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ORIGINAL ARTICLE

Sensitivity of fishery resources to climate change in the warm-temperate Southwest Atlantic Ocean

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Abstract

Climate change impacts on fishery resources have been widely reported worldwide. Nevertheless, a knowledge gap remains for the warm-temperate Southwest Atlantic Ocean—a global warming hotspot that sustains important industrial and small-scale fisheries. By combining a trait-based framework and long-term landing records, we assessed species' sensitivity to climate change and potential changes in the distribution of important fishery resources ($n = 28$; i.e., bony fishes, chondrichthyans, crustaceans, and mollusks) in Southern Brazil, Uruguay, and the northern shelf of Argentina. Most species showed moderate or high sensitivity, with mollusks (e.g., sedentary bivalves and snails) being the group with the highest sensitivity, followed by chondrichthyans. Bony fishes showed low and moderate sensitivities, while crustacean sensitivities were species-specific. The stock and/or conservation status overall contributed the most to higher sensitivity. Between 1989 and 2019, species with low and moderate sensitivity dominated regional landings, regardless of the jurisdiction analyzed. A considerable fraction of these landings consisted of species scoring high or very high on an indicator for potential to change their current distribution. These results suggest that although the bulk of past landings were from relatively climate-resilient species, future catches and even entire benthic fisheries may be jeopardized because (1) some exploited species showed high or very high sensitivities and (2) the increase in the relative representation of landings in species whose distribution may change. This paper provides novel results and insights relevant for fisheries management from a region where the effects of climate change have been overlooked, and which lacks a coordinated governance system for climate-resilient fisheries.

Keywords Trait-based assessment · Climate change vulnerability · Ocean warming · Global change · South America

Introduction

Climate change affects the productivity, structure, and composition of marine ecosystems upon which fisheries rely (Hoegh-Guldberg and Bruno 2010; Pinsky et al. 2013; Bindoff et al. 2019; Tittensor et al. 2021). Even though fishing effort is commonly the main determinant of the status of exploited stocks, there is increasing evidence that stock resilience is affected by climate change through impacts on processes such as growth, reproduction, and also the behavior of organisms (Rijnsdorp et al. 2009; Brander 2010; Poloczanska et al. 2016; Pinsky et al. 2020). For instance, ocean warming has mostly exacerbated exploitation patterns, leading to declining fisheries, with few exceptions where warming waters benefited fishing yields (Free et al. 2019). Distributional range shifts of fishery resources, both latitudinally and bathymetrically, are also documented responses to ocean warming (Dulvy et al. 2008; Bates et al. 2014; Robinson et al. 2015; Barange et al. 2018; Morley et al. 2018; Fredston-Hermann et al. 2020; Pinsky et al. 2020). The magnitude and persistence of these responses are often species-specific and are modulated by habitat preferences (Roberts et al. 2020; Wang et al. 2020; Champion and Coleman 2021) and dietary plasticity of marine species (Monaco et al. 2020). While ocean warming and consequent species responses have concentrated most research efforts, evidence of the impacts of diverse climate change-induced drivers (e.g., acidification, deoxygenation, and sea-level

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rise) has been accumulating (Cooley and Doney 2009; Popova et al. 2016; Pauly and Cheung 2018).

Climate change effects manifest across spatio-temporal scales, ranging from changes in fishers' and fleets' behavior (Gianelli et al. 2019a; Rubio et al. 2021) to local species landings composition and variation in yields between nearby ports (Sumaila et al. 2011; Rogers et al. 2019). Even governance conflicts may arise from stocks shifting within national or between international jurisdictions (Pinsky et al. 2018: Palacios-Abrantes et al. 2022). The concurrent and interrelated nature of climate-induced drivers has proven difficult to interpret, and meaningfully integrate into fisheries management. Regional and global models to project future catches that include several climate-induced drivers usually fail to provide species-specific information valuable to fisheries managers and the fishing industry (Cheung et al. 2010, 2018). Moreover, correlational and mechanistic approaches for analyzing climate change impacts on exploited populations rely on long-term and extensive spatial monitoring programs, are data-intensive, and require considerable modeling expertise (Hare et al. 2016). Consequently, exhaustive analysis is infeasible for all commercially important species, given their diversity and often limited data availability.

Methodologies for simultaneous analysis of several climate-induced drivers that are suitable for concurrent application for many species are increasingly being implemented to fill critical knowledge gaps (Jones and Cheung 2018). In developing countries, trait-based assessments have increasingly become a primary approach to quantifying vulnerability to climate change or any of its constituent components (i.e., exposure, sensitivity, and adaptive capacity) (Ortega-Cisneros et al. 2018; Cochrane et al. 2019; Pinnegar et al. 2019; Giddens et al. 2022; Ramos et al. 2022). In developed regions meanwhile, such approaches have guided research and management efforts (Pecl et al. 2014; Hare et al. 2016; Spencer et al. 2019; Farr et al. 2021). Trait-based approaches can jointly assess data-rich and data-poor species because they draw on existing species knowledge and, when unavailable, use expert elicitation methods (Frainer et al. 2017). Based on the premise that biological attributes are effective indicators of the capacity of a species to respond to environmental changes (Sunday et al. 2015; Hare et al. 2016), trait-based assessments help increase awareness about possible climate-induced effects on marine fishery resources, detect knowledge gaps, and prioritize research and management efforts.

Climate change impacts on marine species have scarcely been documented in the Southwest Atlantic Ocean (SWAO) (Bertrand et al. 2018), particularly for exploited stocks (Sumaila et al. 2011; Gianelli et al. 2019b; Franco et al. 2020a, b; Costa et al. 2021). This knowledge gap is alarming, as the area is one of the largest and most fast-warming regions of the global ocean (Hobday and Pecl 2014; Yang et al. 2020), and also holds exceptional biodiversity of marine vertebrates threatened by climate change (Ramírez et al. 2017). Furthermore, decades of intensive fishing have caused several stocks to decline to unsustainable biological levels (Cardoso and Haimovici 2015; Gianelli and Defeo 2017; Haimovici and Cardoso 2017). Ocean warming occurs within this context where 40% of regional fish stocks assessed are being fished unsustainably (FAO 2022). Additionally, since most exploited species lack formal stock assessments or regionally coordinated management efforts, reports of unsustainable fishing may be underestimated (Costello et al. 2012). This intertwined reality of climate change and unsustainable fisheries is worrying, as it could undermine species' responses to current and future environmental changes, despite management efforts to rebuild stocks (e.g., CTMFM 2016). Hence, understanding which fishery resources are more resilient or sensitive to climate change is urgently needed for proper management in this region.

In this study, we assessed the ecological sensitivity of fishery resources to climate change in Southern Brazil, Uruguay, and the northern shelf of Argentina, a hotspot of ocean warming. We applied a flexible, participatory, and cost-effective framework to quantify and categorize ecological sensitivity, a synthetic measure of species' intrinsic resilience to change. We also assessed the relative importance of fish and shellfish landings for each country and major fishing ports within the study area. Finally, by combining these two approaches, we estimated the ecological sensitivity to climate change as well as the potential for changes in the distribution of the ensemble of species that comprise each country's landings.

Methods

We conducted a series of concatenated methodological steps, divided into three discrete phases (Fig. S1): (1) study planning and scoping, (2) scoring, and (3) data analysis.

