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Research article

Projecting future changes in distributions of small-scale pelagic fisheries of the southern Colombian Pacific Ocean

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ABSTRACT

Small-scale fisheries (SSF) contribute to nearly half of global landings and provide multiple socioeconomic benefits to coastal communities. The Pacific coast SSF represents 37% of the total fisheries landings in Colombia. Scientific literature continually shows that tropical marine habitats are most vulnerable to oceanic changes associated with climate change. This study prioritized three pelagic species (*Euthynnus lineatus*, *Scomberomorus sierra*, and *Cynoscion albus*) based on their landing statistics to develop potential current and future species distributions using five ensembled machine learning models including Artificial Neural Network (ANN), Maximum Entropy (MaxEnt), Boosted Regression Tree (BRT), Random Forest (RF), and Classification Tree (CT). Future distributions of these species in the medium-term (2050s) and long-term (2080s) were modeled using the Representative Concentration Pathways (RCP) 2.6 and 8.5 emission scenarios for four ensembled General Circulation Models (GCMs) obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5). In addition, change detections were calculated to identify contraction and expansion of areas, and the distributional core shift was determined to estimate the spatial movements. Results indicate that *E. lineatus* and *S. sierra* will potentially move to deeper waters away from the coastline. Alternatively, *C. albus* could be a species to potentially gain more importance for the fishing sector due to potential variations in climate. These results constitute a critical scientific basis for evaluating the climate change vulnerability of the fishing sector and the decision-making process in the future of small-scale fishery management in the southern Colombian Pacific Ocean.

1. Introduction

Greenhouse Gas (GHG) emissions have accelerated global warming, affecting the physical-chemical conditions of the oceans, including variations in temperature, salinity, currents, oxygen availability, nutrients, and ocean acidification (FAO, 2019). These changes affect the distribution, abundance, and productivity of phytoplankton and zooplankton, the first levels of the trophic chain, and other marine species that depend on them (Perry et al., 2005; Pörtner, 2010; Jennings and Collingridge, 2015; Lotze et al., 2019). Tropical and subtropical fishing grounds will be the most affected by these changes (Sobel and Camargo, 2011), which are mainly associated with temperature. As a result, marine species will move towards other zones in which habitat conditions will be optimal for their development (FAO, 2012).

Projections indicate that a temperature increase of up to 3 °C is expected for the next century, triggering a response to a warming climate in coastal species, with shifts in the horizontal and vertical distributions (Hobday et al., 2015). These effects could greatly impact artisanal and small-scale fisheries since catches are mainly done in coastal and continental platform waters. Thus, human systems will also be affected, primarily those that support their income and food security on the fishing of marine species (FAO, 2012; Lam et al., 2012).

Small-scale fisheries are widely recognized for their contribution to nearly half of global landings and the multiple socioeconomic benefits they provide to coastal communities (Herrón et al., 2019). Fishing in developing countries represents 45% of the world's fish commerce, ascending to US $13 billion per year. At the same time, fish represent more than 20% of the animal protein consumed worldwide, which comes from 107 million tons of fish destined for direct human consumption. This gives an average world consumption of 13 kg per capita each year, and for Colombia, 4.5 kg per capita per year (Gutiérrez, 2010).

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The Pacific region of Colombia provides 80% of the total catch volume of the country (Tilley et al., 2018), representing 3% of the gross domestic product (Boyd, 2010). Artisanal and small-scale fisheries hold the main supply of hydrobiological resources on the Pacific coast and are currently responsible for a significant proportion of the seafood consumed in the country, with gross revenues in the range of US $10–20 million per year. In 2017, landings from artisanal and small-scale fisheries in the Pacific region were valued at US $10.8 million, of which Buenaventura (56.9%) and Tumaco (21.2%) accounted for the majority of the landings since these two ports are the largest of the region (Castellanos-Galindo et al., 2018). In addition, it is estimated that approximately 400,000 people—mainly in coastal communities—depend exclusively on fishing activity as an economic activity for their livelihood (Esquivel et al., 2014). Specifically, on the Pacific coast of Nariño, it is estimated that there are approximately 149 artisanal fishermen associations that group more than 4,500 people who are dedicated to artisanal fishing and collection of crustaceans and molluscs, contributing to the food security of the communities Government of Nariño & Mayor of Tumaco (2014).

On the other hand, public agencies state that the fishery of marine species in the Colombian Pacific represents 37% of the total landings in the country. Among the most important species captured in the Pacific Economic Exclusive Zone (EEZ) of Colombia are the seerfish (*Scomberomorus sierra*), black skipjack (*Euthynnus lineatus*), and whitefin weakfish (*Cynoscion albus*). These commercially important species represented 15% of the total landings in the Pacific in 2018, with seerfish having the highest landing (Duarte et al., 2018).

For the EEZ of the Colombian Pacific Ocean, Herrera et al. (2015) project that by 2100 under a pessimistic climate scenario (A1B), total fish landings will decrease by 8.2% compared to 2010 (77,257 tons). Nevertheless, it is critical to understand how the effects of climate change can impact the geographical distribution of marine species (Kamaruzzaman et al., 2021) that are targeted by the fishing industry, where technological development has aided progress in this field. In addition, knowledge about the distribution of species is essential in matters of conservation, management, and sustainable use.

Remote monitoring of oceanographic variables facilitates gathering important information for Species Distribution Modelling (SDM). The use of models to predict the distribution of fish based on estimations of future changes in marine ecosystems is an efficient and valuable tool that can be used to determine the impacts of climate change on distribution (Porfirio et al., 2014; Kamaruzzaman et al., 2021) of commercially important marine species. With SDMs, it is possible to generate probabilistic maps, among other analyses, that reflect the suitability of the species' habitat based on the environmental characteristics of their geographic environment (Phillips et al., 2006). To achieve this, the SDMs are based on correlations between the known occurrence data of the species based on their environmental preferences that each occurrence locality presents (Elith and Leathwick, 2009).

In this context, SDMs are important decision-making tools for many biogeographic applications, for example, identification of protected and conservation areas, assessment of the effects of climate change, and prediction of areas with possible invasion of species (Miller, 2010); all these applications can support studies of conservation and sustainable use of fishery resources. However, in Colombia, few studies have evaluated the effects of climate change on fisheries (Rojas-Higuera and Pabon-Caicedo, 2015; Herrera et al., 2019). Furthermore, none of the studies known to date have used ensemble modelling and machine learning methods to determine the shifts in the spatial distribution of commercially important marine species in the Colombian Pacific.

In this study, 3 pelagic species (*E. lineatus*, *S. sierra,* and *C. albus*) were prioritized for spatial and annual distribution based on landing statistics and the livelihood of the fishing communities of the district of Tumaco and the Colombian Pacific region of Nariño. The distribution analysis was performed under climate change scenarios (RCP 2.6 and RCP 8.5) in two periods of time, known as the medium term (2036–2065, named 2050) and long term (2066–2095, named 2080), using temperature, salinity, net primary productivity, and velocity and direction of ocean currents in an ensemble of 5 machine learning models to determine the effects of climate change on the future distribution of the three most important species for the small-scale fisheries of the south Colombian Pacific.

2. Methods

2.1. Study area

The Colombian Pacific has an Economic Exclusive Zone (EEZ) of 339.500 km^2 and a coastline that extends from the borders of Panama (7°13′21″ N, 77°53′ 25″ W) to Ecuador (1°27′48″ N, 78°51′43″ W) (DIMAR, 1988; Correa and Morton, 2010). Its continental shelf encompasses five fishing grounds where different types of species can be found (straddling stocks, white fish stocks, and demersal species) that are harvested by industrial and small-scale fisheries (Díaz-Merlano et al., 2011).

The Colombian Pacific Ocean basin is affected by North and South Trade Winds, which influence the dynamics of the surface water masses generating the so-called Intertropical Convergence Zone (ICZ) (Devis-Morales et al., 2002). These water masses are part of the anticyclonic system of the eastern Pacific currents, among which the California currents and the northern equatorial (Northern Hemisphere) and the Peruvian, Humboldt, and southern equatorial currents (Southern Hemisphere) stand out (Devis-Morales et al., 2002).

