]. In the *E. anchoita* fishery in Argentina, operational management measures include size limits, closed seasons, a total allowable catch and biological reference points based on annual biomass estimates derived from acoustic surveys [121]. The fishery has been well-managed and is sustainably exploited by the country [12]. For cartilaginous fishes like *M. schmitti*, *S. guggenheim*, and Rajiformes, the three countries have enacted National Plans of Action for Conservation and Management [22,32,77]. Moreover, Argentina and Uruguay have implemented a Regional Action Plan [27] through the binational fisheries management body known as the Joint Technical Commission of the Maritime Front (Comisión Técnica Mixta del Frente Marítimo, CTMFM by its acronym in Spanish). Other long-term management success includes the industrial Patagonian scallop (*Zygochlamys patagonica*) in Argentina, which has been granted international certification by the Marine Stewardship Council [100,134]. In southern Brazil, management practices for the last 60 years have relied on effort control and seasonal fishing closures [110]. Recent significant ad hoc measures include implementing global quotas for the mullet (*Mugil liza*) fishery [128], introducing spatio-temporal management and selectivity regulations for fishing devices targeting deep-sea red crab (*Chaceon notialis*) [127], and closing coastal areas to trawl fishing [62].

3) Regular monitoring, control, and surveillance (MCS) and enforcement systems. Over the past decades, Uruguay and Argentina have implemented daily catch reporting and electronic logbook systems for MCS in the AUCFZ [87]. Information from vessel monitoring systems (VMS) and onboard observers is cross-checked with catch and effort data, providing redundancy and complementarity in control measures [86]. The Integrated Fisheries Control System (SICAP, by its acronym in Spanish), implemented in Argentina, employs a range of tools to enhance the monitoring and control of fishing activities [121]. These tools include an advanced information system, on-board video cameras for monitoring discards, real-time location surveillance through VMS, and naval patrols and overflights monitoring the ships [21]. Mesh sizes are controlled by on-board inspectors, the Coast Guard, and at landing sites [84]. Regular sampling is also conducted on board through an Observer Program. In Southeast and South Brazil, collaboration with the oil and gas industry has led to improvements in landing control for both industrial and small-scale fisheries. Logbook coverage has increased with the implementation of a fully digital system. While VMS and on-board observers were introduced in the 2000s, the official observer program was discontinued over a decade ago [109]. In April 2021, the Brazilian Secretariat of Aquaculture and Fisheries and Global Fishing Watch signed a memorandum of understanding to share satellite tracking data of 1500 Brazilian fishing vessels participating in the Satellite Fishing Vessel Tracking Program (https://globalfishingwatch.org/brazil/).

4) Collaborative governance systems. Relevant stakeholders play an important role in fisheries planning and management. Collaborative governance by the CTMFM, the Argentina-Uruguay binational body, has proven to be an effective platform for fisheries research and assessment, enabling the implementation of adaptive management systems based on long-term surveys of key stocks. In Argentina, the governance system in Marine Stewardship Council-certified fisheries like the Patagonian scallop *Z. patagonica* and the king crab *L. santolla* is supported by the active participation of the fishing industry [100,134]. The industry has played an important role in consultation processes aimed at establishing guidelines for stock assessment and management systems, as well as the implementation of MCS tools. This consultation process and interaction between the government and industry have generated a solid institutional framework [111]. Likewise, in Uruguay, a participatory governance framework has been institutionalized in small-scale fisheries through the creation of Local Fishery Councils, which actively involve fishers in setting management guidelines [7,50].

3.3.2. Weaknesses and challenges

Despite the examples provided above, concerns about the status of fish stocks in the SWAO persist. In 2018, 53 % of the assessed stocks in FAO Fishing Area 41 were fished at unsustainable levels, ranking it among the three worst-performing statistical areas (out of the 16 areas defined by the FAO), surpassed only by the Mediterranean & Black Seas and the Southeast Pacific [38]. Although this percentage decreased to 40 % in 2022 [40], several management and governance challenges still need to be addressed to promote fisheries sustainability, including:

1) Increasing effects of climate change-related stressors acting simultaneously on ecosystem and fisheries productivity. Climate-change related stressors acting simultaneously in this ocean warming hotspot have led to cascading effects on the assemblages that underpin the region's main fisheries [25,42,53]. Rising SST is a key long-term driver of the tropicalization of the SWAO [95,106]. Tropicalization trends were also reflected in an increase in the relative abundance of warm-water species in commercial catches, both in Brazilian waters [16,108,131] and in Uruguay and the AUCFZ [51]. However, effective and long-term monitoring systems must be implemented to detect both ecosystem and socioeconomic changes (e.g., [15]).

