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Review

An overview of social-ecological impacts of the El Niño-Southern Oscillation and climate change on Galapagos small-scale fisheries

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ABSTRACT

Small-scale fisheries in the Galapagos Marine Reserve face significant challenges due to climatic anomalies and human-induced changes such as weak governance and overfishing. This overview explores the social-ecological impacts of the El Niño-Southern Oscillation (ENSO) and climate change on Galapagos small-scale fisheries, including the progress and challenges of ENSO and climate change research in this multiple-use marine protected area. The extreme El Niño events of 1982/83, 1997/98, and 2015/16 caused significant ecological shifts and fluctuations in fisheries productivity. While some species have shown increases in biomass, likely linked to sea surface temperature changes and altered ecosystem dynamics, the impacts on others remain uncertain or underexplored. Sailfin grouper (*Mycteroperca olfax*) and spiny lobster (*Panulirus penicillatus* and *P. gracilis*) fisheries have exhibited mixed responses to the El Niño, illustrating the complex nature of ENSO's ecological effects, which are further exacerbated by overfishing. The socio-economic impacts on fishing communities include reduced landings, longer search times, higher fishing costs, and increased livelihood insecurity. Future projections suggest an increasing vulnerability to ENSO and climate change, emphasizing the need for an ecosystem approach to fisheries. Key strategies include enhancing adaptive capacity, promoting sustainable practices, and adopting a social-ecological and transdisciplinary research approach. However, progress in ENSO and climate change research is hampered by weak governance, characterized by institutional barriers that hinder the formulation and enforcement of solid fisheries governance policies. To strengthen the resilience of Galapagos small-scale fisheries, interinstitutional and intersectoral collaboration is essential, supported by international cooperation and strategic investments to bolster local research capabilities.

1. Introduction

Small-scale fisheries face increasing threats from climatic and anthropogenic drivers (Belhabib et al., 2018; Castrejón and Charles, 2020; Villasante et al., 2021, 2022), with the El Niño-Southern Oscillation (ENSO) and climate change being significant disruptors (Bertrand et al., 2020; Jaureguiberry et al., 2022). These climatic stressors exacerbate the negative impacts caused by human activities such as overfishing, pollution, and market globalization on the food security and livelihoods of fishing communities (Gianelli et al., 2021; Ortega et al., 2012; Villasante et al., 2021). They affect the oceanographic and climatic conditions that determine the distribution and abundance of marine fish and invertebrates, influencing their availability and accessibility (Jaureguiberry et al., 2022; Scheffers et al., 2016). Additionally, ENSO and climate change increase the risk of natural disasters, by increasing the frequency and intensity of extreme weather events like hurricanes, floods, droughts, and heatwaves (Belhabib et al., 2018; Bertrand et al., 2020; van Aalst, 2006).

The Eastern Tropical Pacific (ETP) is heavily influenced by ENSO, a climate pattern marked by periodic fluctuations in sea surface temperatures (SST) and atmospheric pressure in the equatorial Pacific (Bertrand et al., 2020; Wang and Fiedler, 2006). ENSO has two phases: El Niño, the warm phase, and La Niña, the cool phase (Bertrand et al., 2020). During the El Niño, weakened trade winds elevate SST, suppress nutrient-rich upwelling, and reduce primary productivity, disrupting marine ecosystems. La Niña events enhance upwelling, increasing

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nutrient availability and boosting marine productivity, though cooler temperatures can stress some species. The impact of ENSO is likely exacerbated by climate change, characterized by long-term shifts in global temperatures and weather patterns (Collins et al., 2010; Wang et al., 2017). Since 1960, ENSO variability has increased, with more frequent and intense El Niño and La Niña events, likely driven by anthropogenic greenhouse gas emissions, which have intensified the vertical stratification of the equatorial Pacific Ocean (Cai et al., 2018; Liu et al., 2013; Paltán et al., 2021). This increased variability is projected to result in more extreme weather patterns and greater impacts on marine ecosystems, such as severe coral bleaching, shifts in species distributions, and the migration of commercially important fish species to cooler waters during stronger El Niño events, while intensified La Niña events may exacerbate upwelling of hypoxic waters, further stressing marine life (Bertrand et al., 2020; Glynn et al., 2017; Manzello et al., 2017). Bertrand et al. (2020) categorized ENSO events into five types, from extreme El Niño events with intense warming to strong La Niña events with significant cooling. The most severe El Niño events have occurred more frequently since the 1970s, likely due to shifts in the onset region from the eastern to the western Pacific (Wang et al., 2019). Extreme or Super El Niño events, such as those in 1982/83, 1997/98, and 2015/16, have been particularly impactful due to their pronounced warming effects (Chen et al., 2017, 2022; Hameed et al., 2018).

Fishing communities in Latin America are particularly susceptible to these challenges, due to environmental, socio-economic, and institutional factors. Many communities distributed in coastal areas are highly exposed to extreme weather events and the long-term, large-scale effects of climate variability, including SST anomalies, increased wind intensity, and sea-level rise (Defeo et al., 2013; Franco et al., 2020; Gianelli et al., 2021). Most of these communities rely on fishing for income and food security and are characterized by high poverty levels and limited access to alternative livelihoods, making them particularly vulnerable (Defeo et al., 2013). Restricted access to financial resources, technology, and infrastructure further hinders their ability to adapt. Additionally, weak governance and inadequate fisheries management, reflected in a lack of effective policies to support sustainable fishing practices and community resilience, exacerbate the impacts of climate variability and change (Defeo and Castilla, 2012). These interconnected factors make Latin American fishing communities particularly vulnerable to the compounded effects of climatic and anthropogenic drivers of change (Castrejón and Defeo, 2015; Defeo et al., 2013; Ortega et al., 2012), affecting the distribution and production of fish stocks, the viability of fishing operations, and the economic contribution of fisheries to poverty reduction (Allison et al., 2009). The precise impacts and direction of climate-driven change on fisheries are uncertain. Still, research suggests that these changes could lead to increased economic hardship or missed opportunities for development in countries that depend upon this sector, especially those with limited capacity to adapt (Allison et al., 2009). Therefore, understanding and anticipating these complex interactions between ENSO and marine ecosystems is crucial for developing effective adaptation strategies in the face of climate change.