The EEZ of the southern Colombian Pacific Ocean has an area of 142,140 km^2, equivalent to 42% of the total EEZ of the country. The region includes ten municipalities in the provinces of Cauca and Nariño, for which it was named the Nariño Economic Exclusive Zone (NEEZ) for this study. The NEEZ is bordered to the north with the EEZ and to the centre and north with the Colombian Pacific and Gulf of Panama; to the east with the coasts of Nariño and Cauca; to the south with the coast of Ecuador; and to the west with the equatorial waters of the Pacific Ocean (Figure 1).

The inhabitants of this zone are mainly afro descendants (>95%) that support fishing, agriculture, and/or extraction activities (timber and gold mining) to subsist (Escobar, 2008) and therefore have a high dependence on the extraction of natural resources (Castellanos and Zapata-Padilla, 2019). A significant proportion of households depend on small-scale fisheries to obtain their food and income. These fisheries supply the local and national markets, representing between 15% and 40% of the landings in the coastal zone (De La Hoz et al., 2013; Herrón et al., 2019).

2.2. Methods

The methodological development of the study comprises three general phases:

I) Modelling of the current geographic distribution of species of fishing interest in the southern Colombian Pacific.
II) Modelling of the future geographic distribution of species of fishery interest under climate change scenarios.
III) Detection of changes in the distribution of species of fishery interest under climate change scenarios.

Baseline information on species occurrence was obtained from national and international databases, such as the Smithsonian Tropical Research Institute Online Information System for Coastal Fishes of the Eastern Pacific (https://biogeodb.stri.si.edu/sftep/es/pages) (Robertson and Allen, 2015), Marine Environmental Information System (SiAM) of the José Benito Vives de Andréis' Institute for Marine and Coastal Research (INVEMAR) (*http://siam.invemar.org.co/*), Global Biodiversity Information Facility (GBIF) (*https://www.gbif.org/en/*), and Ocean Biodiversity Information System (OBIS) (*https://obis.org/*).

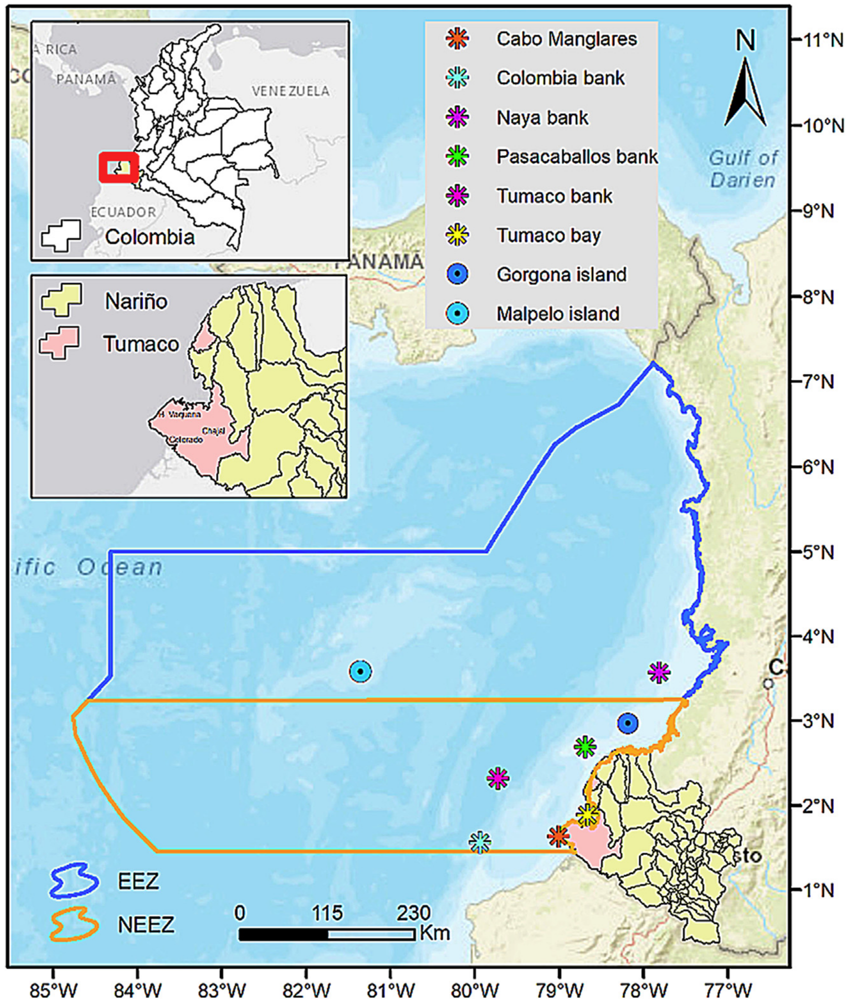

Figure 1. Study area in the southern Colombian Pacific.

The oceanographic variables temperature, salinity, current (velocity and direction), and net primary productivity were used to develop a SDM (Table 1). Variables for the current scenario (Phase I) were obtained from Copernicus Marine Environment Monitoring Service (CMEMS) (http://marine.copernicus.eu/) and ECMWF (European Centre for Medium-Range Weather Forecasts) Ocean ReAnalysis ORAP5.0 (*https://www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis*) of the MyOcean2 project with a spatial resolution of ¼ degree. ORAP5.0 is based on the Nucleus for European Modelling of the Ocean (NEMO) ocean model and the Variational NEMO (NEMOVAR) data assimilation system (Zuo et al., 2014). Annual averages of oceanographic variables (1979–2013) were determined as a current scenario (climatology) at all available depths (approximately 0. 5 m–271 m) to model the distribution of each species according to the depths of biological preference; thus: 0 m and 27 m for *Euthynnus lineatus*, 17 m and 54 m for *Scomberomorus sierra* and 0 m and 41 m for *Cynoscion albus*.

Table 1. Oceanographic variables used in the SDM.

Oceanographic variables	Units	Resolution
Temperature	°C	1/4°
Salinity	PSU	
U currents	m/s	
V currents	m/s	
Net primary productivity	mgC/m^2/day	

Five machine learning models—Artificial Neural Network (ANN), Maximum Entropy (MaxEnt), General Boosting Model (GBM) also known as Boosted Regression Tree (BRT), Random Forest (RF), and Classification Tree (CT)—were ensembled to model the distribution of the selected species at the depths mentioned above in the annual season, using the BIOMOD2 package of R Studio. We used 75 percent of the species occurrence data for training and the remaining 25 percent for testing for the model.

The future distribution scenarios (Phase II) were constructed using an ensemble of oceanographic variables derived from the Atmosphere-Ocean General Circulation Model (AOGCMs) (*https://esgf-node.llnl.gov/projects/esgf-llnl/*), including the Max Planck Institute for Meteorology Earth System Model (MPI-ESM-MR) and (MPI-ESM-LR), the Earth System Model that the Met Office Hadley Centre used (HadGEM2-ES), and the Centre National de Recherches Météorologiques Earth system model (CNMR-CM5). These GCMs were selected because they best simulated the Choco jet, an essential atmospheric feature of Colombian and northern South American hydroclimatology (Sierra et al., 2018). These data were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under two climate change Representative Concentration Pathways RCP 2.6 (radiative forcing reached almost 3 W/m^2 by 2100) and 8.5 (an increase in radiative forcing, leading to 8.5 W/m^2 by 2100) and at two time scales of analysis: medium term (2036–2065 called 2050) and long term (2066–2095 called 2080).

Statistical downscaling (delta method) was used to reduce the spatial resolution to the regional scale (4 km) (Ådlandsvik, 2018; Ramirez-Villejas and Jarvis, 2010; Hernández-Díaz et al., 2016). For future

SDMs, we include the projection of the same oceanographic variables (except net primary productivity, which was assumed to be constant due to its future projection's unavailability in the models used).

Finally, the effect of climate change was evaluated on the geographic distribution of the species; the changes between the current and future distribution probabilities at the annual level were quantified (Phase III). For this, we considered the differences in the probability of spatial distribution of the species of interest (future - current distribution), utilizing four pre-established classes (Table 2):

In addition, the core distributional shift for species of interest at different depths was calculated using SDM Toolbox, a comprehensive phyton-based toolbox for macroecology, landscape, and other ecology studies based in ArcGIS (Brown et al., 2017). This toolbox uses binary species distribution to summarize it into a single central point (centroid); as a result, a vector file representing the magnitude and direction of the predicted change over time was obtained. The threshold used to convert continuous probability into binary rasters was 50% (Brown, 2014).