Study planning and scoping

Study area

To delimit the study area, we used a bioregionalization approach (Marine Ecoregions of the World: MEOW), which classifies coasts and shelves in a nested biogeographic system of realms, provinces, and ecoregions (Spalding et al. 2007). An ecoregion is defined as an area with a common set of biophysical features and the resulting region-specific species composition. In this study, we analyzed the "Río de la Plata," "Uruguay–Buenos Aires shelf," and "Río Grande" ecoregions (Fig. 1) (29–41°S), all belonging to the warm-temperate Southwestern Atlantic

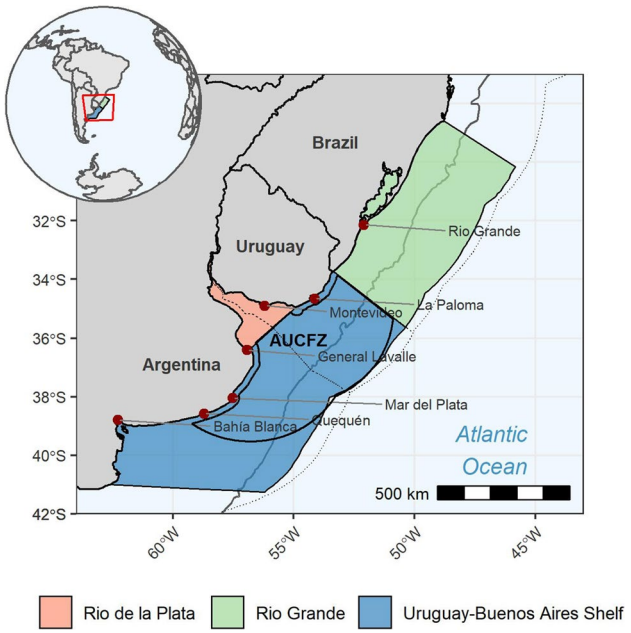

Fig. 1 The study area selected for the sensitivity assessment of key fishery resources to climate change. Ecoregions included in the study area and major fishing ports are denoted. The 200-m isobath (gray line) and jurisdictional limits (Exclusive Economic Zone: dashed lines, and the Argentinean-Uruguayan Common Fishing Zone (AUCFZ): solid black line) are shown

province. The confluence of two western boundary currents (Brazil and Malvinas) with contrasting thermohaline characteristics results in a strong latitudinal and longitudinal thermal gradient within the selected ecoregions (Franco et al. 2020a, 2022). Furthermore, the distribution of several marine species is bounded by the study area (Menni et al. 2010) and includes high endemism of sharks and rays (Menni et al. 2010; Stein et al. 2018; Derrick et al. 2020; Sabadin et al. 2020). The study area also hosts economically important fishing ports in Southern Brazil (Rio Grande), Uruguay (La Paloma and Montevideo), and the northern shelf of Argentina (General Lavalle, Mar del Plata, Necochea-Quequén, and Bahía Blanca) (Fig. 1). This socio-economic relevance, the transitional characteristics in oceanography and biodiversity, and the fact that the ecoregions are among the most prominent marine warming hotspots worldwide make the study area particularly relevant for assessing the effects of climate change on key fishery resources.

Expert recruitment and species prioritization

We recruited experts from academia, fisheries research and management agencies (see co-authors' affiliations). Based on their expertise within each taxonomic group, we divided them into four assessment working groups: bony fishes, chondrichthyans, crustaceans, and mollusks. Working groups were composed of 4–6 experts (16 in total) and included five senior researchers, three early career researchers, and eight Ph.D. or master's students.

We identified the potential set of species to assess based on official records of landings, and discussed and ranked them within each working group using the following criteria: (1) ecological, cultural, and economic relevance for regional small-scale and industrial fisheries, and (2) species distribution within the selected study area. The final set of species for assessment was based on the prioritization of each group, and bounded by two limiting factors: (1) the availability of voluntary expert time and labor, and (2) an agreed minimum of three species assessments to be completed by each expert. Highly migratory species (e.g., tuna, billfishes, and pelagic sharks) were not considered, as the study area does not cover much of their life cycle.

Assessment framework

We applied a modified vulnerability assessment framework that uses expert elicitation methods (at individual and group level) to quantify and categorize the expected sensitivity and exposure to climate change for a set of species in a defined region (Hare et al. 2016). As one of the pillars of the Climate Vulnerability Assessments developed by the US National Oceanic and Atmospheric Administration (Morrison et al. 2015), this methodological approach has been widely validated and implemented (Hare et al. 2016; Spencer et al. 2019; Farr et al. 2021; Giddens et al. 2022; Ramos et al. 2022). We purposefully limited our assessment to the sensitivity component of vulnerability because of the currently existing high uncertainty for many climate exposure factors in the region (e.g., warming below the mixed layer, ocean acidification, and deoxygenation (Franco et al. 2020a, b)), and their effects on marine life, including species of utmost economic importance (Bertrand et al. 2018). Moreover, using global models to predict regional oceanography is challenging because of the specific oceanographic (e.g., a confluence of currents, presence of oceanic fronts) and coastal features of the study area (e.g., a wide estuary, coastal lagoons).

Scoring

Using the same information collated for assessing sensitivity, we also compiled life-history synopses for each assessed species (Supplementary Material 2). These fact sheets also provided tallies distribution ("Sensitivity scoring" section) and data quality scores for each sensitivity attribute ("Data quality scoring" section), the overall sensitivity score (OSS), the potential for distributional change, and the certainty in these scores. A brief description of stock status and existing

management tools were also provided, along with potential species responses to climate change effects in the SWAO.

Sensitivity scoring

Ecological sensitivity is a measure of species' intrinsic resilience to change, which is assessed based on current biological attributes that are indicative of their ability/inability to respond to potential environmental changes (Morrison et al. 2015). For sensitivity scoring, experts used available information (e.g., scientific and gray literature, species profiles) and followed the process in Morrison et al. (2015). Experts scored twelve sensitivity attributes (Table 1) based on a 5-tally system that allowed each expert to distribute their tallies to well-defined sensitivity categories—low, moderate, high, and very high—based on expert certainty. For instance, if there was high certainty for a given attribute, an expert placed all their tallies into a single category; otherwise, tallies were distributed among several categories. In instances when information was unavailable, the experts relied solely on their knowledge for scoring. The number of species scored by each expert ranged between 3 and 18 species. To foster robustness of individual expert judgment, we applied the IDEA protocol (Investigate-Discuss-Estimate-Aggregate), i.e., a structured expert elicitation method that consists of two rounds of individual scoring (estimation) mediated by a group discussion held between rounds (Hemming et al. 2018). Once the initial scoring round was completed, experts discussed aggregated results and were allowed to modify their scoring as new information was made available from discussions. A consensus among experts was not pursued, and the final results may reflect divergent opinions. This approach aimed to remove linguistic ambiguity and avoid methodological misinterpretations and individual biases (Hemming et al. 2018).

Table 1 displays the meaning of low and high scores for each attribute, while the specific criteria that define the corresponding sensitivity categories can be found in Appendix A of Morrison et al. (2015).

Data quality scoring

Experts also provided input on the quality of the information available for conducting the sensitivity assessment based on a 4-level system (0 = no data, 1 = expert judgment, 2 = limited data, 3 = adequate data), following Morrison et al. (2015). No data means that no information to score an attribute was available (e.g., very little is known about the species or related species, and there is no basis for forming an expert opinion). Expert judgment means that the attribute score reflects the evaluator's judgment and is based on their general knowledge of the species (or related ones) and its relative role in the ecosystem. Limited data means that information used to score the attribute may be based on related or similar species, come from outside the study area, or that the source's reliability may be inadequate. Finally, adequate data means that the score is based on data that has been observed, modeled, or empirically measured and comes from a reliable source. For each species and attribute, the average data quality was determined as the mean of scores provided by experts.

Data analysis

Mean sensitivity and sensitivity categorization

We calculated a mean sensitivity for each attribute as the weighted average of the number of tallies in each category and their respective assigned value (low = 1, moderate = 2, high = 3, very high = 4):

$$\frac{((L \times 1) + (M \times 2) + (H \times 3) + (VH \times 4))}{(L + M + H + VH)} \quad (1)$$

where L, M, H, and VH are the total number of tallies in the low, moderate, high, and very high-sensitivity categories. Thus, mean attribute sensitivity varied between 1 and 4.