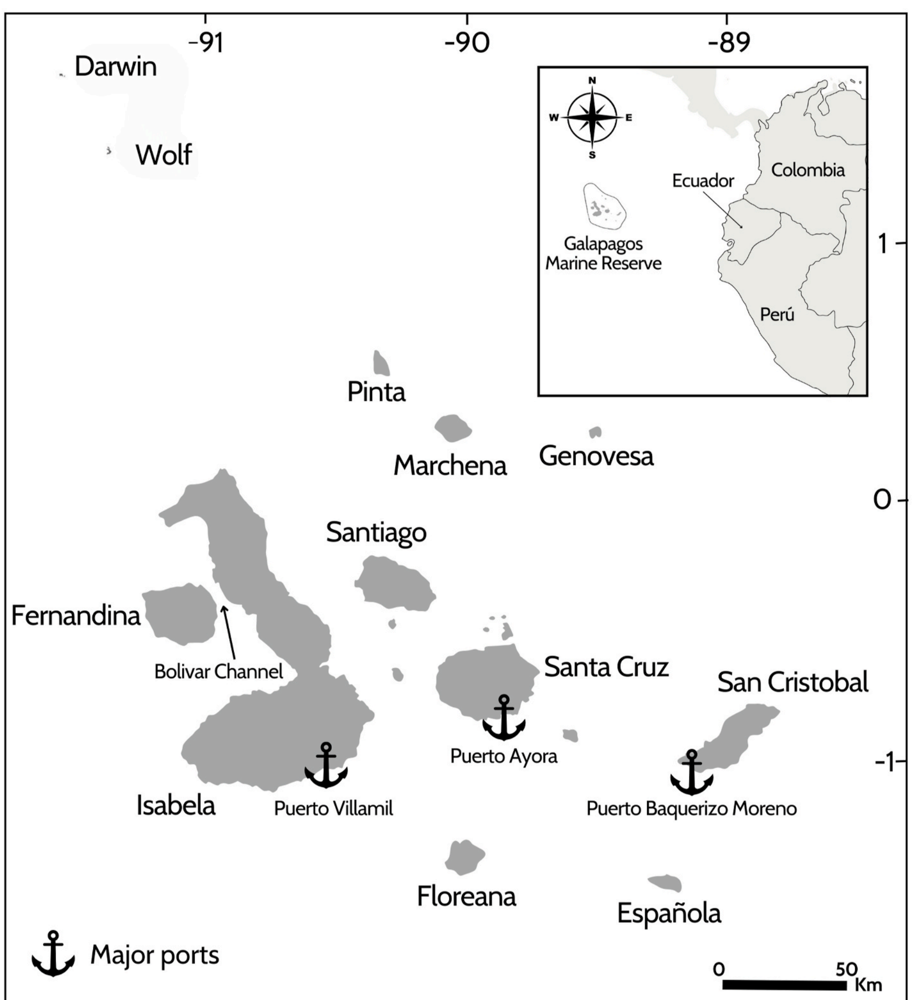

Fig. 1. The Galapagos marine Reserve, Ecuador. Adapted from Castrejón and Charles (2013).

The Galapagos Islands are uniquely positioned to assess the impacts of climate variability and change on marine ecosystems and small-scale fisheries (Defeo et al., 2013; Dueñas et al., 2021; Paltán et al., 2021). Located in the ETP, approximately 1240 km from mainland Ecuador (DPNG, 2014, Fig. 1), this UNESCO Natural Heritage Site lies at the convergence of three major oceanic current systems that fluctuate seasonally between warm and cool waters. The region is heavily influenced by the ENSO (Bertrand et al., 2020; Wang and Fiedler, 2006). Future projections suggest that the Galapagos could be significantly affected by extreme and moderate El Niño events (Bertrand et al., 2020). These climatic shifts pose significant risks to marine ecosystems, coral reefs, and the prevalence of invasive species, with profound implications for small-scale fisheries (Glynn et al., 2017, 2018; Manzello et al., 2017; Paltán et al., 2021). In addition to ENSO, the archipelago is also experiencing the broader impacts of climate change. Since the early 1980s, a warming trend of approximately 0.6 °C has been observed, accompanied by a noticeable drying trend and delayed onset of the wet season (Paltán et al., 2021). Future projections indicate potential increases in precipitation and more frequent hot and wet conditions (Paltán et al., 2021).