3. Results and discussion

3.1. Current and future distributions of the pelagic species

3.1.1. Black skipjack (Euthynnus lineatus)

E. lineatus is a pelagic species that is distributed in the eastern Pacific from the Gulf of California to northern Peru, including the Galapagos Islands (Collete and Nauen, 1983; Collete et al., 2011). In Colombia, it has been recorded along the entire Pacific coast and open ocean areas, as well as on Gorgona Island (Zapata and Usma, 2013). On the north coast of the Colombian Pacific (Tobón-López et al., 2008), the central zone (Zambrano et al., 2018b) and in the Choco zone, it has been recorded as part of the main species in artisanal fishing, being caught with hand lines, spinels, and gillnets (Díaz-Merlano et al., 2016).

E. lineatus showed high probabilities of occurrence along the coastal zone of the NEEZ at 0 m and in open waters at 27 m in the current scenario (Figure 2). At 0 m depth, the species shows a greater probability of presence along the entire coast and Tumaco Bay, approximately 60 km offshore. From this distance, the probability of distribution is significantly reduced when moving out to sea, especially in the southern zone of the Nariño Pacific, around "Cabo Manglares" (an important area of conservation and environmental preservation under the name of Cabo Manglares National Integrated Management District, Bajo Mira y Frontera) and Tumaco Bay. In the northern part of the study area, off the coasts of Valle del Cauca and Cauca, a greater probability of presence is observed when the distance of 60 km from the shore is exceeded compared to the southern area (Tumaco and "Cabo Manglares"), whose values are between 50% and 60% probability. However, there was a greater probability of *E. lineatus* in the coastal zone of Nariño Province, at approximately 96%. The artisanal and semiindustrial fishermen of Tumaco and the Pacific region of Nariño state that they tend to harvest this species mainly at distances greater than 2.5 nautical miles (5 km) in the fishing banks known in the region as the "Tumaco bank", which is consistent with the results of the current distribution.

On the other hand, the distribution of *E. lineatus* at 27 m depth shows a greater geographic range of presence that extends more than 120 km away from the coast, up to approximately longitude -80.5°W, although with a lower probability of distribution (between 40% and 60%). This distribution includes other well-known fishing banks in the region, including "Colombia bank," "Naya bank", and "Pasacaballos bank". At this depth, the species can be captured by fleets or boats that have engines that allow them to be mobilized at greater distances from the coast and that also have the means to conserve the product until its use.

Regarding the future distribution, at 0 m depth, the probability of occurrence of the species increases in the RCP 2.6 scenario to 2050 in the coastal zone. Under this climate change scenario, there is a slight increase in the average probability of occurrence of 1.7% for the entire study area; the results may suggest that the waters near the "Naya bank" will have a higher occurrence of this species in comparison with the current scenario and with the probabilities of occurrence near the other known fishing banks in the region, whose probability of presence will be approximately 75% and 78% for the waters near the "Pasacaballos" and "Tumaco banks", respectively. An opposite behaviour is obtained for the RCP 2.6 scenario to 2080, with average probability values of 29% for the study area. Compared to the average value of the current distribution (33%), it represents a decrease in the average probability of 4%. Under this scenario, the least impacted fishing area will be the waters near the "Tumaco bank".

In the RCP 8.5 scenario to 2050 (at 0 m depth), an increase in the probability of occurrence greater than that obtained under the RCP 2.6 scenario for the same period (2050) is observed, where the average probability value for the study area increases by 2.5%. The area with the greatest probability of occurrence extends from the coastal strip to the open sea, expanding the range of the species with probabilities above 75%. The RCP 8.5 scenario to 2080 generally shows an increase in the probability of occurrence for the entire study area, from 34% to 38% (4.6% increase), with an expansion of the area of most significant probability in waters off the coast of Valle del Cauca and Cauca, with values of 80% probability of occurrence of the species. The waters near the "Tumaco" and "Pasacaballos" banks are conserved with relatively stable probabilities of occurrence compared to the current scenario.

At a depth of 27 m, it is observed that the probability of occurrence of the species is higher in all future scenarios. Zapata and Usma (2013) concluded that climatic phenomena such as "El Niño" and "La Niña" can generate adequate conditions for some species in the coastal zone of the Colombian Pacific, which could explain the increase in the probability of occurrence of this species that occurs mainly in the coastal zone. This additionally indicates that *E. lineatus* is more likely to be harvested at a depth of 27 m than at surface level, therefore requiring that fishers have adequate fishing gear to reach these depths with their fishing autonomy.

The average probability of occurrence of *E. lineatus* at a depth of 27 m for the entire study area in the RCP 2.6 scenario by 2050 increases by 15%, conserving the coastal zone as the area with the highest probability of occurrence of the species. In the RCP 2.6 scenario to 2080, the coastal waters to the south of Nariño, at the height of "Cabo Manglares", present a reduction in the probability of occurrence of approximately 20%, affecting the productivity of the waters near the "Colombia bank" and, to a lesser extent, the waters near the "Tumaco bank". However, the results obtained in the RCP 8.5 scenario to 2050 again show a significant increase in the probability of occurrence of the species in the future in the entire study area, on the order of approximately 18%, also showing an expansion in the area and high probability of the species moving towards the open sea, up to approximately 81° longitude, which could benefit tuna fishing by vessels with high autonomy. This is a similar behaviour obtained with the RCP 8.5 scenario in 2080, with a general increase in the probability of occurrence in the entire study area of approximately 13%, with values of a high probability of occurrence that are even higher than those obtained in the previous climate change scenario (84%).

3.1.2. Seerfish (Scomberomorus sierra)

Scomberomorus sierra is a species restricted to the eastern Pacific Ocean that is distributed from the coast of the Gulf of California (Mexico) to Peru, including the Galapagos, Cocos, and Malpelo Islands (Collete et al., 2011). It is a highly migratory pelagic-neritic species present on the

Table 2. Classes defined in the change detection process according to Herrera et al. (2019).

Class	Interpretation
No change	Probability reduction or gain ≤10%
Positive change	Probability gain >10%.
Negative Change	Probability reduction >10%.
Absence	The difference between future and current probability is equal to 0%