We then assigned a categorical sensitivity for each species based on a predefined decision rule in which the species sensitivity is a function of the number of attributes with means above predefined thresholds (very high: four or more attributes with mean sensitivity > 3.0, high: at least two attributes with a mean sensitivity > 3.0, moderate: at least two attributes with a mean sensitivity > 2.5). Species not exceeding the moderate threshold were categorized as low sensitivity.

We also obtained a ranking of species' OSS by summing the scores for each sensitivity attribute (i.e., a cumulative weighted score) for each of the 28 species (12 = lowest possible sensitivity, 48 = highest possible sensitivity) (Pecl et al. 2014; Ramos et al. 2022). We refrained from estimating a mean sensitivity score for each species as averaging procedures tend to minimize the importance of high-scoring sensitivity attributes (Morrison et al. 2015).

Lastly, we used the Kruskal–Wallis (KW) and post hoc Dunn's tests with Bonferroni adjustments to assess whether there were significant differences in OSS as a function of major taxonomic groups (bony fishes, chondrichthyans, crustaceans, mollusks) and species habitat types (benthic, demersal, pelagic). We also used KW and Dunn's tests to assess differences between attribute sensitivities, considering all species grouped, and discriminated by taxonomic group.

Potential for changes in species distribution

To explore the potential for changes in species' distribution (i.e., species' capacity to expand or relocate their distributional

Table 1 Sensitivity attributes and the underlying rationale for their inclusion in the assessment of ecological sensitivity to climate change. Illustrative examples for low and very high scores are provided. Adapted from Morrison et al. (2015)

Attribute	Relation to climate change	Low score	Very high score
Stock size/status	Healthy stocks are better prepared to cope with climate change. Climate resilience in overexploited stocks may be compromised	High abundance (e.g., $B/B_{MSY} \geq 1.2$)	Low abundance (e.g., $B/B_{MSY} < 0.5$)
Population growth rate	Highly productive species are thought to be more resilient to environmental changes as they can rapidly recover from impacts	High productivity (e.g., von Bertalanffy $K > 0.25$/year)	Low productivity (e.g., von Bertalanffy $K \leq 0.10$/year)
Habitat specificity	Habitat specialists are likely to be more sensitive as they lack compensatory habitats or other microhabitat options	Habitat generalist with abundant habitat availability (e.g., widespread abiotic habitats)	Habitat specialist on a limited habitat type (e.g., specific and/or uncommon biological habitats)
Prey specificity	Trophic generalists are more resilient to changes in resource availability than those dependent on a few diet items. Diet breath increases the prevalence and establishment of climate-migrant species, as they can better adapt to novel food sources	Prey generalist (e.g., relies on a large variety of prey or diet items)	Prey specialist (e.g., dependent on one prey type and limited to switch between diet items)
Sensitivity to temperature	Species with wide temperature requirements and/or latitudinal coverage may better tolerate a warming ocean	Large temperature range ($\geq$ 15ºC)	Narrow temperature range ($<$ 5ºC)
Sensitivity to acidification	Shell-forming and oxygen-demanding organisms are expected to be more affected by a high pCO_2. Species that depend (trophically and/or for settlement) on acidification-sensitive taxa may be indirectly affected	Insensitive taxa to direct (physiological) and/or indirect (food, shelter) effects of acidification	Sensitive taxa with demonstrated negative direct acidification effects
Adult mobility	Sessile species, crawlers, or swimmers with low motility may be unable to move or shift range distribution when unfavorable environmental conditions persist	Highly mobile adults	Sessile adults
Dispersal of early stages	Species with high dispersal potential of egg and larvae may colonize new habitats, replenish areas that temporarily became unfavorable, and increase genetic diversity. Dispersal potential is mediated by intrinsic (e.g., buoyancy, swimming capacity) and extrinsic limitations (e.g., currents, fronts)	High dispersal (e.g., duration of planktonic eggs and larvae greater than 8 weeks and/or larvae are dispersed > 100 km)	Low dispersal (e.g., benthic eggs and larvae, or little to no planktonic early life stages)
Requirements for early stages	Species with several early life stages (eggs and larvae) that require different habitats and/or specific environmental conditions for survival and settlement are more prone to be affected by a changing environment	Larval requirements are relatively resistant to environmental change	Larval requirements are specific and likely to be impacted by environmental change (e.g., specific known biological and physical requirements for larval survival)
Spawning cycle	Protracted spawners enhance offspring survival in a changing environment. Discrete spawning events over short-time periods may be susceptible to recruitment failure due to asynchrony and uncoupling to environmental factors and food availability peaks	Year-round spawning (e.g., monthly)	Short spawning duration (e.g., yearly spawning over a brief period)
Complexity in the reproductive strategy	Species that rely on climate-driven environmental triggers or cues to initiate reproductive-related activities (e.g., migration, aggregation, maturation, copulation, egg laying, egg hatching) may alter their timing and magnitude under climate change conditions	Low complexity (i.e., no more than one characteristic that suggests a complex reproductive strategy)	High complexity (i.e., four or more characteristics that suggests a complex reproductive strategy)
Other stressors	Stocks already affected by other stressors may suffer climate change effects more profoundly	Low number of other stressors (e.g., species experiencing no known stress other than fishing)	High number of other stressors (e.g., species experiencing four or more known stressors other than fishing)

range), we used a subset of attributes (Hare et al. 2016): Sensitivity to temperature, Adult mobility, Early life stage dispersal, and Habitat specificity (Table 1). A high potential for changes in species distribution was assumed for species with high sensitivity to warming, high mobility and dispersal capacities, and low specificity to habitat types (Table 1).

Certainty in sensitivity scores

We used Bootstrap analysis to estimate the certainty of both the sensitivity scores and the potential for changes in distribution scores (Hare et al. 2016). For a given sensitivity attribute, scores across all experts were randomly drawn 1000 times with replacement, and the sensitivity score was recalculated following Eq. 1. Applying the same logic as in the "Mean sensitivity and sensitivity categorization" section, we estimated categorical sensitivity for each iteration and species. Results from each iteration were allocated to their respective sensitivity category (low, moderate, high, and very high). Certainty was estimated as the fraction of bootstrapped iterations that matched each species' original sensitivity category (Ramos et al. 2022). Following Hare et al. (2016) and Ramos et al. (2022), we classified certainties as Very high (> 95%), High (91–95%), Moderate (70–90%), and Low (< 70%). An analogous procedure was applied for the four attributes that constitute a proxy for potential for changes in species distribution ("Potential for changes in species distribution" section). Finally, we used leave-one-out analysis to assess the importance of each sensitivity attribute in determining overall species-specific sensitivity.

Combining sensitivity scores and landings at the country/state level

We compiled landings statistics and combined those with the results for ecological sensitivity and potential distribution changes for each country/jurisdiction within the study area. In doing so, we obtained two annual time series of the ensemble of species in each country's landings according to their ecological sensitivity to climate change and potential for change in distribution. This procedure allowed us not only to focus on the species level, but also on the potential effect of climate change on each country's combined landings.

For Brazil (State of Rio Grande do Sul), official statistics were only available from 1997 to 2011. Therefore, we relied on long-term landings statistics systematically collected by the Federal University of Rio Grande (FURG) for 16 species from 1989 to 2019.[1] For Uruguay, we used official landings statistics from 1989 to 2019. Finally, for Argentina (Buenos Aires Province), we used landing statistics from 1989 to 2019 of marine fisheries published by Sánchez et al. (2012) and Navarro et al. (2014, 2019). We filtered landing statistics to match species included in the ecological sensitivity assessment (Fig. S2) and to those landed by the industrial fishing fleets in major fishing ports within the study area (Fig. S4, Fig. S5). It is noteworthy that Brazilian and Argentinean landings only include catches landed at Rio Grande state and Buenos Aires province, respectively, whereas landings statistics from Uruguay included total industrial landings.