The geographic isolation and unique location of the Galapagos have not only fostered the archipelago's unique biodiversity, but also present significant challenges for governance, long-term research, and sustainable resource management (Castrejón et al. 2024a, 2024b; Escobar-Camacho et al., 2021). The Galapagos Islands have a complex history of human interaction with marine resources. By the mid-1990s, Galapagos fisheries shifted gradually from an industrial, export-driven activity, focused primarily on tuna, sharks, and spiny lobsters, toward a local, small-scale economic activity (Castrejón et al., 2014; Castrejón and Defeo, 2024). The lucrative nature of these fisheries led to intense exploitation, resulting in significant ecological and social challenges, including overfishing, illegal fishing, and conflicts between conservation and resource use (Castrejón and Defeo, 2024; Defeo et al., 2016; Ramírez-González et al., 2020a; Usseglio et al., 2016). In response to these growing pressures, the Galapagos Marine Reserve (GMR) was established in 1998, covering approximately 146,599 km^2 of terrestrial and marine area (DPNG, 2016) (Fig. 1). Its aim is protecting the archipelago's marine ecosystems while allowing for sustainable use of its resources. The GMR is a multiple-use marine protected area, where different zones are designated exclusively for conservation, tourism, research, and small-scale artisanal fishing.

Small-scale fisheries are a strategic sector for the economy and food security of nearly 30,000 residents and over 329,000 visitors annually in the Galapagos (Castrejón et al., 2024b; DPNG, 2024; Ramírez-González et al., 2022; Rodríguez-Jácome et al., 2023). Approximately, 65 species of shellfish and finfish are commercially harvested by ca. 400 full-time and part-time small-scale fishers, who are distributed in three islands (San Cristóbal, Santa Cruz, and Isabela) (Castrejón, 2011; Castrejón and Charles, 2020; Schiller et al., 2014). The most important fishery resources, in terms of volume and economic value, are spiny lobsters (*Panulirus penicillatus* and *P. gracilis*), brown sea cucumbers (*Isostichopus fuscus*), and yellowfin tuna (*Thunnus albacares*) (Ramírez-González et al., 2022). The small-scale whitefish fishery in the Galapagos, known locally as "pesca blanca," primarily targets demersal fish species. The most significant among these are sailfin grouper (*Mycteroperca olfax*), whitespotted sandbass (*Paralabrax albomaculatus*), mottled scorpionfish (*Pontinus clemensi*), and misty grouper (*Hyporthodon mystacinus*) (Marin and Salinas-de-León, 2018). Understanding small-scale fisheries in the GMR as a social-ecological system is crucial for effective management (Castrejón et al., 2014). This approach recognizes the strong interdependence between human communities and marine ecosystems, where the well-being of one directly impacts the other (De Young et al., 2008; Ostrom, 2007). By adopting a social-ecological systems approach, policymakers can better address the challenges posed by environmental changes, ensuring the sustainability of the marine ecosystems and the communities that rely on them (González et al., 2008).

Although the Galapagos is a sanctuary for several marine species, weak governance, overfishing, illegal fishing, and bycatch of endangered, threatened, and protected species represent additional threats to small-scale fisheries (Alava et al., 2023; Alava and Paladines, 2017; Castrejón, 2020a,b; Castrejón and Defeo, 2015; Escobar-Camacho et al., 2021). Some target species, such as sailfin grouper and brown sea cucumbers have been overfished. As climate change is likely to exacerbate the effects of ENSO and human-induced threats by affecting the availability and accessibility of these species to fishing (Eddy et al., 2019; Monnier et al., 2020; Wolff et al., 2012), it is crucial to understand how these climate stressors will impact fishery resources and people who depend on them to sustain their livelihoods. This knowledge can inform resilience-building policies to enhance the adaptive capacity of fishery resources, communities, and institutions to climate change (Cinner et al., 2018; Grothmann and Patt, 2005).

A systematic review by Dueñas et al. (2021) on the effects of ENSO and increased climate variability on the biodiversity of the Galapagos Islands, highlighted the significant threat that more frequent extreme climatic events pose to endemic marine biodiversity, while also noting the varied impacts on terrestrial species. The present overview expands upon the work of Dueñas et al. (2021) by adopting a broader social-ecological perspective, examining the impacts of extreme El Niño events and climate change on small-scale fisheries within the GMR. It explores how ENSO and climate change, combined with overfishing and weak governance, challenge the resilience of Galapagos fisheries. This study also evaluates the challenges in advancing ENSO and climate change research, emphasizing the integration of an ecosystem-based approach to fisheries management that integrates ecological and socioeconomic considerations to effectively mitigate and adapt to climate change in the Galapagos. To provide a comprehensive overview, a broad literature review was conducted, searching the terms "Galapagos", "fisheries", "ENSO", "El Niño", "La Niña", "climate change" or "global warming" through Web of Science, Scopus, and grey literature from NGOs, governmental organizations, and other relevant institutions. The overview focused on identifying studies discussing the impacts of ENSO and climate change on marine ecosystems, fisheries, and local communities, as well as those exploring adaptive capacity to climate variability and change.

2. ENSO and climate change impacts on the Galapagos marine ecosystem and fishery resources

Major variations in weather and climate in the ETP, including the Galapagos Islands, are primarily driven by the Pacific Decadal Oscillation (PDO) and ENSO (Wang et al., 2017; Wang and Fiedler, 2006). The PDO is a long-term ocean-atmosphere phenomenon characterized by alternating warm and cool phases in the North Pacific Ocean, typically lasting 20–30 years, which influence regional climate and marine heatwaves (Ren et al., 2023). In contrast, ENSO is a shorter-term climate pattern with more frequent oscillations in SST and precipitations, occurring every 2–7 years (Bertrand et al., 2020; Wang and Fiedler, 2006). Climate change introduces additional long-term shifts. Projections for the end of the century, based on the Intergovernmental Panel on Climate Change (IPCC) high-emission scenario, known as Representative Concentration Pathway (RCP) 8.5, indicate an average SST increase of 3.5 °C in the Exclusive Economic Zone (EEZ) off the Ecuadorian coast and 3.9 °C in and around the Galapagos EEZ, and less pronounced changes in ocean acidity (Monnier et al., 2020).