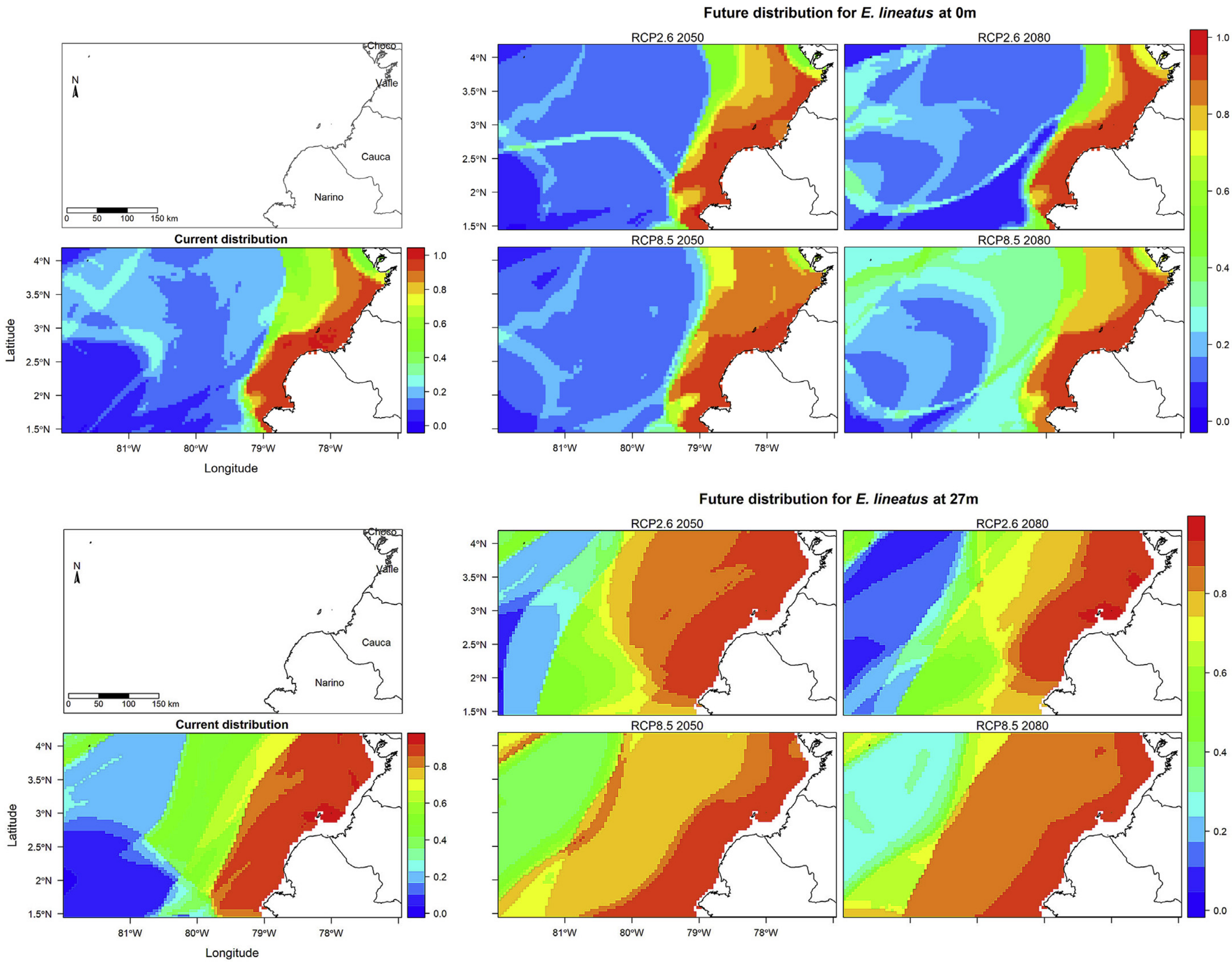

Figure 2. Current and future distributions of *E. lineatus* under climate change scenarios; the top map composition shows the results at 0 m, and the bottom map shows the results at 27 m.

surface of coastal waters. Its vertical distribution is between 10 and 60 m (Nieto-Navarro et al., 2010). In the Colombian Pacific, it has been recorded in the provinces of Chocó, Cauca (on Gorgona Island) and Nariño in the municipalities of Tumaco and Francisco Pizarro (Eraso-Ordoñez et al., 2017). It represents one of the most important species for artisanal fishing along the entire Colombian Pacific coast (Tobón-López et al., 2008; Diaz-Merlano et al., 2016).

S. sierra, which was modelled at depths of 17 m and 54 m, showed a high probability of occurrence along the coastal waters of the NEEZ in the current scenario that later decreased in future scenarios of climate change at both depths. However, under RCP 8.5 in 2080, the species' probability of occurrence will increase in open waters at the 17 m depth (Figure 3).

The modelling of the current period geographical distribution of this species at a depth of 17 m shows a high probability of occurrence (>97%) in the coastal zone and continental shelf in front of the Valle del Cauca and Cauca provinces. In return, a lower probability of presence is observed in the coastal zone in front of Tumaco Bay, on the order of 80%, which rapidly decreases with the increase in the distance offshore. From approximately longitude -79.2°W, a very low probability appears. These results are consistent with the literature, considering that the distribution, migration, and spawning of the *S. sierra* occur in the coastal areas of the Pacific (Aguirre-Villaseñor et al., 2006) and that fishers from Tumaco and the region usually manifest fishery harvests between depths of 6–39 m for this species.

On the other hand, the current distribution of this species at a depth of 54 m allows us to visualize a wider area of presence in front of the Nariño coast with probabilities that oscillate between approximately 75 and 98% around longitude -79.2°W, covering waters near the bank of Tumaco. Lower values of probability of presence are observed to the south of the EEZ in waters off the coast of "Cabo Manglares", with values between 39% and 70%, but still higher than the probability presented for the modelling at 17m (9% and 20%). Therefore, the capture of the *S. sierra* in areas such as "Colombia bank" will depend on having fishing autonomy that allows reaching a depth greater than 17 m.

Under the RCP 2.6 scenario at 2050 (17 m depth), *S. sierra* presents an increase in the probability of occurrence of 7% compared to the current distribution, despite the decrease in the probability of occurrence in coastal waters of Valle del Cauca and Cauca (going from values between 97% and 98% at present to values of 77%–79%). In the RCP 2.6 scenario to 2080, the probability of the presence of the *S. sierra* shows a slight decrease in the entire study area (approximately 2%), mainly affecting coastal waters in the north of the study area. The coastal waters of the south of the study area, in front of Tumaco Bay and "Cabo Manglares", would have increases in the probability of the presence of the species for the two periods (2050 and 2080) of this RCP scenario.

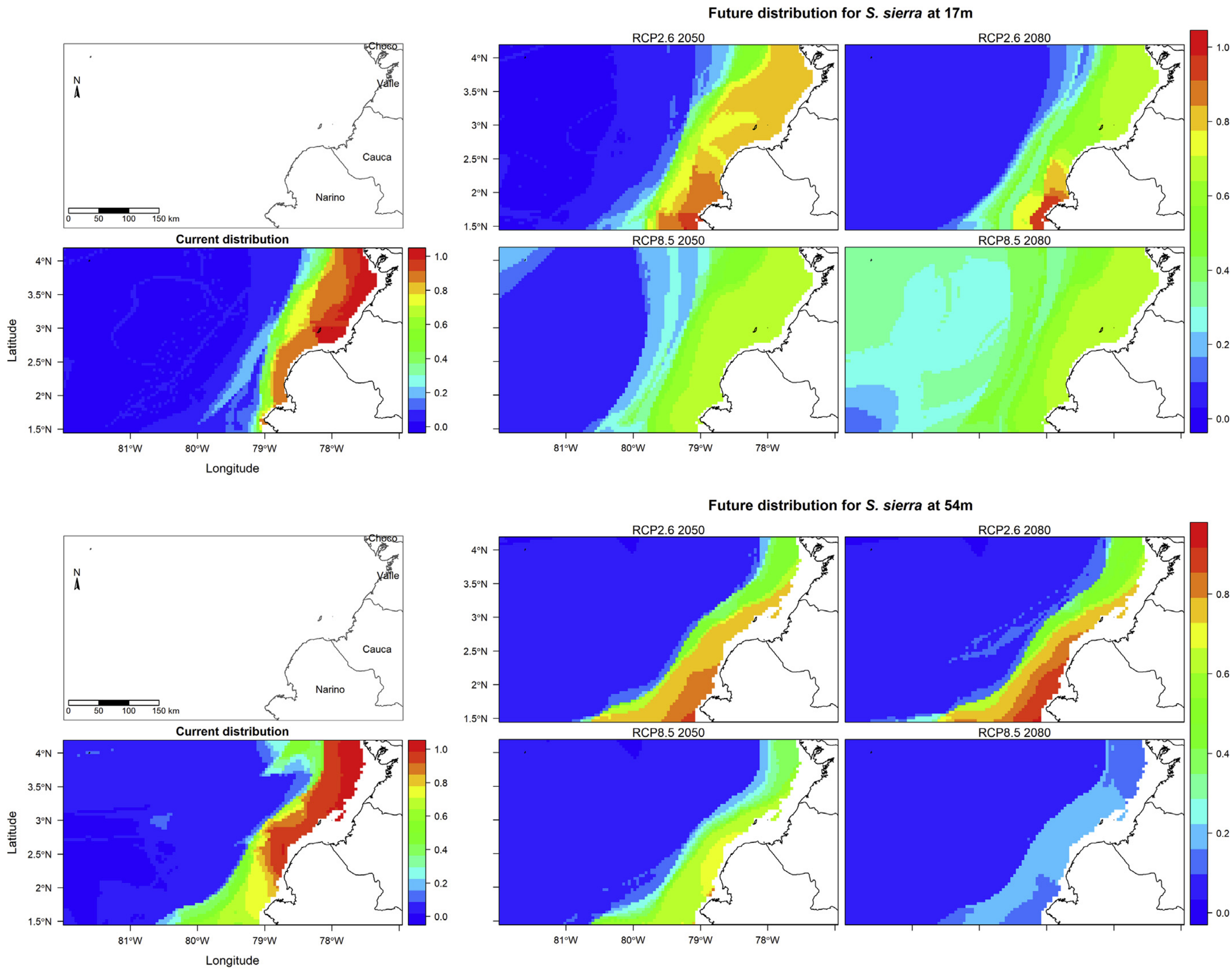

Figure 3. Current and future distributions of *S. sierra* under climate change scenarios; the top map composition shows the results at 17 m, and the bottom map composition shows the results at 54 m.