[1] Yet, to assess the proportion of landings of the species evaluated here over total landings, we used official Rio Grande landings statistics for 1997–2011 published by IBAMA/CEPERG. Landing coverage during this period is more comprehensive than in subsequent and previous years.

Results

A final set of 28 species (bony fishes = 10, chondrichthyans = 8, crustaceans = 4, mollusks = 6), representing 49% of the initial set of 57 species were prioritized for assessment of their ecological sensitivity (Table S1). All selected species represent key fishery resources—in economic, ecological, and/or cultural terms—to the industrial and/or small-scale fisheries sub-sectors in at least one of the countries involved (Table S2). For instance, only considering the industrial subsector, the species assessed here represent 69% of official reported landings for Brazil (Rio Grande, 1997–2011), 94% for Uruguay (1989–2019), and 70% for Argentina (Buenos Aires, 1989–2019) (Fig. S1).

Species' ecological sensitivity to climate change

Two sciaenids, *Micropogonias furnieri* and *Cynoscion guatucupa*, and a merluccid, *Merluccius hubbsi*, ranked highest among bony fishes (OSS range = 25.1–25.9) (Fig. 2A). Conversely, the forage fish *Engraulis anchoita* was ranked to have the lowest sensitivity to climate change. *Umbrina canosai*, *Urophycis brasiliensis*, and *Macrodon atricauda* were ranked in the range of 21.6–23.4 OSS.

Within chondrichthyans (Fig. 2A), guitarfishes (*Zapteryx brevirostris* and *Pseudobatos horkelii*) ranked highest (OSS = 26.3 and OSS = 26.7, respectively), and *Carcharias taurus* ranked third. *Squatina guggenheim* and *Mustelus schmitti* scored similarly in the middle-low range of OSS (23.0–23.6), along with *Galeorhinus galeus* (OSS = 22.9). *Squalus acanthias* showed the lowest ecological sensitivity (OSS = 21.9).

Within crustaceans (Fig. 2A), the pink shrimp (*Penaeus paulensis*) showed the second-highest sensitivity across groups (OSS = 31.2).

Finally, within mollusks (Fig. 2A), two sub-groups of species were differentiated based on their contrasting life histories (e.g., mobility, specialization of habitats), i.e., bivalves-gastropods (*Amarilladesma mactroides*, *Zidona dufresnei*, *Mytilus* spp., and *Zygochlamys patagonica*) and

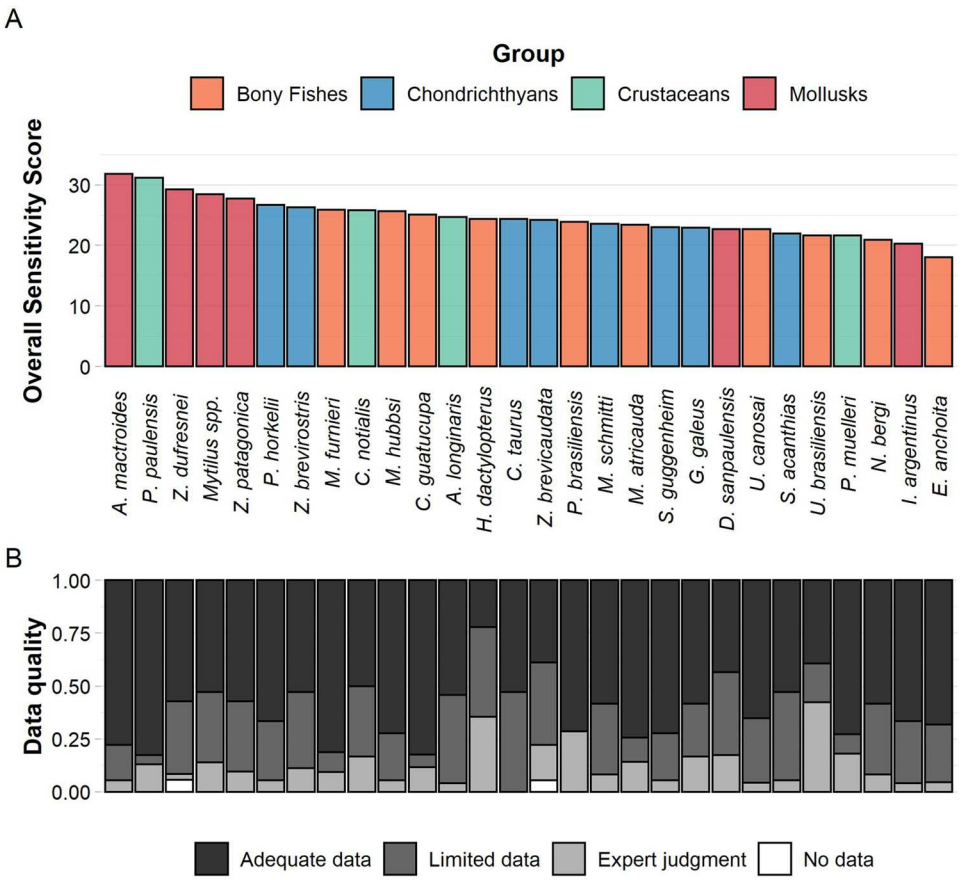

Fig. 2 **A** Rankings of sensitivity (cumulative weighted scores) of key fishery resources ($n = 28$) to climate change in the warm-temperate Southwest Atlantic Ocean. **B** Relative frequency of data quality per fishery resource

squids (*Doryteuthis sanpaulensis* and *Illex argentinus*). The yellow clam (*A. mactroides*) had the highest sensitivity (OSS = 31.8) among mollusks and across groups.

Species' OSSs were not biased by data quality. The quality of information used to assess species sensitivity was considered mostly adequate and, to a lesser extent, limited (Fig. 2B). Only a minor fraction of the scores were based solely on expert judgment, and a marginal proportion was assigned without any scientific basis (Fig. 2B). Data-deficient species included a bathydemersal species (*Helicolenus dactylopterus*), a coastal fish (*U. brasiliensis*), an offshore demersal ray (*Zearaja brevicaudata*), and a benthic snail (*Z. dufresnei*). In contrast, *A. mactroides*, *P. paulensis*, *M. furnieri*, and *C. guatucupa* showed the highest data qualities. Sensitivity to ocean acidification and the effect of other stressors were the attributes with the greatest uncertainty among species (Fig. S3).

No significant differences were found when comparing OSS across major taxonomic groups ($H(3) = 3.39$, $p = 0.33$). The range of OSS shown by chondrichthyans and bony fish groups were similar (Fig. 3A), but the latter included species with lower sensitivities (Figs. 2 and 3A). Crustaceans' sensitivities were species-specific and scattered throughout the entire range of estimated values (Figs. 2A and 3A). Even though four of the five most sensitive species were mollusks (Fig. 2A), high intra-group variability was found due to contrasting life histories of sedentary mollusks and squids (Fig. 3A). On the other hand, significant differences were found when aggregated by habitat type ($H(2) = 13.13$, $p < 0.01$) (Fig. 3B). Fishery resources with benthic habits showed the highest sensitivities (median = 28.5; IQR = 1.57) and significantly differed from demersal (benthic vs. demersal: $p = 0.01$) and pelagic fishery resources (benthic vs. pelagic: $p < 0.01$). Sensitivities of demersal fishery resources (median = 24.0; IQR = 2.35) did not differ from pelagic ones (median = 20.3; IQR = 2.32) (benthic vs. demersal: $p = 0.07$).