A substantial amount of research has highlighted the profound impacts of ENSO, especially during the extreme El Niño events of 1982/83 and 1997/98 (Table 1). They have been marked by significant environmental changes and disruptions to marine life and fisheries (Table 1). Extreme El Niño events are characterized by Oceanic Niño Index (ONI) values that significantly exceed the typical El Niño threshold ($>$0.5) (Fig. 2). Although the 1986/87 El Niño registered the second-highest

Table 1
Observed social-ecological impacts of the ENSO, with emphasis on the extreme El Niño events in 1982/83, 1997/98, and 2015/16. Perceptions about El Niño and climate change, and the effects of other climatic variables on Galapagos marine ecosystems, fishery resources, and fishers' behavior, are also included. CPUE: Catch per Unit Effort; RCP: Representative Concentration Pathway; SST: Sea Surface Temperature.

Climatic event/variable	Impact	Source
El Niño 1982/83	Mean SST increased above 28.5 °C, drastically declining primary productivity.	Wang and Fiedler (2006)
	Decline in Galapagos penguins, marine iguanas, flightless cormorants, fur seals, and sea lions.	Edgar et al. (2010)
	Massive coral mortality (95–99%) across the archipelago, devastating all but one of the 17 known reefs.	Glynn (1994)
	Significant perturbation of macroalgal productivity caused severe impacts on endemic grazers like marine iguanas.	Edgar et al. (2010); Robinson and del Pino (1985); Tompkins and Wolff (2017).
	Substantial declines in landings of sailfin grouper, white-spotted sand bass, and Galapagos sheepshead wrasse	Robinson and del Pino (1985)
El Niño 1997/98	CPUE and landings of Galapagos sailfin grouper increased, while black mullet declined. More sexually immature individuals were caught, coinciding with adult groupers migrating to deeper waters.	Nicolaides and Murillo (2001)
	Spiny lobsters and brown sea cucumbers reached their highest production levels two and five years after the El Niño 1997/98 event, respectively.	Defeo et al. (2013)
El Niño 2015/2016	Increased landing rates and catchability of larger predatory fish, including the grape-eye seabass and Pacific dog snapper, due to diminished prey biomass.	Marin and Salinas de León (2020)
ENSO events (1994–2014)	No significant correlation between sailfin grouper abundance, SST, and Oceanic Niño Index.	Ramírez-González et al. (2020b)
	Negative correlation between yellowfin tuna biomass and SST. Higher temperatures were associated with lower tuna biomass under RCP 4.5 climate change scenario.	Ramírez-González et al. (2020b)
ENSO events (1997–2011)	No significant correlation was found between the spawning biomass and recruitment of red spiny lobster stocks and ENSO events.	Szuwalski et al. (2016)
	Increased fishing effort during the El Niño events	Castrejón and Charles (2020)
El Niño perceptions	Fishers noted warm SST, coral bleaching, increased fishing difficulty, and greater distances during the El Niño events.	Cavole et al. (2020)
Climate change perceptions	Fishers perceived changes in SST, solar radiation, and other climatic and oceanographic conditions. These changes have caused shortages in fishing and more diving accidents.	Rodríguez-Jácome et al. (2019)
Climatic and oceanographic conditions	An inverse relationship between SST and CPUE of spiny lobsters.	Murillo-Posada et al. (2019)
	Fishers in the Galapagos red spiny lobster fishery base their decisions on expected revenue, travel distance, wave intensity, and air temperature. Precipitation and moon visibility had little impact on their choice of fishing locations.	Bucaram et al. (2013)

ONI value since 1950, it has not been classified as an Extreme El Niño event (Chen et al., 2022) because its ecological impact, including the Galapagos Islands, was relatively mild compared to the 1982/83 and 1997/98 El Niño events (Bertrand et al., 2020; Snell and Rea, 1999). This is primarily due to the less pronounced atmospheric disturbances during the 1986/87 El Niño, which led to more moderate climatic effects in the Galapagos. Consequently, the biological responses observed in 1987, such as mortality and reproductive failure in key species like marine iguanas (*Amblyrhynchus cristatus*), Galápagos penguins (*Spheniscus mendiculus*), and sea lions (*Zalophus wollebaeki*), were not as severe (Dueñas et al., 2021; Snell and Rea, 1999).

The 2015/16 El Niño, although classified as an Extreme El Niño event (Chen et al., 2017, 2022), had also a milder impact compared to the 1982/83 and 1997/98 El Niño events. While the 2015/16 El Niño caused significant disruptions, particularly in terms of warmer sea surface temperatures and altered marine currents (Chen et al., 2017), the extent of ecological damage was less pronounced than that of previous extreme El Niño events (Bertrand et al., 2020). This contrasts with the devastating impacts of the 1982/83 and 1997/98 El Niño events in the Galapagos, which were characterized by severe weather patterns, extreme rainfall anomalies, and significant species mortality and declines in marine biodiversity (Table 1).

Looking forward, model-based projections highlight that ongoing climate change, particularly under the RCP 8.5 scenario, could lead to significant ecological shifts within the GMR (Table 2). Climate change is expected to interact with ENSO events, potentially amplifying their impacts on marine ecosystems. As the frequency and intensity of El Niño events may increase under future climate scenarios (Table 2), the combination of climate change and ENSO-related stressors could exacerbate ecosystem degradation, further challenging the resilience of species and fishers' livelihoods.