Climate change has impacted basal and intermediate trophic ecosystem levels, such as: (a) intensification of harmful algal blooms (HABs) with a greater representation of tropical species [52]; (b) mass mortalities, reduced abundance, smaller individual sizes, and an increase in disease occurrence in cool-water suspension-feeders [103]; (c) increased abundance, stronger recruitment, and extended reproductive and recruitment periods in coastal mollusks, polychaetes, and crustaceans of subtropical/tropical origin (e.g., [20,74]); and (d) reduced larval connectivity of species with cool water affinities [92]. Rising sea levels [126], increase in intensity and periodicity of onshore winds [52] and in extreme events such as heatwaves [85], have also contributed to the changing dynamics of the SWAO (reviewed in [42]). These drivers have particularly impacted small-scale fisheries, rendering these social-ecological systems even more vulnerable [53,71]. A 40-year analysis of Uruguay's intertidal yellow clam (*Mesodesma mactroides*) fishery reveals the positive impact of participatory governance and the negative effects of climate change on this vulnerable species [52,53].

There is a failure to adequately assess and anticipate climate-induced changes in marine species in the SWAO, evidenced by several critical shortcomings:

(a) Fisheries assessment, management, and governance are unprepared for the changes in stock abundance and structure, as well as the geographical distribution shifts anticipated due to climate change. The effectiveness of current static time-area fisheries closures in the region is challenged by climate-related changes in species distributions and fisheries operations [11,25,108]. In addition, managing transboundary species facing climate change demands international cooperation.

(b) Global climate models predict a decrease in overall fisheries catches for Brazil, Uruguay and Argentina by 2050 and 2100, even with a high uncertainty [8,24]. In addition, the implementation of multi-species and ecosystem models that integrate environmental drivers and trophic interactions for stock assessments [26], has been hampered by the lack of data needed to increase the reliability of these models.

(c) Holistic climate-change vulnerability assessments including social, ecological, and institutional issues are lacking. Past research efforts addressed the sensitivity, exposure, and adaptive capacity of marine species and fishing-dependent communities [13,53]. However, social-ecological vulnerability assessments should be conducted to identify adaptive strategies for the fishing industry and communities [48]. Institutional vulnerability assessments could also identify factors that facilitate or hinder institutional adaptation to changes in stock abundance and availability.

2) Incongruence between ecological and management scales, leading to an institutional misfit. Key straddling stocks, such as Argentine shortfin squid and Argentine hake, migrate between the regulated EEZs of Brazil, Uruguay, and Argentina and adjacent unregulated international waters (Fig. 3). Foreign fleets in these areas introduce significant uncertainty in stock assessments and management effectiveness, increasing the risks of overfishing and resource conflicts. This further highlights the urgent need for coordinated regional governance and stronger international agreements. Effective management strategies must transcend national interests, supported by a robust institutional framework for policy and legal implementation.

Fisheries management and governance in the SWAO are primarily confined to national jurisdictions or, at best, the Argentina-Uruguay commission (CTMFM) (Fig. S1 in Supplementary Material). This institutional setup is insufficient for addressing external drivers that threaten transboundary and straddling stocks on a larger spatial scale, leading to a mismatch between the human and biophysical components of the social-ecological system and resulting in an institutional misfit (sensu [36,37]). This misalignment affects coordination and creates discrepancies between the spatial scales underlying life histories, fishing processes, management practices, and institutional arrangements.