At the same depth (17 m) under the RCP 8.5 scenario at 2050, the maximum probability value is reduced to 68%. The presence of the species along the entire coastal zone up to 80° longitude remains at average levels of approximately 65%. Compared to the current scenario, the species exhibits an extension of the area of presence along the coast but a reduction in its probability of occurrence, indicating that it may be present in a greater area of the continental shelf, but its capture would potentially be reduced. In the long term (2080), a behaviour similar to the results obtained in the medium term is observed, presenting an extension of the area of presence of the species towards the open sea, although with low values of probability of occurrence (approximately 20%). The area with the highest probability of occurrence is conserved along the entire coast; however, the maximum values are reduced to 68%.

At a depth of 54 m, the average probability of occurrence for the entire study area under the RCP 2.6 scenario by 2050 shows a slight reduction of 2%, moving the area with the highest probability towards the southern coastal part of the study area. The maximum probability value is reduced, going from 98% to 86%, significantly affecting the productivity of the waters near the "Naya bank". In the long term (RCP 2.6 to 2080), the distribution of *S. sierra* would present a decrease of 1.3% in the average probability of occurrence. Under the RCP 8.5 scenarios in the medium and long term, the distribution of the species would be significantly affected, with reductions in the average probability of occurrence throughout the study area of 6% and 12% in 2050 and 2080, respectively. Of the results obtained under this scenario, those that occur in the long term (2080) are the lowest, with a maximum probability of occurrence of 17%, while for the medium term (2050), the maximum probability is reduced to 79%, concentrating on the southern zone in front of Tumaco Bay. These results are similar to those obtained by Herrera et al. (2019), and they are worrying considering the suggestion of Herrón et al. (2018) that this species, together with *Lutjanus guttatus* and *Brotula clarkae,* is already in a state of overexploitation.

3.1.3. Whitefin weakfish (Cynoscion albus)

Cynoscion albus is found in the eastern Pacific from Baja California to Peru (Robertson and Allen, 2015). In the Colombian Pacific, fishing is recorded in the northern zone (Zambrano et al., 2018b) and the southern zone of Colombia (Zambrano et al., 2018a). The results obtained for *C. albus*, modelled at depths of 0 m and 41 m, showed stable behaviour between the current and future distributions, with high probabilities of occurrence along the coast at the superficial level and in open waters at 41 m depth. Consequently, the species will continue to be available in the future for the small-scale fisheries of the region (Figure 4).

Distribution modelling at 0 m depth shows a high probability of occurrence in the bays and estuaries of the region, mainly in the area

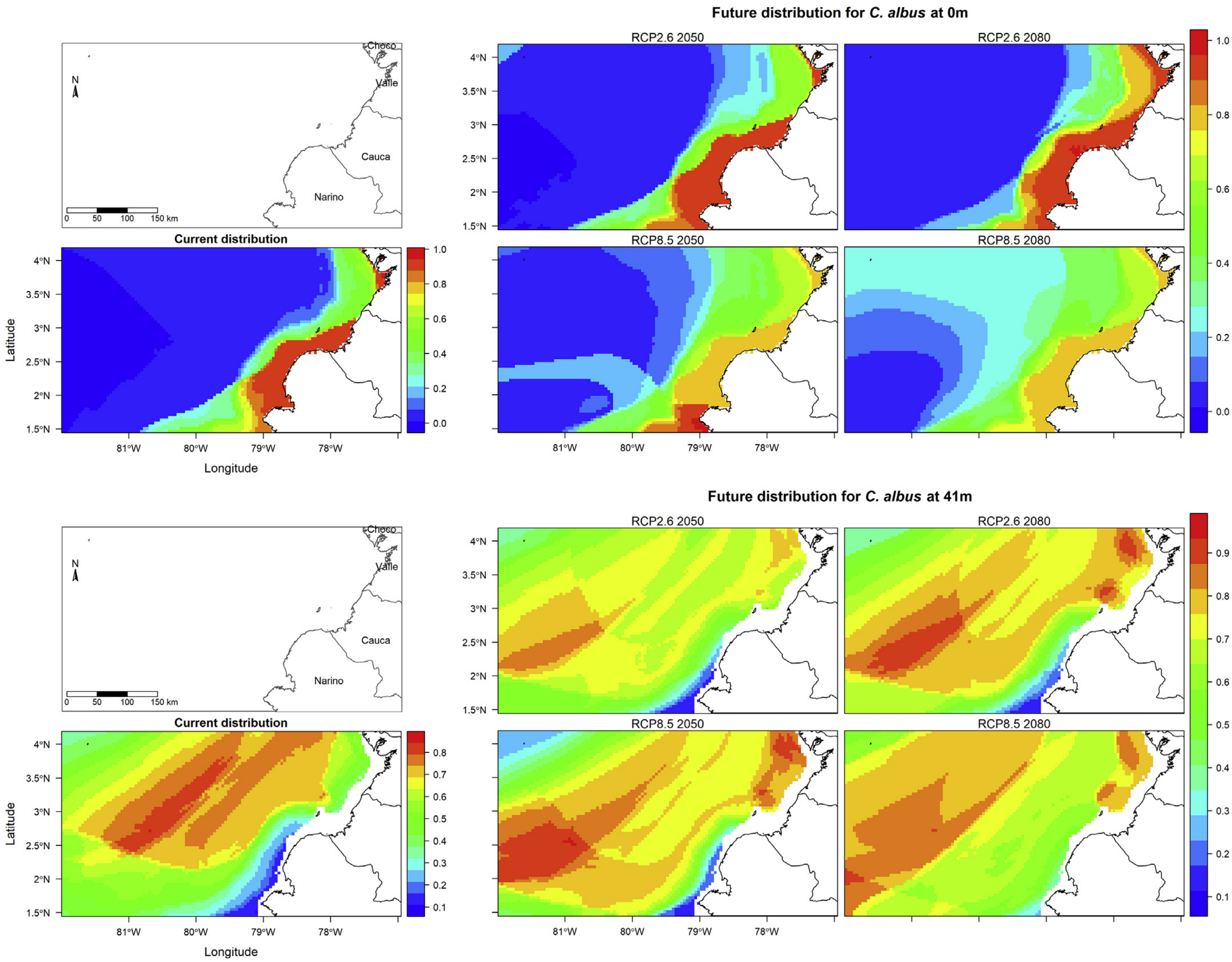

Figure 4. Current and future distributions of *C. albus* under climate change scenarios; the top map composition shows the results at 0 m, and the bottom map composition shows the results at 41 m.

of influence of the PNN Sanquianga, with values above 90%, and in the bay of Tumaco, with probabilities of approximately 87%, which is consistent with the literature, establishing that *C. albus* is a coastal species that lives in shallow waters, estuaries, coastal lagoons, and the mouths of rivers with low salinities (Chao, 1995; OSPESCA, 2010) and has been identified as a species dependent on the estuaries and mangroves of the Colombian Pacific to complete its life cycle (Díaz-Merlano et al., 2016). Artisanal fishermen in the region usually catch the species at depths between 6 and 15 m. At a depth of 41 m in the current period, the greatest probabilities are located in the open sea to the northwest of the study area, from 2.5° latitude in the direction of Malpelo Island.

Regarding the future modelling scenarios of the species, the geographical distribution of *C. albus* at 0 m depth shows an increase in the average probability of occurrence throughout the study area and for all the climate change scenarios evaluated, where the greatest increase would occur in the RCP 8.5 scenario at 2080 with 15.17%. Under RCP 2.6 in 2050, the coastal zone of Nariño retains the zone with the highest probability of occurrence, with values of approximately 94%. Regarding the RCP 2.6 scenario in 2080, an increase is observed along the entire north coast, in front of Valle del Cauca Province, with approximate values of 78%, and the coastal area, bays, and estuaries of the provinces of Cauca and Nariño conserve the highest values of probability of occurrence (95%). These results make it possible to infer that climate change scenarios favour potential species occurrence, allowing them to conserve their current habitat.