ENSO and climate change research in the Galapagos fisheries has focused on understanding the impacts of climatic stressors on marine ecosystems and fishery resources (Tables 1 and 2). Key areas of study include the synergistic effects of El Niño and fishing on marine ecosystems; the compound impact of El Niño, climate change, and fishing on commercial species; and the roles that climatic and anthropogenic drivers of change play in influencing small-scale fisheries dynamics and fishers' behavior. Research has focused on economically important species like spiny lobsters, brown sea cucumbers, and sailfin groupers. However, knowledge about the socioeconomic consequences of El Niño and climate change on the Galapagos remains limited. This resource-focused approach has resulted in a fragmented understanding of ENSO and climate change impacts, missing critical interactions between natural and social subsystems. Consequently, policymakers' ability to make informed decisions for climate change adaptation and mitigation within the small-scale fishing sector is restricted, highlighting the necessity to transition toward a social-ecological system approach in fishery science (Castrejón et al., 2014).

2.1. Ecosystem impacts

The 1982/83 El Niño event stands out as one of the most extreme natural disturbances recorded in the Galapagos Islands during the last century, significantly elevating mean SST above 28.5 °C and precipitating a marked decline in primary productivity (Wang and Fiedler, 2006). This decline was driven by disrupted upwelling, which reduced the supply of nutrient-rich waters essential for phytoplankton growth. This environmental shift had far-reaching impacts on the archipelago's marine ecosystems, notably affecting the survival, reproduction, and distribution of higher trophic-level organisms, such as Galapagos penguins, marine iguanas, flightless cormorants (*Phalacrocorax harrisi*), fur seals (*Arctocephalus galapagoensis*) and sea-lions (Edgar et al., 2010).

During and following the 1982/83 El Niño event, reef-building corals within the Galapagos suffered persistent population declines (Glynn, 1994; Glynn et al., 2017, 2018). According to Glynn (1994), coral mortality rates escalated to 95–99% across the islands, primarily due to severe bleaching exacerbated by sea urchin bioerosion and significantly low recruitment rates. This led to the near-complete degradation of the archipelago's structural coral reefs. Of the 17 known structural coral

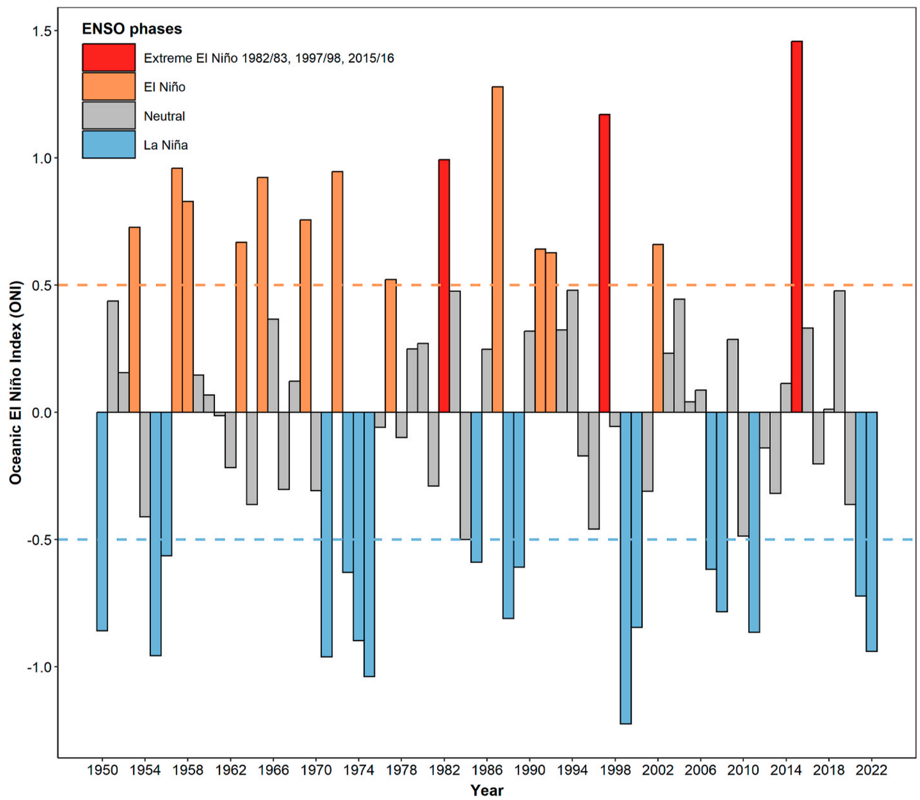

Fig. 2. Annual average of the Oceanic Niño Index (ONI) and the El Niño-Southern Oscillation (ENSO) phases from 1950 to 2022. The horizontal dashed lines at 0.5 and −0.5 represent the thresholds for El Niño and La Niña conditions, respectively. "Neutral" conditions occur when ONI values range between −0.5 and 0.5. The years 1982/83, 1997/98, and 2015/16 represent the most extreme El Niño events studied in Galapagos. Source: NOAA (2024).

reefs reported before 1982/83 El Niño, only one has persisted in Darwin Island to the present day (Glynn et al., 2018). Coral ecosystems were reduced to fragmented coral communities or disappeared entirely, resulting in a critical loss of habitat and biodiversity (Glynn et al., 2017, 2018). The long-term socioeconomic consequences of losing the ecosystem services provided by coral reefs—such as fishery resources and tourism—have not been fully investigated. Further research is needed to assess the resilience of local communities to these environmental changes and to explore the potential for a social-ecological collapse (*sensu* Cumming and Peterson 2017) associated with the disappearance of Galapagos coral ecosystems.