The disaggregation of species sensitivity by attribute and the leave-one-out analysis allowed for visualizing the role of each attribute in determining final species sensitivity scores (Fig. 4A, Table S3), and the particular combination of attributes and species that warrant further attention. Almost 40% of the species assessed were classified into the high-sensitivity category, and 32%, 21.4%, and 7% into the moderate, low, and very high-sensitivity categories, respectively (Fig. 4B). The attribute that contributed most to species sensitivity was the current status of populations (stock status/size) (Fig. 4A, Tables S3 and S4), particularly in chondrichthyans (Tables S3 and S5). Within this group, the slow population growth rates and the complexity of reproductive strategies also contributed to high-sensitivity values (Fig. 4A,

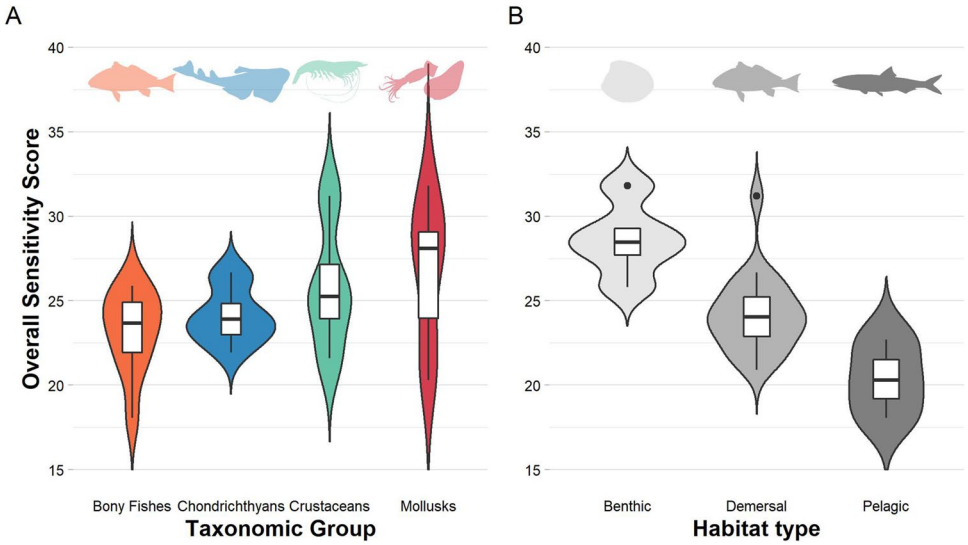

Fig. 3 Overall sensitivity score by (**A**) major taxonomic group (bony fishes, chondrichthyans, crustaceans, mollusks) and (**B**) habitat type (benthic, demersal, pelagic). The medians and the interquartile range (IQR) are represented by horizontal solid black lines and boxes, respectively. Whiskers extend up to 1.5 × IQR

Tables S3 and S5). Therefore, almost all chondrichthyans assessed showed high sensitivities, except for *S. guggenheim*, whose sensitivity was moderate (Fig. 4B). The current stock status of bony fishes, such as *M. furnieri*, *M. hubbsi*, and *U. canosai*, was of concern. The latter was also true for sessile and sedentary mollusks (i.e., *A. mactroides*, *Z. dufresnei*, *Mytilus* spp., and *Z. patagonica*), whose sensitivities were also affected by expected impacts from ocean acidification (Fig. 4A, Table S3). Consequently, these four species showed high to very high sensitivities (Fig. 4B). Crustacean sensitivities to climate change were mainly driven by stock status and complexity in the reproductive strategy (Fig. 4A). The pink shrimp (*P. paulensis*) also showed high sensitivity to their attributes related to ontogenetic changes (e.g., habitat requirements in early life stages), which contributed to an overall very high sensitivity (Fig. 4B).

Certainty assessment of species sensitivities showed that 25% of the species assessed were classified with very high certainty (> 95%), 7% with high certainty (91–95%), 18% with moderate certainty (70–90%), and 50% with low certainty (< 70%; Fig. 4B, Table S6).

Species' distribution change potential

A total of 48.6% of the species assessed exhibited moderate potential for changing their distribution, whereas 28.6% had

Fig. 4 **A** Ecological sensitivity per individual attribute ($n = 12$) for each assessed species ($n = 28$), separated by taxonomic group. Attributes and species are ranked from highest to lowest overall sensitivity scores. **B** Ecological sensitivity expressed in discrete categories (very high, high, moderate, low) predefined by a decision rule. Certainty from the bootstrap analysis is indicated by the number of asterisks: very high certainty (****): > 95%; high certainty (***): 91–95%; moderate certainty (**): 70–90%; low certainty (*): < 70%

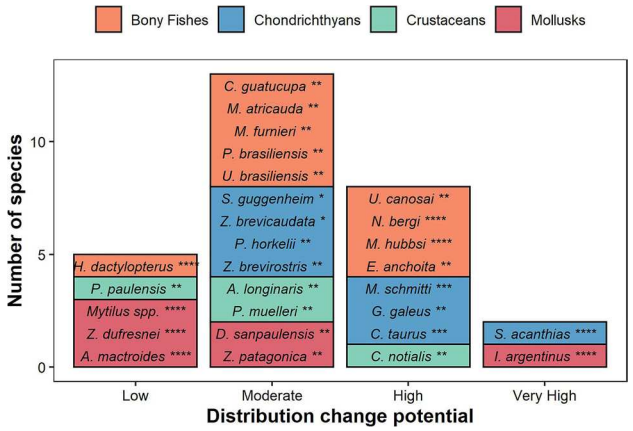

Fig. 5 Distribution change potential expressed in discrete categories (very high, high, moderate, and low) for each species assessed based on scoring four attributes (adult mobility, dispersal of early stages, habitat specificity, and sensitivity to temperature). Certainty from the bootstrap analysis is indicated by the number of asterisks: very high certainty (****): > 95%; high certainty (***): 91–95%; moderate certainty (**): 70–90%; low certainty (*): < 70%

a high potential for adjusting their distribution, including key regional fishery resources such as *M. hubbsi*, *U. canosai*, *E. anchoita*, and *M. schmitti* (Fig. 5). A commercially important cephalopod (*I. argentinus*) and a by-catch shark species (*S. acanthias*) presented a very high potential to change their distribution range. However, 18% of the species had a low potential to adjust their distribution in response to climate change. These fishery resources included benthic species and/or habitat specialists in any or all life stages (*A. mactroides*, *Mytilus* spp., *P. paulensis*), low mobile snails with egg-attaching strategy (*Z. dufresnei*), and a bathydemersal species with preferences for rocky bottoms (*H. dactylopterus*).

Certainty assessment of the species' potential for changes in distribution showed that 29% of the species assessed were classified with very high certainty (> 95%), 11% with high certainty (91–95%), 53% with moderate certainty (70–90%) and 7% with low certainty (< 70%; Fig. 5, Table S7).

Landings and sensitivity to climate change

In Rio Grande (Brazil), landings were comprised mainly of demersal sciaenid fishes with moderate (*M. furnieri*, *U. canosai*, *M. atricauda*) and low sensitivity (*C. guatucupa*), and penaeid shrimps with very high (*Penaeus* spp.) and moderate (*Artemesia longinaris*) sensitivities to climate change. Small tunas (Scombridae) and other bony fishes (e.g., *Mugil* sp., *Pomatomus saltatrix*), whose sensitivities were not assessed, also accounted for a substantial fraction of total landings (Fig. 6).

Uruguayan landings were largely dominated by three bony fish species, two with moderate sensitivity (*M. furnieri* and *M. hubbsi*) and one with low sensitivity (*C. guatucupa*) (Fig. 6). Invertebrate landings were mostly represented by the short-fin squid (*I. argentinus*) and the red crab (*Chaceon notialis*), with moderate and high sensitivity, respectively.

In Argentina, most catches were landed in Mar del Plata fishing port (95%, Fig. S4) and were largely dominated by two species with moderate sensitivity: *M. hubbsi* (catches reported north of 41°S) and *I. argentinus* (Fig. 6 and Fig. S5). *M. schmitti* (high sensitivity), *S. guggenheim* (moderate sensitivity), and other chondrichthyans such as Squaliformes and Rajiformes (mostly *Bathyraja* spp.), whose sensitivities were not assessed, also contributed to landings (Fig. 6). *Macruronus magellanicus*, *Genypterus blacodes*, some notothenioid fishes, and species of the order Rajiformes were a substantial fraction of landings reported for northern Argentinean fishing ports (Fig. 6). However, these species were probably caught further south and may therefore not be representative of species assemblage and landings composition of the study area considered here. Hence, these species were not considered for assessment of their sensitivity to climate change.