On the other hand, the results obtained from the modelling under the RCP 8.5 scenario at 2050 (at 0 m depth) show that despite presenting an increase in the average probability for the entire study area (9.4%), the entire area up to 2° latitude from the coastline presents a considerable reduction in the probability of occurrence, with values ranging from 64% in the north in front of Valle del Cauca to 79% in the south in front of the bay of Tumaco. The increases in probability are shown towards the open sea in the north of the study area, with values between 30 and 40%. For the long term, the distribution of *C. albus* would also increase for the open waters north of the study area. However, the probability of surface occurrence along the entire coastal zone would be affected, with reductions being observed, especially in Valle del Cauca Province.

The distribution of *C. albus* at a depth of 41 m shows a higher probability of open waters, both in the current scenario and in future climate change scenarios. In the RCP 2.6 scenario in 2050, the most visible increases are those located in the coastal waters of Nariño and front of Valle del Cauca, possibly benefiting the waters near the "Pasacaballos" and "Colombia" banks (60% and 45%, respectively). In the long term (2080), the areas with the highest probability are located in open waters between 80°W and 81.5°W longitude and 2°N and 3°N latitude, and the probability of occurrence in coastal regions of Valle del Cauca would benefit the fishing of this species in the waters near Gorgona Island and the "Naya

Bank", as well as the populations in the north of this province. However, the waters closest to the coast up to a bathymetry of 41 m depth present the least probability of occurrence, indicating that fishermen from the Tumaco region will have to venture out to sea to guarantee the capture of the species to this depth.

The results of the modelling carried out in the RCP 8.5 scenario in 2050 show that *C. albus* will also have an expansion in its geographical distribution in the study area at a depth of 41 m, with the highest probabilities concentrated in two specific areas: in open sea waters (between 81°W and 80°W longitude and between 2°N and 3°N latitude) and in coastal waters in front of Valle del Cauca. For the long term (2080), it is observed that the trend of expansion in the distribution of the species is conserved, presenting high values of probability of occurrence of the species towards the open sea and in waters near Malpelo Island.

3.2. Potential changes in the distribution of the pelagic species under climate change scenarios

Change detection indicates that superficial *E. lineatus* will contract in its distribution, mainly in the coastal zone of Nariño Province. In terms of areas of change, the category of positive change represents the highest proportion compared to the areas that will present negative changes, increasing as the climate change scenario becomes more critical (Figure 5). Expansions or positive changes will be reflected in open waters from -79.5° longitude, indicating that the species will present horizontal movement towards open waters under all the evaluated climate change scenarios in the future (RCP 2.6 and 8.5 in medium and long terms). These results would affect the capture of the species by artisanal fishers in the region, having to travel greater distances out to sea to fish it at the surface level.

In contrast, at 27 m depth, the species will have positive changes (expansions) in open waters in most climate change scenarios, with the critical medium-term scenario (RCP 8.5 in 2050) having the greatest increase or positive change except for RCP2.6 in the long term (2080), which will present some areas with contractions (Figure 5). These results reflect an expansion in the range of the species in the future to a depth of 27 m, making it accessible in a large part of the study area provided that adequate equipment and fishing gear are available to reach this depth; this would also depend on the dynamics of fishery management that are carried out in the present to guarantee its future availability.

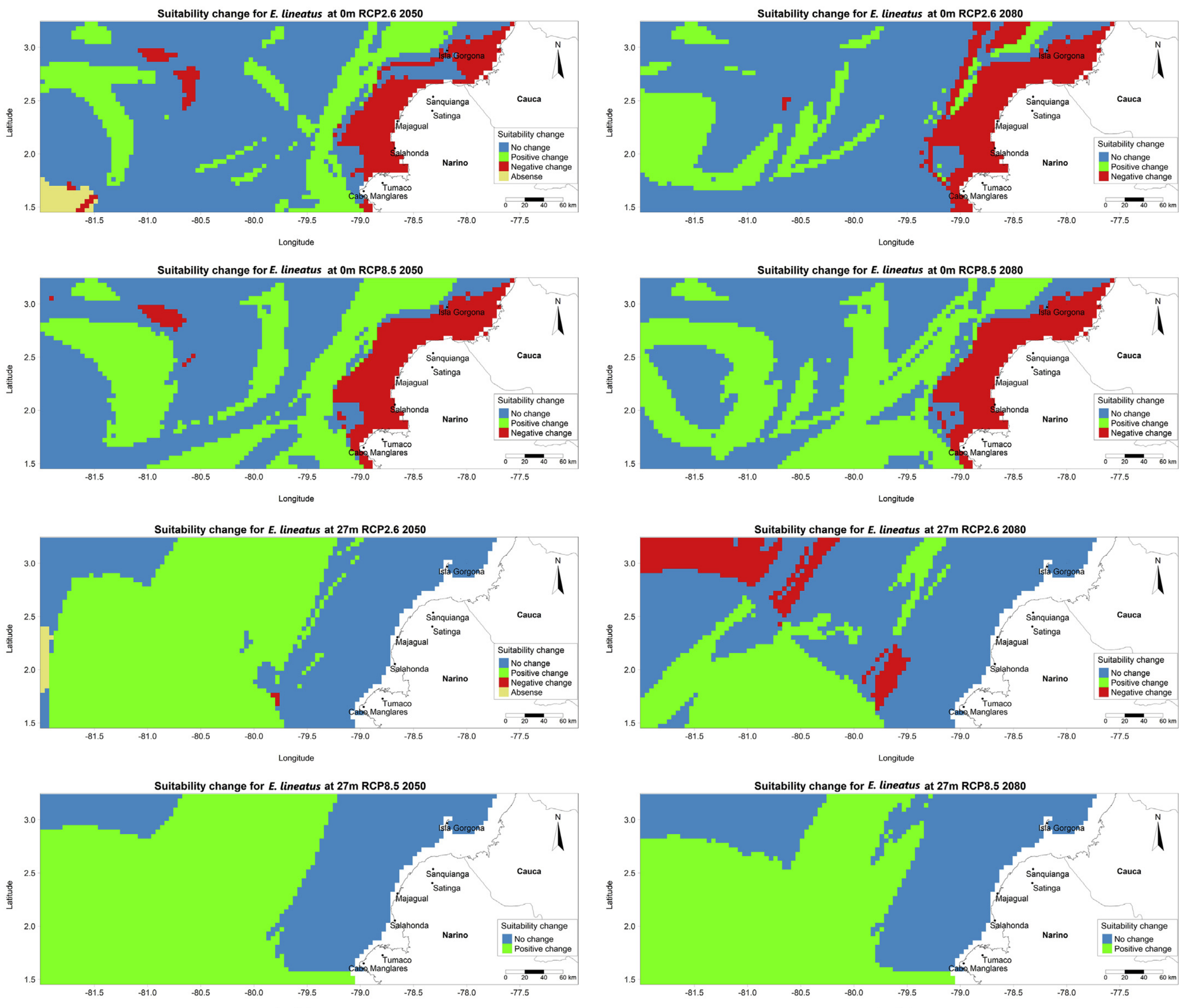

Figure 5. Changes in the probabilities of distribution of *E. lineatus* under climate change scenarios; the top map composition shows the results at 0 m and the bottom map composition at 27 m.

S. sierra will potentially migrate from coastal waters to open waters of the continental shelf at 17 m depth since contractions will appear in coastal waters (Cauca and northern Nariño). In contrast, expansions are shown in open waters. The greatest contractions will occur under the most critical scenario (RCP 8.5) in the medium and long term; likewise, the most significant areas of expansion will be presented in this scenario and in terms of time. However, considering the results described above, although the species may expand its range of distribution, it will present a lower probability of presence. The areas of absence at this depth would be greater in the mitigation scenario in the medium and long term. They would be located in open waters from -79.5°W longitude, while there would be no absence of the species in the long term.

At a depth of 54 m, changes in the distribution of *S. sierra* would be more critical since it would present greater areas of contraction along the entire coastal zone, especially in the nonmitigation scenario (RCP 8.5) in the medium and long term. These contractions added to the areas of absence and of no change translate into a possible scarcity of the species at this depth, with the exception of some small areas to the south of the study area that would present positive changes (expansions) under the mitigation scenario in the medium and long term (Figure 6).

It is important to highlight that the "no change" areas observed at a depth of 54 m correspond to areas in open waters or contiguous to the continental shelf where the probability of occurrence of the species is significantly low. The previous results obtained from the modelling of the current and future distribution show probability values of 10% or less. Therefore, it can be suggested that the distribution of the sierra at a depth of 54 m in the future will be potentially impacted, especially under the nonmitigation scenario (RCP 8.5).