The 1982/83 El Niño event also triggered extensive changes in macroalgal productivity and community composition (Edgar et al., 2010; Robinson and del Pino, 1985; Tompkins and Wolff, 2017). These alterations included not only shifts in macroalgal communities, but also the local extinction of specific macroalgal species. The impact extended to marine iguanas, an endemic macroalgal grazer, highlighting the broad ecological ramifications of El Niño (Edgar et al., 2010; Tompkins and Wolff, 2017). Edgar et al. (2010) suggest that these ecological impacts may have been exacerbated by anthropogenic pressures such as overfishing, which potentially intensified the environmental effects of the 1982/83 El Niño event by reducing populations of large predatory fish (sharks, serranid groupers, carangid jacks, scombrid tunas and mackerel, and lutjanid snappers), and lobsters (*P. penicillatus, P. gracilis* and *S. astori*). This reduction in predatory control likely facilitated the expansion of sea urchin (*Eucidaris galapagensis*) populations across the archipelago, leading to the formation of urchin barrens (i.e., heavily grazed reefs with crustose coralline algae) and further biodiversity loss (Edgar et al., 2010). This hypothesis is informed by quantitative surveys conducted across the archipelago between 2000 and 2001. The results showed that, as fishing pressure increased with proximity to fishing ports, the density of predatory fishes and lobsters significantly decreased, while the density of sea urchins increased, and coral density decreased. Although the data were collected two decades after the 1982/83 El Niño event, Edgar et al. (2010) apply this model retrospectively to hypothesize that similar patterns may have occurred during that time, driven by the compounded overfishing and climatic stress effects. Further research is needed to validate this hypothesis over a longer period and across different regions of the Galapagos.

The subsequent 1997/98 El Niño reaffirmed the sensitivity of the Galapagos marine ecosystems to climatic extremes. Wolff et al. (2012) utilized a trophic mass balance model to simulate the 1997/98 El Niño's impact on subtidal communities and marine vertebrates in the Bolivar Channel (Fig. 1), comparing these predictions with historical biomass data from 1994 to 2009. This study revealed significant reductions in primary productivity (33–46%), leading to declines in the biomass of 21 functional groups, some by over 50%, including herbivorous zooplankton, mullets, small planktivorous reef fish, jacks, mackerels, predatory marine mammals, and seabirds. Conversely, eight functional groups, including sea cucumbers, sea stars, sea urchins, lobsters, benthic predatory fish, barracudas, groupers, rays, and sharks, increased their biomass during this period. Detritivores like sea cucumbers probably benefited from ENSO-altered conditions due to the increased accumulation of organic matter (detritus) on the seafloor, resulting from the mortality of various marine organisms caused by the decline in primary productivity (Wolff et al., 2012). The 1997/98 El Niño also significantly impacted fishing, with total catches reduced by 56% and a shift toward higher trophic level species in the catch due to the reduction of small planktivorous fish. While the model effectively demonstrated the cascading effects of reduced primary productivity through the food web, not all functional groups responded as expected based on observational data. This discrepancy suggests that additional environmental and anthropogenic factors not captured by the model, such as El Niño-triggered recruitment events or reduced competition due to

Table 2
Model-based predicted ecological impacts of the El Niño and climate change on Galapagos marine ecosystems and fishery resources. EEZ: Exclusive Economic Zone; RCP: Representative Concentration Pathway; SST: Sea Surface Temperature.

Climatic event/variable	Impact	Source
El Niño	Primary production in the Bolivar Channel declined, reducing the biomass of 21 out of 29 functional groups. This assessment was based on a trophic model covering the projection period from 1994 to 2009, which included the extreme 1997/98 El Niño event.	Wolff et al. (2012)
	Overfishing has reduced sailfin grouper biomass by 85%, altering its crucial role as a keystone species under normal conditions and during El Niño events. The trophic model, based on data from 1994 to 2009, projected long-term ecological effects over the next 100 years.	Eddy et al. (2019)
Climate change	RCP 8.5 scenario: a significant SST increase will reduce sailfin grouper biomass (8–16%) by 2100.	Monnier et al. (2020)
	Rising temperatures will affect sailfin grouper larvae transport and recruitment.	Liu et al. (2013); Kendall et al. (2016)
	Sea level rise will impact the mangrove habitats of sailfin grouper's juveniles; while temperature increases will affect the rocky reef habitats of adults.	Alongi (2002); Gilman et al. (2008)
	The abundance of skipjack and yellowfin tuna will increase in tropical areas and EEZs of most coastal countries by the end of the century.	Erauskin-Extramiana et al. (2019)
	RCP 8.5 scenario: yellowfin tuna biomass will increase by more than 50%, while catches will increase by 52–107% by the end of the century. However, larvae mortality from ocean acidification will increase, leading to a 20% decrease in biomass by 2100.	Senina et al. (2018)
	Favorable conditions for yellowfin tuna biomass in the Galapagos due to suitable oxygen and SST for larval growth, but less ideal for spawning.	Arrizabalaga et al. (2014); Senina et al. (2018); Wexler et al. (2011)

overfishing, may have influenced the population dynamics of certain species like lobsters and sea cucumbers. While Wolff et al. (2012) did not assess the social consequences caused by the 1997/98 El Niño, the disruptions to fishing likely affected the local economy and food security, highlighting the importance of integrating social dimensions into future research.