Sequential fisheries, where two fleets target different life stages of a species, have become increasingly significant in the region. These fisheries are particularly critical for transboundary coastal stocks that are exploited in all three countries, such as the whitemouth croaker (*M. furnieri*) and the stripped weakfish (*C. guatucupa*), which account for 5 % and 1 % of the historical catch in FAO Area 41, respectively (Table 1). In these cases, small-scale fisheries target these stocks within the 12 nm coastal zone using gillnets or longlines, while industrial fisheries, using bottom trawling, operate beyond this zone, despite frequent conflicts between the fleets [66]. The socioeconomic importance of these small-scale fisheries has been growing in the three countries [53]. However, these fisheries often suffer from a lack of up-to-date and long-term statistical data, and fragmented catch reporting.

3) Lack of autonomy and sovereignty: illegal fishing. Illegal, unreported, and unregulated (IUU) fishing has significant economic and ecological impacts, resulting in losses in both aquatic biodiversity and the economy. In recent years, the most significant cases of IUU fishing have been closely tied to instances of forced labor, with fleets often failing to report their positions ([34,102] and references therein). A global analysis of the deactivation of the AIS in commercial fisheries revealed that up to 6 % (> 4.9 million hours) of vessel activity remains hidden [142]. One of the four hotspots where AIS is disabled is located south of the SWAO, near Argentina's EEZ in the Patagonian region [142], where the Argentine shortfin squid and the Argentine hake are primary fishing targets. The Argentine shortfin squid is targeted by several foreign fleets for extended periods and is often transshipped at sea, enabling these fleets to evade the oversight that usually comes with port calls [132]. Frequent illegal transboundary fishing is evidenced by numerous cases of vessel detentions and catch confiscations.

The response of South American nations to IUU fishing could be strengthened with solid institutional arrangements [67]. Given the dynamics of fishing effort in the SWAO (Fig. 3), the evidence of illegal activities detailed in the previous paragraph, and the increasing exploitation of fisheries resources in the open ocean globally, a coordinated effort by the three countries is urgently needed. This effort should be supported by a new institutional arrangement aimed at enhancing coordination among the countries.

4. Discussion

The assessment of 70 years of catch statistics in the Southwest Atlantic Ocean (FAO Area 41), indicates that 40 % of the fishery resources are not being managed sustainably [40]. This suggests that there is room for improvement in the status of these fisheries. Given that these resources underpin the exploited stocks in the SWAO (Fig. 1), changes in management strategies are required to reverse the declines observed in recent decades. However, the nature of the primary resources in the region requires management approaches that transcend geopolitical boundaries. Indeed, the long-term analysis of catch statistics shows that most of the region's fishery resources are transboundary (Table 1), and the main resources (e.g., Argentine hake *M. hubbsi* and the Argentine shortfin squid *I. argentinus*) are also straddling stocks exploited by international fleets [3,140]. For both resource types, management plans designed with a national geopolitical perspective lose significance and call for the development of other approaches and conceptual frameworks that prioritize the intrinsic characteristics of the life cycles and distribution of the resources.

The SWAO has experienced an increase in SST at rates exceeding the global average, along with changes in wind direction, intensity, and ocean circulation, largely driven by climate change (see Section 2.2 and Fig. 1). These climatic and oceanographic changes have triggered significant shifts in the SWAO, a recognized biodiversity hotspot [122]. These shifts have influenced the structure of biological assemblages and altered the abundance and distribution of transboundary stocks along the continental shelf (reviewed in [42]; see also [95,106]). Such changes have impacted the composition of catches in the region, as demonstrated by long-term studies that used the mean temperature of the catch as a proxy [51,108].

4.1. Transboundary stocks

Transboundary stocks have been pivotal in shaping historical catch trends, both in FAO Area 41 and specifically in the SWAO. Argentine hake and the Argentine shortfin squid have represented 40 % of the total catch in the past 70 years. Additionally, coastal transboundary resources have characterized regional catches, especially whitemouth croaker, anchovy, mackerel, and stripped weakfish, which together accounted for 8 % of the total catch in FAO Area 41 (Table 1).