Our results showed that, regardless of the country or jurisdiction, the vast majority of landings consisted of species with low or moderate ecological sensitivity to climate change (Figs. 6 and 7A). Brazilian (Rio Grande) landings were primarily species with low to moderate sensitivity, the latter category increasing slightly through time (Fig. 7A). A single species (*P. paulensis*) targeted by small-scale and industrial fleets, contributed with a very high sensitivity to the species landed in Rio Grande. Landings composition of Uruguay and Argentina remained stable over time when classified by sensitivity to climate change (Fig. 7A).

When landings were combined with the species' potential for changes in distribution, contrasting patterns were observed between jurisdictions (Fig. 7B). Brazilian (Rio Grande) landings were primarily species with moderate and high potential for changes in their distribution, the latter category steadily increasing through time. Uruguayan landings were mainly composed of species with high and moderate distribution change potential. Finally, in Argentina (Buenos Aires), a significant proportion of landings had a very high distribution change potential (almost entirely represented by *I. argentinus* caught in the study area).

Discussion

This assessment represents a stepping stone toward better understanding and prediction of climate change impacts on fishery resources in the warm-temperate SWAO. Most species showed moderate or high sensitivities, with related life-history traits explaining similar sensitivities within taxonomic groups and life habits (e.g., pelagic vs. benthic species). Above all, the worrying stock and/or conservation

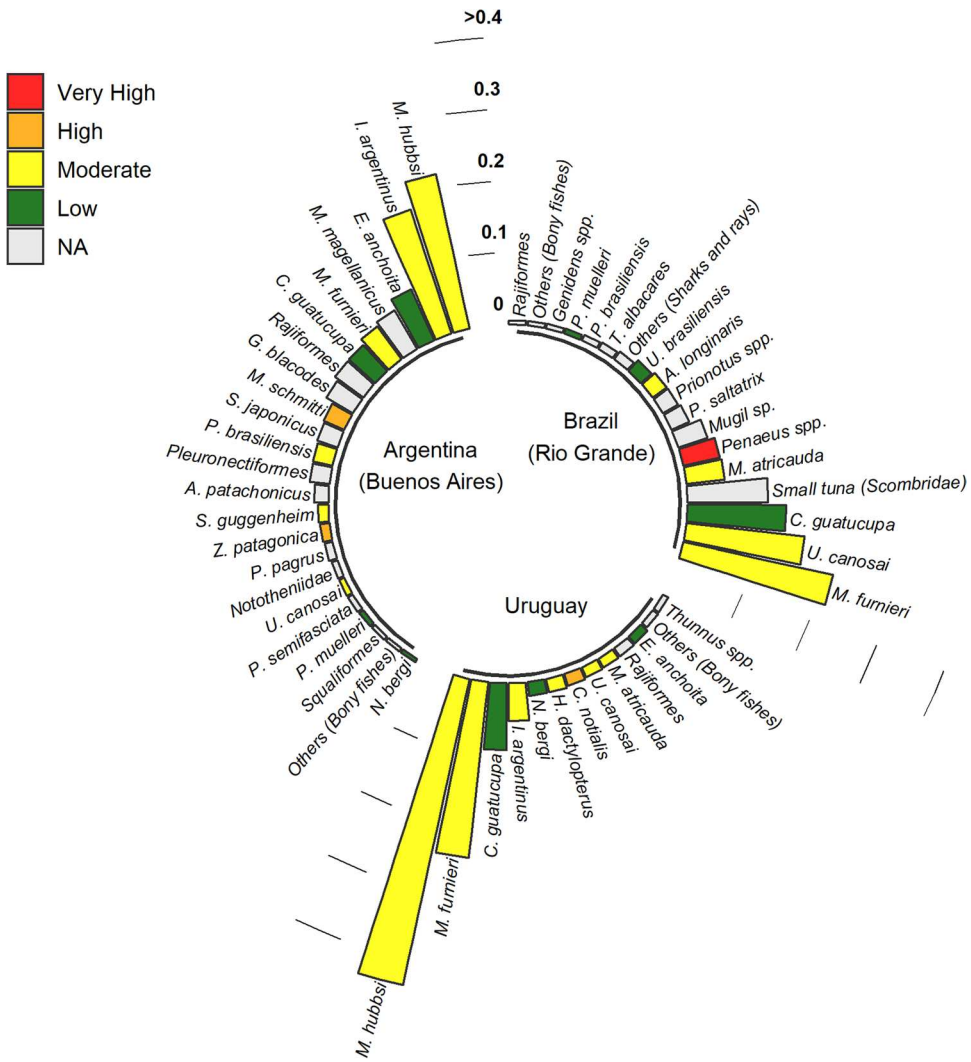

Fig. 6 Fishery resources landed (fraction of total landings) by the industrial fishing sub-sector in southern Brazil (Rio Grande: 1997–2011), Uruguay (1989–2019), and northern Argentina (Buenos Aires: 1989–2019). Species were classified based on their sensitivity to climate change. Species with less than 0.005 of total landings were excluded

status of fishery resources (several of them unmanaged) was the attribute that mainly contributed to high-sensitivity scores. Regardless of the jurisdiction analyzed, landings were mostly comprised of species with low and moderate sensitivities, a finding consistent with global-scale vulnerability assessments (Jones and Cheung 2018). Furthermore, a considerable fraction of landings consisted of species with high or very high potential to change their current distribution. These results suggest that, even though the bulk of past landings were from relatively climate-resilient species, future catches may be jeopardized by the recent increases in landings of species whose distribution may change. In addition, many benthic fishery resources showed high sensitivities and low potential to change their distribution, making them more susceptible to climate-induced changes.

Bony fishes support the most important regional fisheries and have received more research and management attention than other fishery resources (e.g., Cardoso and Haimovici 2015; Jaureguizar et al. 2016), but climate change impacts remain poorly understood (Franco et al. 2020a, b). Species that comprise this group (primarily coastal and demersal fishes in our assessment) are relatively climate-resilient, as estimated sensitivities were low or moderate, whereas the potential for changes in distribution was moderate-high. Other trait-based assessments support similar findings for these types of bony fishes (Hare et al. 2016; Ortega-Cisneros et al. 2018; Giddens et al. 2022; Ramos et al. 2022). Evidence of climate impacts on bony fishes within our study area primarily come from catch-only data and information about species' thermal preferences (e.g., Gianelli et al. 2019b; Verba et al. 2020). For instance, the increase in SST implies a trend towards unfavorable thermal conditions for *M. hubbsi*, a cold-water affinity species with moderate sensitivity and a high potential for distribution change. A past poleward climate-mediated distribution shift in *M. hubbsi* supports this hypothesis (Bas et al. 2020). A recent study for the warm-temperate SWAO showed that under climate change scenarios, SST would determine future fish larvae