On the other hand, modelling results for *C. albus* show that for the future climate change scenarios executed at 0 m and 41 m depths, the whitefin weakfish will present expansions in the distribution under all climate change scenarios along the continental shelf at 0 m depth and in open waters at 41 m depth (Figure 7), which can benefit its capture by small-scale fisheries.

At the surface level (0 m), there would be expansions in waters of the continental shelf and open waters in all the scenarios and periods of climate change evaluated; likewise, the coastal zone would not present

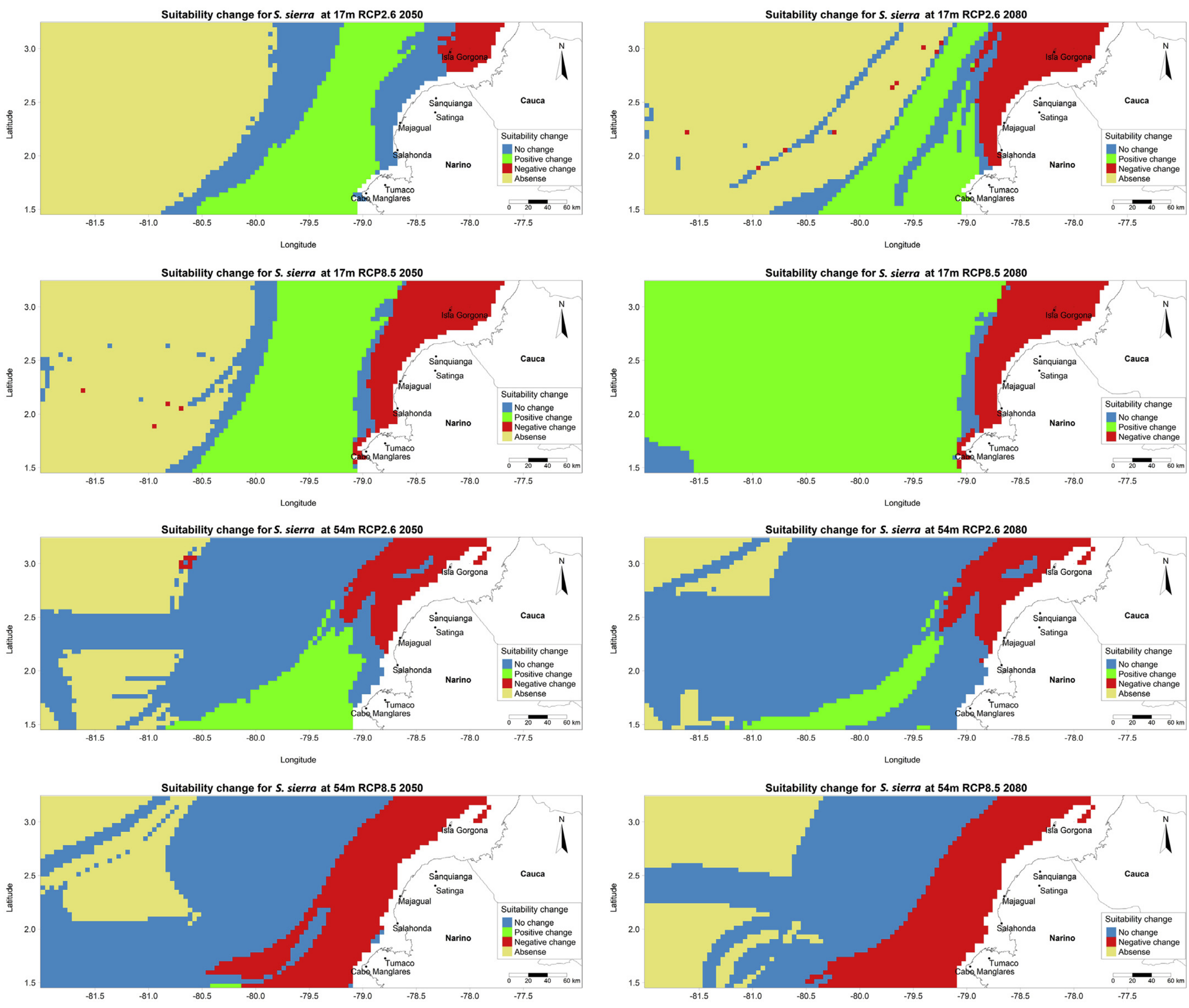

Figure 6. Changes in the probabilities of distribution of *S. sierra* under climate change scenarios; the top map composition shows the results at 17 m and the bottom map composition at 54 m.

changes in its distribution, conserving relatively high values of probability of occurrence of the future species. The area of absence would be reduced compared to its current distribution, presenting lower areas in the critical scenario (RCP 8.5) in the medium and long term, which suggests that the new ocean conditions favour the distribution and would expand its range in the future.

At 41 m depth, the changes in the distribution of the species will also be mainly positive, with expansions in open and coastal waters in much of the study area (Figure 7). Under the mitigation scenario, there would be a more extensive study area without changes in the distribution of *C. albus*. However, its proportion would be very similar to the areas with positive change. In contrast, in the long-term nonmitigation scenario, the ratio of area with positive change exceeds the percentage of area without change. At this depth, there would be no areas with an absence of the species.

3.3. Core distributional shifts of the pelagic species

Centroid changes at 0 m depth for *E. lineatus* show that the species will move further to open waters in the southwest direction under the business-as-usual scenario (RCP 8.5), whereas results obtained for the mitigation scenario (RCP 2.6) show that core distribution will return towards the northeast direction, close to the current distribution, in the long term (Figure 8, left -supplementary material-). At 27 m depth, the core distribution will present movements towards open waters under both RCPs in the medium term (2050). Subsequently, the centroid will orientate to the east in a long time. Nevertheless, the movement will be a short distance, locating the species in open waters (Figure 8, right -supplementary material-).

For *S. sierra*, the core distributional shift of the species at 17 m depth will be towards the southwest of the current distribution at the medium term. Later, in the long term, the species will move towards the west at a shorter distance (Figure 9, left -supplementary material-). The distributional shift of the centroid at 54 m depth will only be given in the medium term (2050) towards the south of the studied area for both scenarios (Figure 9, right). In the long term, no distributional shift centroids are generated under the BAU scenario (RCP 8.5) since no potential occupation area will be available. Similarly, the shift centroid for the mitigation scenario (RCP 2.6) in the long term (2080) is not available in Figure 9 (right -supplementary material-), as the core shift will not be significant.