Long-term environmental trends suggest that climate change is at least partially responsible for the declining trends of some key transboundary resources with cool-water affinities, including the Argentine hake [51]. This suggests the need for a shift in management strategies, transitioning from static to dynamic and adaptive approaches that align with the observed changes in oceanographic and environmental conditions [139]. Such adaptive management plans could include the allocation of quotas that may vary over time based on stock availability, and the implementation of dynamic Marine Protected Areas (MPAs) or other Area-Based Management Tools (ABMTs) that consider variations in environmental conditions and the life cycles of exploited species. Gullestad et al. [58] found that catch quotas in the Northeast Atlantic were allocated after the last cooler period of the Atlantic Multidecadal Oscillation (AMO), with stock distributions shifting equatorward. The current lack of consensus on managing widely distributed fish stocks is linked to poleward distribution shifts attributable to the global signal that is accelerating the spatial effect of the current warmer AMO. Similar effects could impact fishing quota allocation in the SWAO, highlighting once again that the interplay between climate, biodiversity, and fisheries management and governance is essential for establishing resilient social-ecological systems [107].

The southward displacement of the Brazil Current [145] and the associated increase in SST, along with evidence of tropicalization of fisheries in the SWAO, could lead to a scenario marked by a significant decline in key cold-water species at their trailing distribution edges, or an expansion at the leading edges of climate-invader warm-affinity species. Brazil, Uruguay, and Argentina will need to face this new scenario with coordination and cooperation aimed at improving fishery management plans, generating coherent policies within and between national jurisdictions. Palacios-Abrantes et al. [105] showed that 67 % of the globally exploited marine species are transboundary and that catches of these species are declining more than those of non-transboundary species, which has direct implications for fisheries management. The study highlights the need to strengthen effective and equitable international cooperation (see also [139]). Increasing adaptive capacities in the SWAO requires efforts at multiple levels to: 1) promote international cooperation to ensure equity and distributive justice; 2) strengthen collaborative scientific research at the regional level to enhance understanding of the impacts of climate change on fishery stocks and to develop effective adaptation strategies that foster fisheries resilience and sustainability; 3) adapt policies and flexible regulatory frameworks to accommodate changes in stock distributions; and 4) implement monitoring and evaluation systems that provide updated and reliable information on stocks and environmental conditions at a regional scale. More than 50 years ago, the Regional Fisheries Advisory Commission for the Southwest Atlantic (CARPAS by its acronym in Spanish, see Fig. S1) was established to address regulatory gaps on transboundary stocks within the EEZs of the three countries. Although it operated formally from 1961, it had not convened since 1974 and was officially abolished by FAO Conference Resolution 13/97 [97]. A similar institutional arrangement involving the three countries could enhance scientific programs and management effectiveness by addressing the transboundary nature of key fishery resources and their vulnerability to climate change.

Currently, many of the main transboundary resources in the SWAO are managed in a compartmentalized manner that align more with geopolitical boundaries than with the life cycles of the resources. For management purposes, the functional definition of a stock is often delineated by human-imposed spatial boundaries that frequently do not align with biologically meaningful population units, as is common with transboundary stocks [19,41,105]. Thus, the identification of stocks and their potential connectivity requires special attention. Considering larval connectivity and metapopulation dynamics is crucial for managing transboundary species. Biophysical modeling highlights the importance of recognizing metapopulation structures by incorporating larval transport [78]. In warming hotspots like the SWAO, such models should also account for the effects of SST on connectivity patterns. The compartmentalized management currently in place could be significantly improved by including genetic analyses that would provide stronger science-based evidence for the identification of stocks and their connectivity. This evidence would enable the development of management plans that are more consistent with the nature of the resources and the dynamics of the fishing process.

The spatially explicit approach through the FAO subareas shows overlaps with the main distribution areas of key resources in the SWAO, and also with the bioregionalization of coastal and shelf areas provided by Spalding et al. [135]. This macroscale analysis reinforces the concept of social-ecological and institutional fit [36,37] towards the development of regional management plans and institutional arrangements grounded in sound scientific evidence. A large-scale analysis of essential variables defined by the bioregionalization approach [135] could help identify sensitive habitats and vulnerable ecosystems that may require additional management measures to improve the status of stocks. It could also offer insights into ecological explanations for the observed patterns that are currently obscured by the lack of integrated regional environmental and fisheries observations. An adjustment of the institutional structure would allow for an improved social-ecological and institutional fit that aligns the environmental dynamics with the dynamics of the fishing process [147].