After the 1982/83 and 1997/98 El Niño events, some species have shown partial recovery over time, such as macroalgal communities (Tompkins and Wolff, 2017), while others, including coral reefs, sea cucumbers, and sailfin groupers, remain degraded (Glynn et al., 2017; Ramírez-González et al., 2020a; Usseglio et al., 2016). This incomplete recovery results from the combined pressures of recurrent El Niño events and human-induced stressors like overfishing (Defeo et al., 2013, 2016; Castrejón et al., 2020). In this context, Eddy et al. (2019) explored the combined impacts of fishing and El Niño on the Galapagos sailfin grouper and related ecosystems using Ecopath and Ecosim models for Floreana Island and the Bolivar Channel, originally developed by Ruiz and Wolff (2011) and Okey (2004). By analyzing normal years (2000–2001) and the extreme 1997/98 El Niño event, Eddy et al. (2019) projected future scenarios over the next 100 years. Their findings revealed that overfishing has depleted the Galapagos sailfin grouper population by about 85%, leading to significant changes in its role as a keystone predator. This depletion triggered cascading effects throughout the food web, resulting in increased biomass of species such as parrotfishes, sponges, and octopus due to reduced predation pressure. Eddy et al. (2019) concluded that while El Niño events have temporary disruptive effects, overfishing creates more persistent ecological imbalances, as ecosystems struggle to recover from the long-term absence of critical keystone species like the sailfin grouper.

The long-term effects of extreme El Niño events, combined with sustained fishing pressure, highlight the vulnerability of target and non-target species. However, the absence of continuous, systematic, and comprehensive ecosystem-based monitoring hinders our understanding of the full recovery processes for species and marine ecosystems. While fishery monitoring programs exist for species like sea cucumbers and spiny lobsters (Castrejón et al., 2014), many other commercially important species, such as sailfin groupers, tuna, slipper lobsters, and octopus, are inadequately monitored. Moreover, although ecological monitoring has been ongoing since the early 2000s, this data has not been effectively integrated with fishery monitoring efforts (Castrejón et al., 2024a).

The lack of coordination between these programs creates significant gaps in understanding how commercial species are impacted by natural and human-induced disturbances, making it challenging to detect subtle ecosystem changes or recovery trends. Coordinating and integrating ecological and fishery monitoring efforts is crucial for gaining a holistic view of ecosystem health, tracking species recovery, and improving the management of targeted fisheries and marine biodiversity. Establishing a robust, long-term, ecosystem-based monitoring program would provide critical insights into the resilience of Galapagos marine ecosystems, supporting more effective management strategies to mitigate the impacts of escalating environmental and anthropogenic stressors.

2.2. *Impacts on commercial species*

The El Niño phenomenon and the broader implications of climate change present significant challenges and opportunities for the management of fishery resources in the Galapagos. These environmental factors affect various commercial marine species and their small-scale fisheries differently. The most studied species are the spiny lobsters, brown sea cucumbers, sailfin groupers, and tuna, each exhibiting variable responses to climatic stressors (Table 3).

2.2.1. *Brown sea cucumbers and spiny lobsters*

Significant increases in the productivity of Galapagos spiny lobsters and brown sea cucumbers small-scale fisheries following the 1997/98 El Niño event have been observed (Defeo et al., 2013). The production of these species peaked two and five years post-1997/98 El Niño, attributed to recruitment pulses and increased fishing effort, following the reopening of the sea cucumber fishery in 1999. The high production of spiny lobsters was also attributed to these factors, along with reduced predator abundance (e.g., demersal fish) and increased prey availability (e.g., sea urchins) post-1997/98 El Niño (Defeo et al., 2013). Szuwalski et al. (2016) revealed no significant correlation between ENSO events and lobster (*P. penicillatus*) spawning biomass or recruitment, despite observing an increase in biomass due to substantial recruitment events that occurred in 2005 and 2007, and decreased fishing mortality between 1997 and 2010. Nevertheless, Szuwalski et al. (2016) highlighted the uncertainties in their estimates, attributing them to inconsistencies in fishery-related data collection, which have led to information gaps affecting catch rates.

Koslow et al. (2012) and Woodings et al. (2019) have shown that warm oceanographic conditions associated with El Niño and the PDO correlated with higher larval abundance and potential species range shifts, suggesting that warmer conditions could predict future spiny lobster recruitment and fishery productivity. In the Galapagos, while Defeo et al. (2013) suggest potential correlations between El Niño and spiny lobster productivity, the available evidence remains inconclusive.

Local environmental conditions, specific ENSO event characteristics, and fishing pressures may all influence spiny lobster stocks. For example, fishing effort in the Galapagos spiny lobster fishery varied significantly between 1997 and 2011, contributing to the overexploitation and subsequent recovery of spiny lobster stocks (Castrejón and Charles, 2020). Overexploitation likely increased the species' vulnerability to environmental changes, reducing their resilience to extreme El Niño events. Conversely, as spiny lobster stocks recovered, the increased biomass and a healthier, more diverse age structure likely improved their ability to withstand climatic fluctuations, enhancing their resilience to the impacts of subsequent El Niño events. This hypothesized mechanism is supported by patterns observed in other marine species, where recovery from overexploitation often leads to increased resilience to environmental variability (Sumaila and Tai, 2020). Further research is essential to better understand the complex interplay between spiny lobster stocks, climatic factors, local environmental conditions, and fishing pressure.

2.2.2. *Sailfin grouper and other whitefish species*

The sailfin grouper's responses to the El Niño events and the broader implications of climate change are diverse and complex (Tables 1–3). During the 1982/83 El Niño, Robinson and del Pino (1985) reported a marked decrease in landings of sailfin grouper, white-spotted sand bass (*Paralabrax albomaculatus*), and Galapagos sheepshead wrasse (*Semicossyphus darwini*). Based on observation of whitefish fishery landings and firsthand reports from fishers, the authors suggested that this decline was primarily due to the fish migrating to deeper, cooler waters in search of more favorable conditions, which reduced their catchability.