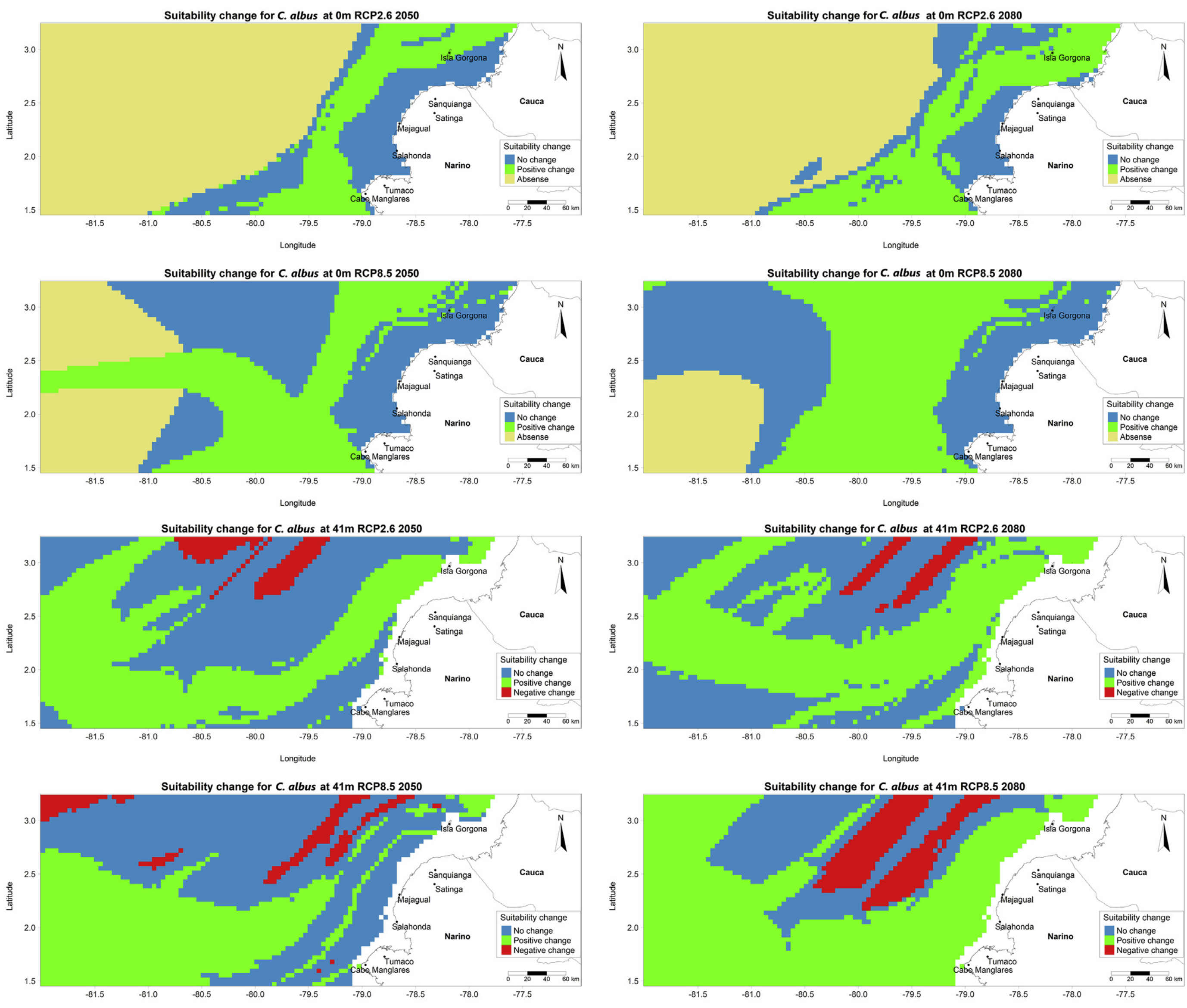

Figure 7. Changes in the probabilities of distribution of *C. albus* under climate change scenarios; the top map composition shows the results at 0 m, and the bottom map composition shows the results at 41 m.

Table 3. Probability of presence by species extracted from sample points near the sites and fishing grounds of recognized importance in the study area.

Species	Depth (m)	Probability (%) recorded at the fishing point close to:			
		"Naya" bank	"Pasacaballos" bank	"Tumaco" bank	"Colombia" bank
E. lineatus	0	68.4	61.8	95	11
	27	86.9	89.2	91.2	83.1
S. sierra	17	85.4	12	9.5	8.2
	54	93.4	85.9	71.4	46.7
C. albus	0	7.8	34.8	86.3	30
	41	71.6	41.9	28.3	34.5

C. albus at 0 m depth shows small northward movements of the core distribution of the species, close to the coastal waters of the region, for both scenarios in the medium and long term (Figure 10, left -supplementary material-). At 41 m depth, the core distribution of the species, currently located in open waters, will move towards the southeast, with significant distances shown in the medium term for both scenarios (Figure 10, right -supplementary material-); however, the core distribution will continue to be in the open waters of the study area.

The consolidated analysis of changes in the distribution of the three pelagic species allowed us to identify positive negative changes in the future under the climate change scenarios evaluated. In general, it is observed that for *E. lineatus*, *S. sierra*, and *C. albus*, the probability of presence increases at a greater depth. However, in the case of *C. albus*, it only occurs in waters near the "Naya" and "Colombia" banks, while in the waters near the "Tumaco" and "Pasacaballos" banks, the probability decreases with increasing depth. Tables 3 and 4 show a synthesis of the changes that the species will present in the future, summarizing the area with the highest proportion identified in the change detection process and displayed on a colour scale for better interpretation.

Regarding the oceanographic variables in the ensemble of models used for *E. lineatus* modelling, salinity was the important variable for the modelling carried out at 0 m depth. At a depth of 27 m, the importance of the variables was more heterogeneous among the models used, where primary productivity, salinity, and temperature were significant. However, with close ranges among all models except MaxEnt, the only significant variable was salinity. These factors presented a greater benefit in the geographical distribution of the species if it is considered that the main ocean currents transport heat, salts, oxygen, carbon dioxide, and nutrients. The movement of these water masses involves upwelling areas. Therefore, there is a positive effect on net primary productivity, creating attractive habitats for tuna species (Nicol et al., 2020). Lehodey et al. (2011) determined that the projected primary productivity in the eastern equatorial region will remain relatively high, bringing food sources for the larvae, and therefore, the spawning areas would change towards this region. Consequently, changes in primary productivity could directly affect the abundance and distribution of larvae and juveniles of tuna species.

For *S. sierra*, the variable that most contributed to all the ensemble models at 17 m depth was salinity. At 54 m depth, primary productivity was considered the essential variable, closely followed by temperature and salinity. The species could possibly be migrating horizontally towards open surface waters motivated by changes in salinity, which in the future would be more minor in the open sea; likewise, it would also be migrating vertically in the water column.

The changes in the distribution of *C. albus* at the surface level (0 m) would be motivated mainly by primary productivity and, to a lesser extent, by U currents. In comparison, at 41 m, the variables that provide more significant importance to the modelling and those mentioned above include temperature. General studies have also shown the importance of other variables, such as primary productivity in the distribution and its changes in pelagic species, as Krumhardt et al. (2016) determined that primary productivity increased in equatorial Pacific waters, which would mean more food for this species.

4. Conclusions and recommendations

Among the pelagic species analysed, we observed that *C. albus* is the only species that would not present an adverse change in its distribution in the future. In contrast, the species may expand in its geographical distribution, which may favour its availability for the region's fishermen—possibly making it a promising species in the future. This would depend on fishery management and the sustainable management strategies undertaken to conserve the sector and the natural ecosystems on which it depends. *E. lineatus* presented negative changes at some of the evaluated depths. Nevertheless, it will also have positive changes at other depths, which will allow its capture to continue if the fishermen adapt

Table 4. *The colour scale shows the magnitude of positive (green) and negative (red changes). For the soft green and soft red colours, it is understood that the change is slight or partial for the study area.

Species	Depth (m)	Climate change scenarios evaluated			
		RCP 2.6		RCP 8.5	
		2050	2080	2050	2080
E. lineatus	0	Contraction in coastal zone			
	27	No change in the coastal area			
S. sierra	17	Expansion in the southern coastal area	Expansion to the south and contraction to the north of the coastal zone		
	54	Expansion to the south and contraction to the north of the coastal zone	Contraction to the north of the coastal zone	Contraction in the coastal zone	
C. albus	0	Expansion to the south of the coastal zone	Expansion to the south and north of the coastal zone	Expansion to the south of the coastal zone	
	41	Expansion to the north of the coastal zone	Expansion in the coastal zone	No change in coastal area	Expansion in the coastal zone

Consolidated changes in the future distribution under the evaluated climate change scenarios* their boats or fishing gear to reach the distances or depths of the new distribution in the future. At the same time, *S. sierra* will be the pelagic species most affected in the future with the climate change scenarios evaluated, showing areas with distribution contraction at the two depths evaluated.

Species distribution models (SDMs) have proven practical and essential in evaluating the impacts of climate change on the distribution of marine species, especially in remote and challenging access regions where in situ data are rarely available. Furthermore, distribution change detection of the species allowed us to confirm the findings obtained in the previous phase of modelling the distribution related to the movement or migration of some of the species. Likewise, it allowed the identification of the areas that would be affected or would benefit by negative or positive changes in this distribution.

The core distributional shift analysis allowed us to infer that small-scale pelagic fisheries could be affected under future scenarios. However, they can be harvested continuously if the capacities of small-scale fisheries are improved along with the current fishery management strategies being maintained or enhanced, considering fishery stocks and the level of exploitation. However, it is essential to emphasize that these results are based on annual data analysis. Therefore, monthly and seasonal analysis of the distribution is recommended to capture detailed core distributional shifts.

These results constitute a critical scientific basis for evaluating the climate change vulnerability of the fishing sector and the decision-making process in the future of small-scale fishery management in the southern Colombian Pacific Ocean.

Declarations

Author contribution statement

John Josephraj Selvaraj: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Leidy Viviana Rosero-Henao: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

María Alejandra Cifuentes-Ossa: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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