4.2. Straddling stocks

An essential aspect requiring immediate attention in the SWAO is given by the straddling nature of the key fishery resources. These stocks are under increasing fishing pressure from international fleets (see Fig. 3), with evidence suggesting that this fishing effort has intensified over time. A similar situation has been documented in other regions: in the Indian Ocean, for example, illegal squid fishing has expanded by 830 % in 5 years [144]. IUU fishing constitutes a threat in the SWAO, warranting the development of robust institutional arrangements [67]. The deactivation of the Automatic Identification System (AIS) in commercial fisheries detected south of the SWAO generates uncertainty about the magnitude of fishing effort being deployed in international waters adjacent to Argentina's EEZ in the Patagonian region [142]. This situation also calls for strengthening the MCS systems of the three countries within their respective EEZs, both individually and cooperatively, and this must be supported by integrated international actions.

Fishing activities in international waters, both legal and illegal, have increased over time, and this has been especially significant for the Argentine shortfin squid ([132], see Section 4.2). This phenomenon has no apparent short-term solution and could undermine management initiatives by the countries in the region. Given the characteristics of resource exploitation in the high seas, the lack of MCS, and the increasing intensity of fishing effort in these waters, efforts to achieve rational and sustainable management of highly mobile resources within jurisdictional waters are insufficient.

All Parties engaged in fishing activities in the international waters of the SWAO must harmonize management measures to eliminate the compartmentalization of fleets operating under different flags. Compartmentalization results in different management strategies and the absence of robust information to feed fisheries statistics and stock assessment models, leading to incompatibilities between monitoring and data collection systems. The issue is further augmented by the uncertainty of stock assessment models of commercial species [35]. There is a clear need for a regionally integrated scientific approach that allows for the robust design of resource management strategies. Article 63 of the United Nations Convention on the Law of the Sea (UNCLOS) lays the groundwork for cooperation, either directly or through subregional or regional organizations, in conserving straddling fish stocks and associated species within EEZs and adjacent areas.

The management of transboundary fishery resources requires robust international collaboration and effective legal frameworks designed to mitigate the effects of IUU fishing and the indiscriminate exploitation of fishery resources. This highlights the importance of ocean governance in the high seas, whose initiatives have lagged behind the urgency needed to at least mitigate the intensity of fishing exerted there, which directly affects coastal states. Straddling stocks that have critical socioeconomic importance for SWAO countries, are not included within the jurisdiction of any Regional Fisheries Management Organization, and therefore there is urgent need for a regional approach with the collaboration of the relevant countries. This becomes even more critical when considering that the various institutions governing the high seas (including Regional Fisheries Management Organizations in fisheries) do not have a real relationship with each other and operate independently, without a general governance framework required to ensure structure, consistency, and coherence [33,76].

The fragmented governance and the lack of a coordinated fisheries management framework to address the pressing issues affecting high-seas fisheries have highlighted the need for a global fisheries management organization. Such an organization would impose centralized coordination among the Parties, and operate through regional and sectoral bodies to improve management effectiveness [76]. Currently, the United Nations is conducting negotiations on the implementation of the treaty on Biodiversity Beyond National Jurisdiction (BBNJ), adopted in 2023, with the aim of creating a legally binding international instrument to complement the UNCLOS. These negotiations are critical for addressing the various problems afflicting marine biodiversity conservation, as well as for generating related policy tools [33]. Despite their limited direct influence on fisheries management, at least in the current context, the governance frameworks being negotiated under the BBNJ agreement could also be relevant for fisheries management [34,76]. For example, the integration of ABMTs and MPAs, both included in the BBNJ, can catalyze the creation of comprehensive strategies for the conservation and sustainable management of straddling stocks. The regional implementation of Other Effective Area-Based Conservation Measures could also help achieve positive and sustained long-term outcomes for in-situ biodiversity conservation ([46] and references therein). Similarly, the internationalization of the Environmental Impact Assessment (EIA) proposed by BBNJ acquires relevance for the SWAO, considering the increase in ocean uses in the region [87].