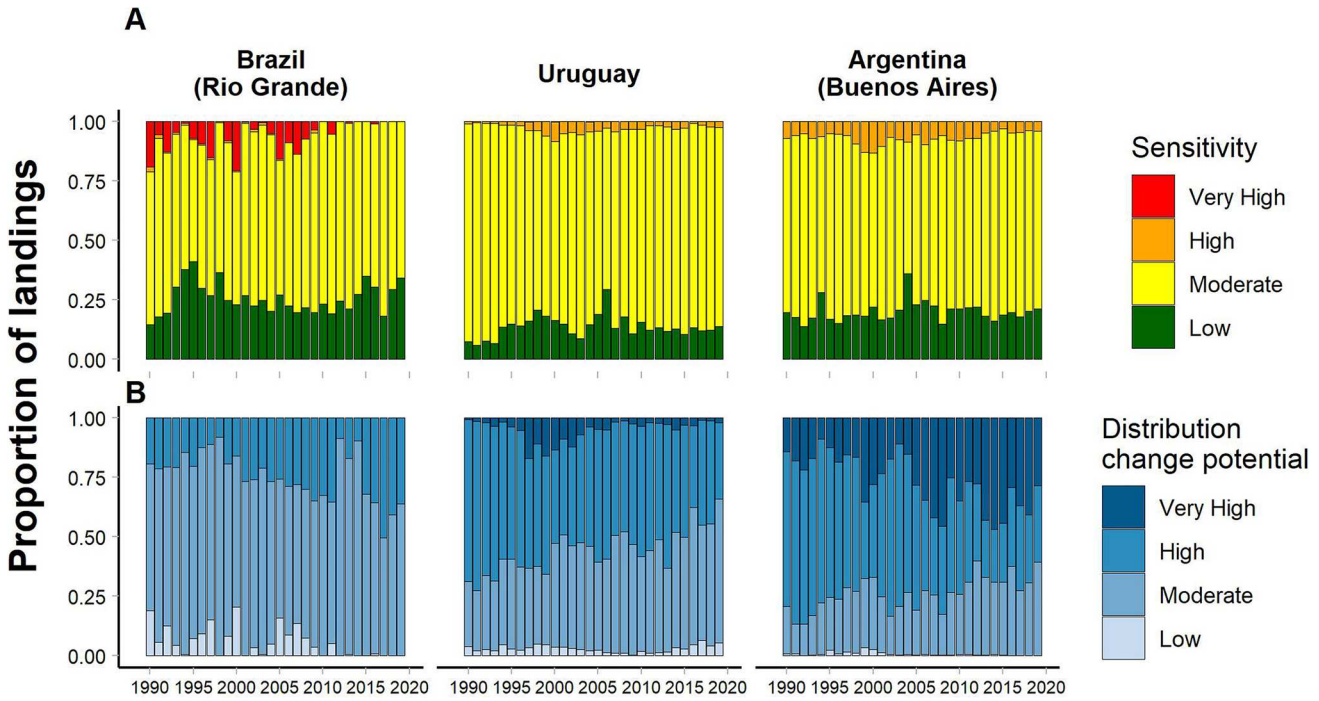

Fig. 7 Temporal trends of annual landings according to (**A**) species' ecological sensitivity to climate change and (**B**) species' distribution change potential within the study area. In (**A**) and (**B**), landing statistics include only those species covered in the present ecological sensitivity assessment and landed by the industrial fishing sub-sector in fishing ports within the study area. Both attributes were expressed by discrete categories (Very High, High, Moderate, and Low) and differentiated by country

distribution, whereas surface salinity and bathymetric gradients better predict fish adult stages distribution (Costa et al. 2021). Even under moderate climate change scenarios, fish larvae and adult stages distributions were predicted to move polewards (Costa et al. 2021). Another fragmentary evidence of climate-induced impacts stems from studies that assess variability in the distribution, abundance, and population structure of coastal-estuarine fishes (e.g., *M. furnieri*, *C. guatucupa*) in response to mid-term environmental variability and change. Without long-term research programs, these studies provide an indirect approach to inferring potential climate-related impacts on species (Jaureguizar et al. 2015, 2016, 2021) and local coastal fishing communities (Camiolo et al. 2019). Pelagic fish in our assessment were represented only by *E. anchoita*, a low-sensitivity species with a high potential to change its distribution. Low sensitivities were also estimated for other small pelagic species in other parts of the world (Pecl et al. 2014; Hare et al. 2016; Jones and Cheung 2018; Ortega-Cisneros et al. 2018; Bueno-Pardo et al. 2021). Yet, early and adult life stages of forage fish are particularly susceptible to changes in circulation and productivity, mediated by climatic variability and change (Chavez et al. 2003; Checkley et al. 2009). This incongruence could stem from the fact that trait-based assessments hardly consider climate-induced changes in primary productivity (Hare et al. 2016; Jones and Cheung 2018), a limitation that could have underestimated the sensitivity of *E. anchoita*.

Chondrichthyans are most threatened by overfishing (Dulvy et al. 2014; Pimiento et al. 2020). Hence, the main individual attribute that contributed to their high sensitivity was stock or conservation status. Other life-history traits such as low population growth may render them susceptible to climate-induced changes (Ortega-Cisneros et al. 2018; Giddens et al. 2022), further jeopardizing this group (Dulvy et al. 2021; Santos et al. 2021). Chondrichthyans distribution (endemic or cosmopolitan) could broadly explain species sensitivity patterns (Jones and Cheung 2018). For instance, two endemic guitarfishes (*P. horkelii* and *Z. brevirostris*), both with conservation concerns and subject to high fishing pressure (either as target species or by-catch), presented the highest ecological sensitivities, while cosmopolitan sharks presented low sensitivities (*G. galeus* and *S. acanthias*). However, this relation does not hold for *C. taurus* (cosmopolitan with high sensitivity) and *S. guggenheim* (endemic with moderate sensitivity) due to the critical population status of *C. taurus* in the region (Cuevas et al. 2021) and the relatively stable stock status of *S. guggenheim* in the Argentinean-Uruguayan Common Fishing Zone (CTMFM 2018; Oddone et al. 2019).

Mollusks, particularly benthic ones, were ranked the most sensitive. Benthic calcifying mollusks are exceptionally responsive to climate-induced changes (Hare et al. 2016; Giddens et al. 2022; Ramos et al. 2022) due to the detrimental effects of acidification (Kroeker et al. 2013) and their limited movement capacity in adult stages. The yellow clam (*A. mactroides*), an endemic species that inhabits exposed sandy beaches, provides a compelling example of well-documented climate-induced impacts (e.g., SST increase) on species' performance and abundance (Ortega et al. 2016) and ultimately, in its small-scale fishery (Defeo et al. 2021; Gianelli et al. 2019a, 2021). On the other hand, deep-sea benthic species, such as *Z. patagonica* (depths up to 200 m: Gutiérrez and Defeo 2003), could be relatively unaffected by SST changes. Yet, it may be susceptible to benthic-pelagic decoupling processes (i.e., sedimentation of phytoplankton blooms: Franco et al. 2020b). Considering its high sensitivity and moderate potential to adjust its distribution, assessing climate change impacts will be critical to sustaining this scallop fishery in a changing SWAO (Pérez-Ramírez et al. 2016).

Life-history strategies (short-lived and semelparous) and their high sensitivity to environmental factors render cephalopods challenging to study under a climate change lens (Doubleday et al. 2016). Interestingly, the two squid species assessed were classified with low sensitivity. Similar studies also classified cephalopods as fishery resources of low or moderate sensitivity (Hare et al. 2016; Ortega-Cisneros et al. 2018; Cochrane et al. 2019). This discordance between trait-based assessments and climate change expectations deserves further attention, as cephalopods' abundance fluctuations are expected to be both climate change indicators and drivers of ecosystem change (André et al. 2010). Evidence of climate-induced changes in cephalopods inhabiting the SWAO is negligible. However, a recent long-term study suggested that increasing temperatures on hatching grounds of *I. argentinus* during key life-history stages would adversely affect the abundance and proportion of mature females (Chemshirova et al. 2021).