In summary, there is an urgent need for an international governance arrangement and a coherent management framework tailored to the spatial scales relevant for the transboundary and straddling stocks that have dominated catch statistics in the SWAO for the past 70 years. This need is especially critical given the significant climate-induced changes on the outer continental shelf and upper slope of the SWAO. The transitional nature of the region—from subpolar to subtropical—makes it particularly vulnerable to meridional shifts in wind patterns and ocean currents. Addressing the synergistic effects of rapid environmental changes and weak governance—both within national jurisdictions for transboundary resources and on the high seas for straddling resources—is an urgent priority. Achieving multidimensional congruence among ecological, social, and institutional settings is crucial for fostering successful fisheries across all scales and intensities in the SWAO.

5. Conclusions and perspectives

The SWAO faces profound challenges stemming from climate change, transboundary resource dynamics, and fragmented governance. As highlighted in this study, the region's fisheries are undergoing significant shifts in species distribution and stock abundance due to increasing SST and other climate-driven changes. These challenges demand immediate and coordinated action to foster adaptive governance and enhance the resilience of SWAO fisheries. To address these issues, we propose the following actionable recommendations (Table 2):

1. **Development of regional agreements**: Establish a robust regional governance framework that transcends national jurisdictions, focusing on harmonizing policies and management strategies for

Table 2
Challenges and proposed actions for enhancing fisheries governance, management, and assessment in the southwest South Atlantic Ocean (SWAO), addressing key issues highlighted in this paper.

Challenges	Recommended actions
Limitations in stock assessment procedures in transboundary and straddling stocks	Integrate genetic analyses for stock identification, enhance data consistency and sharing among countries, and, whenever possible, adopt ecosystem-based and multispecies models
Incongruence between ecological and management scales	Align management frameworks with biological and environmental scales to foster a social-ecological fit
Insufficient monitoring systems	Invest in monitoring and data collection systems, including real-time technologies, with enhanced coordination among countries
Climate-driven species shifts	Develop dynamic and adaptive management frameworks to address shifting species distributions and changes in abundance, fostering collaboration among countries
Lack of adaptive management strategies	Implement flexible and ecosystem-based management approaches
Weak regional coordination	Enhance regional participatory governance frameworks and foster international cooperation
Overfishing and IUU fishing	Strengthen enforcement against IUU fishing and improve transboundary coordination

transboundary and straddling stocks. A strengthened institutional arrangement, similar to the former CARPAS, could enhance scientific collaboration and policy coherence.
2. **Enhanced monitoring systems**: Invest in advanced monitoring technologies, such as satellite tracking, electronic logbooks, and observer programs, to improve data collection and enforce compliance. Strengthening regional collaboration on MCS systems is critical to combating IUU fishing.
3. **Robust enforcement mechanisms**: Establish stricter enforcement measures within national EEZs and in international waters. This includes coordinated patrols, legal frameworks to prosecute IUU activities, and cooperative strategies to manage fishing pressure from foreign fleets.
4. **Dynamic and adaptive management**: Transition from static management tools to adaptive approaches that address climate-induced changes, stock distribution shifts, and market dynamics. This also includes the implementation of dynamic MPAs and the adjustment of quotas based on real-time stock assessments and environmental conditions.

To improve fisheries management and governance in the SWAO, we recommend targeted research in the following areas:

1. **Climate-resilient stock assessment models**: Develop integrated models that incorporate environmental drivers, trophic interactions, and socioeconomic factors to provide reliable projections under different climate scenarios.
2. **Socioeconomic impact studies**: Assess the social and economic implications of shifting fisheries, focusing on vulnerable communities and sectors to inform equitable and sustainable policy decisions.
3. **Vulnerability and adaptation assessments**: Conduct holistic evaluations of the ecological, social, and institutional vulnerabilities of SWAO fisheries to identify and prioritize adaptive strategies.

The complex challenges in the SWAO demand solutions that transcend historical sectoral approaches, emphasizing the interconnectedness of ecosystems, human livelihoods, and governance frameworks. Addressing these challenges requires a multidimensional approach that integrates ecological, social, economic, and institutional dimensions. By fostering regional cooperation and aligning management practices with the realities of the spatial distribution of the stocks and a changing climate, the SWAO can move toward a sustainable future for its fisheries and the communities that depend on them. These efforts will not only enhance the ecological and economic resilience of fisheries but also strengthen the long-term social and institutional foundations needed for enduring stewardship in the SWAO.

CRediT authorship contribution statement

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106584.

Data availability

Data will be made available on request.

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