Crustaceans are probably the least understood group in the region concerning climate-induced changes. Establishing general patterns of climate-induced changes in survival, growth, or calcification in this group has proven difficult (Kroeker et al. 2013), partially because of buffering capacities against detrimental impacts (e.g., osmoregulation, cyclically replaceable biogenic covering, mobility, and plasticity in energy allocation) (Boenish et al. 2022). The broad ecological sensitivities estimated for crustaceans suggest species-specific responses to potential climate impacts. For instance, the single migratory stock of the penaeid shrimp *P. paulensis* ranked second in our sensitivity assessment because of its ontogenetic specificity for abiotic and biotic factors, and its dependence on environmental drivers for recruitment success (Haimovici and Cardoso 2017). Additionally, interdecadal precipitation regimes and the intensification of climate interannual oscillations (i.e., ENSO) were identified as other potential stressors to which *P. paulensis* may be sensitive (Möller et al. 2009; Santana et al. 2015; Gasalla et al. 2017). On the other hand, *P. muelleri*—which notably is not so abundant within our study area—was classified with low sensitivity. However, this result must be revisited when analyzing the impacts of climate change further south of the study area, where the red shrimp fishery is of utmost socio-economic importance (Góngora et al. 2012).

Even though we purposefully decided to assess only the sensitivity component of vulnerability, our results are useful for developing more refined and holistic future assessments. Nevertheless, the inclusion of the exposure component (of vulnerability) would likely result in different outcomes compared to our sensitivity ranking. For instance, other trait-based vulnerability assessments showed that in high-climate exposure regions, species sensitivity matched vulnerability in 60–68% of the cases (Hare et al. 2016; Ramos et al. 2022), whereas, in low-climate exposure regions, sensitivity is a poor predictor of species vulnerability (28% of matches: Spencer et al. 2019). Our study area encompasses a warming hotspot (Hobday and Pecl 2014) and a region where a considerable increase in freshwater runoff is projected (Franco et al. 2020a, b). Therefore, a corresponding pattern between sensitivity and vulnerability may be expected, similar to other high-climate exposure regions. If this would be the case, vulnerability could outweigh sensitivity for species where the former and the latter do not match. We advocate for extending our approach to include not only exposure factors but also integrate the social, economic, and institutional components of fisheries. Social-ecological vulnerability assessments are instrumental for identifying adaptation capacities and strategies to minimize the vulnerability of fishing industries and communities. Notably though, institutional vulnerability assessment is another immediate need in the SWAO where existing fisheries management and governance frameworks are based mainly on the premise that population distributions remain fairly static over time (Franco et al. 2020a, b). These assessments should help identify factors that can boost, or hamper, the adaptation of institutions to changes in the abundance and availability of stocks (Pinsky et al. 2018).

Trait-based assessments are rapid, simple, and efficient for addressing climate-induced changes in multiple species, but their usefulness is conditioned by their comprehensiveness. We identified two main caveats to our approach. First, inferring potential changes in species distributions based on a subset of sensitivity attributes may be an overly bold approach because it could be considered too vague and controversial (Beissinger and Riddell 2021), particularly for predicting species range shifts (see Sunday et al. 2015;

Pinsky et al. 2013; Schuetz et al. 2019). Other factors, such as diet breadth (Bates et al. 2014; Monaco et al. 2020) and seascape topography (Champion and Coleman 2021; Costa et al. 2021), are also documented as critical mediators of changes in marine species distribution ranges. Therefore, our results related to the potential for changes in distribution should be considered with caution and as preliminary working hypotheses. Second, trait-based frameworks often fail to address climate-driven changes in primary productivity (Hare et al. 2016) and potential trophic cascade effects on marine biota. Thus, we call for species-specific mechanistic evidence and correlational studies, as well as ecosystem models, to explore the effects of multiple exposure factors on key fishery resources in the SWAO.

The quality and lack of data were not major limitations for our sensitivity assessment. However, the sensitivity of regional fishery resources to some attributes, such as ocean acidification, remains largely unknown, but may include potential direct detrimental impacts for shell-forming organisms (Kroeker et al. 2013) and oxygen-demanding organisms such as squids (Seibel 2016), as well as indirect effects propagated through food webs. We did not find any relation between data quality and estimated sensitivities, suggesting that sensitivity is not overestimated for data-poor species. As opposed to the strategy used in other studies where the highest scores of sensitivities were given when information was lacking (Ramos et al. 2022), we opted for distributing tallies between sensitivities categories as suggested by Hare et al. (2016). This strategy could explain the low to moderate levels of certainty estimated by bootstrap analysis for many species when classifying sensitivity to climate change.

Landings for this study came from industrial fisheries due to limitations in retrieving long-term databases for small-scale fisheries. Thus, future assessments may benefit from including small-scale fisheries, which are particularly threatened by climate-induced changes (Gianelli et al. 2021; Short et al. 2021). Data gaps in official statistics were partially compensated for by relying on landing monitoring efforts made by the Federal University of Rio Grande. However, data coverage in the State of Rio Grande do Sul (Brazil) during 2012–2019 was far lower than in previous years (Oceana 2021), limiting the scope of our conclusions for this particular region. Finally, future assessments could be complemented by including additional species, particularly those relevant to Brazil (e.g., *Pomatomus saltatrix*, *Mugil* sp.) and Argentina (e.g., Rajijdae spp., *Pagrus pagrus*, *Pseudopercis semifasciata*), where the fraction of unassessed landings is around 30% of total landings.

The potential for changes in the distribution of a particular species or the ensemble of species that comprise a country's landings is, in principle, value-neutral. The directional effects depend on several factors, such as the location of fishing ports or jurisdiction boundaries relative to the geographic distribution of the species. Species with a high potential for redistribution may be more climate-resilient from a biological perspective (Hare et al. 2016), but may result in both winners and losers among nearby fishing communities or neighboring jurisdictions (Rogers et al. 2019).

Even if climate-induced changes in regional fishery resources are not fully understood, the fundamental question is no longer whether marine ecosystems are affected, but how stakeholders can prepare for and adapt to forthcoming changes (Lindegren and Brander 2018). Stock and/or conservation status was the attribute that contributed the most to higher sensitivities of fishery resources in the SWAO. As the single driver that can be endogenously managed by governmental fisheries authorities or coordinated regional efforts for transboundary stocks, fishing effort optimization creates an opportunity to increase fishery resources' resilience to climate change. Benefits of fisheries management improvement and stock rebuilding efforts include potential increased future catch of target species and spillover effects to by-catch species, even accounting for climate change effects (Gaines et al. 2018; Free et al. 2020; Sumaila and Tai 2020).

Accounting for species sensitivity and climate-induced uncertainty could assist fisheries sectors in reducing risks by balancing a fishing portfolio of potentially sensitive and resilient fishery resources (Rogers et al. 2019). Few species have historically dominated landings in the region, particularly in Uruguay. Thus, relying on a few stocks and fishing gear types could impair adaptive capacities (Ojea et al. 2020), particularly if targeted species have high or very high sensitivities and a low or very high potential for changing their distributions. Diversifying fishing gears and vessels to target underexploited fishery resources with low to moderate ecological sensitivity (e.g., *E. anchoita*, *Percophis brasiliensis*, and *Nemadactylus bergi*) may foster adaptive capacity in the industrial sub-sector. However, most small-scale fisheries cannot undertake such changes due to scarce assets and lack of financial capacity (Ojea et al. 2020). Furthermore, the low-range mobility of small-scale vessels limits access to new fishing grounds and, therefore, resource diversification. Thus, small-scale fishing communities that depend on highly sensitive fishery resources (e.g., *A. mactroides*, *P. paulensis*) would be particularly threatened by climate-induced changes.

Our results are helpful for fishery managers, decision-makers, and researchers for identifying highly sensitive species and to guide potential anticipatory and deliberate adaptive responses in local and regional fisheries. Unilateral efforts are being explored to adapt to climate change effects in fisheries in Uruguay (PNA-Agro 2019) and Argentina (Buratti et al. 2022). Yet, the scale, scope, and magnitude of environmental changes in the SWAO will require an integrated regional strategy, and therefore coordination and

cross-linkages between regional and national governance levels are critical to foster climate-resilient fisheries.

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Data Availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. Landings from Brazil, Uruguay and Argentina are available in official national statistics.

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