The 1997/98 El Niño boosted the reproductive activity and recruitment of black mullets (*Mugil cephalus*), leading to increased catches in the following years. The warmer SST during El Niño probably created favorable conditions for spawning and the survival of juvenile black mullets, which contributed to higher recruitment rates (Nicolaides and Murillo, 2001). However, the response of the sailfin grouper was more complex, with initial increases in landings and catch per unit effort (CPUE) during the El Niño event followed by declines as conditions normalized. This pattern may have been driven by changes in the behavior or distribution of sailfin grouper during the 1997/98 El Niño (Nicolaides and Murillo, 2001).

Marin and Salinas-de-León (2018) found that the catchability of larger demersal finfish, including sailfin grouper, mottled scorpionfish, grape eye seabass (*Hemilutjanus macrophthalmos*), misty grouper, white-spotted sand bass, ocean whitefish (*Caulolatilus princeps*), and Pacific dog snapper (*Lutjanus novemfasciatus*) increased significantly during the 2015/16 El Niño. This extreme climatic event likely reduced prey biomass, causing these predatory fish to starve and become more susceptible to baits used by small-scale fishers (Marin and Salinas-de-León, 2018). This increased catchability raised concerns about exacerbating the risk of overfishing, particularly for the sailfin grouper and white-spotted sand bass. Both species are endemic to the ETP and the Galapagos, respectively, and are classified as "endangered" on the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2024). Marin and Salinas-de-León (2018) proposed management actions such as minimum legal size, catch limits, and spatiotemporal closures. Eddy et al. (2019) further suggested developing a participatory, evidence-based management plan to help the Galapagos sailfin grouper recover to sustainable biomass levels, enhancing fishery productivity and the species' ecological role.

An analysis spanning two decades (1994–2014) of sailfin grouper abundances across the Galapagos failed to show a direct correlation with SST or the Oceanic Niño Index (ONI), suggesting that the species' population dynamics may be influenced by a complex interplay of factors beyond just temperature anomalies (Ramírez-González et al., 2020b). However, some individual populations within the Galapagos showed a marked decrease in abundance under extreme El Niño or La Niña conditions, highlighting the need to consider localized environmental conditions and climate forecasts in the conservation and management plans for the sailfin grouper. This species is also projected to face significant habitat displacement and biomass reduction due to rising SST under a high emission scenario (RCP 8.5) (Monnier et al., 2020). SST in the Galapagos could reach an average of 30.9 °C by 2100, which far exceeds the sailfin grouper's preferred thermal range (14.5 °C–23.7 °C) (Aquamaps, 2019; Froese and Pauly, 2024; Heemstra and Randall, 1993; Monnier et al., 2020). Therefore, sailfin groupers could face severe

Table 3
Observed and expected social-ecological impacts of El Niño and climate change reported for the main Galapagos target species. Type of impact: green (increase: +), red (decrease:), yellow (no impact: =), grey (unclear), blank (no data).

Impacts	Brown sea cucumber	Spiny lobsters	Yellowfin tuna	Sailfin grouper
Ecological				
Abundance				
Biomass		=		
Recruitment		=		-
Spawning stock biomass		=		
Sexually immature individuals				+
Social				
Landings	+		+	-
Catch per unit effort		=		+
Catchability		-	-	
Fishing effort				

habitat displacement due to climate change, even under more optimistic mitigation scenarios like RCP 2.6. The RCP 2.6 scenario assumes strong efforts to reduce greenhouse gas emissions, resulting in a more moderate increase in global temperature. Monnier et al. (2020) also estimate that the sailfin grouper's ecosystem biomass will be reduced by 8.3% and 10.8% by 2030 under RCP 2.6 and 8.5 scenarios, respectively. This reduction is expected to be even greater by 2100, with projected declines of 8% under RCP 2.6 and 16% under RCP 8.5.

Climate change and the resultant shifts in oceanic circulation patterns due to rising SST pose a significant threat to the reproductive stages of groupers, including the sailfin grouper, around the Galapagos archipelago. Projections for the years 2025–2050, suggest that global warming will change oceanic circulation patterns around the Galapagos Islands, notably weakening the Equatorial Undercurrent and the South Equatorial Current (Liu et al., 2013). These changes could reduce nutrient upwelling and increase ocean stratification, potentially displacing grouper larvae from their optimal habitats and adversely affecting recruitment (Alongi, 2002; Gilman et al., 2008; Kendall et al., 2016). This issue could be exacerbated by the fact that different life stages of the sailfin grouper inhabit distinct ecological niches, with adults favoring rocky reefs and juveniles relying on mangrove fringes (Aguaiza, 2016; Fierro, 2017). Rising sea levels further disrupt these critical habitats, underscoring the need for adaptive management strategies that protect the full range of grouper habitats, especially mangroves.

2.2.3. Tuna and tuna-like species

Tuna and tuna-like stocks are characterized by dynamic distribution patterns that respond to climate variability and long-term changes in oceanographic conditions (Arrizabalaga et al., 2015; Erauskin-Extramiana et al., 2019; Wexler et al., 2011). These highly migratory and transboundary species are particularly important in the ETP, as they contribute significantly to the livelihoods, food, and economic security of Ecuador, Panama, Costa Rica, and Colombia (Castrejón, 2020a,b). In the Galapagos, the importance of the small-scale tuna fishery, locally known as "pesca de altura," for food security and the economy of residents has experienced substantial growth, mainly driven by an increased demand by tourists and residents (Castrejón et al., 2024b; Viteri Mejía et al., 2022).

Predicted shifts in water properties and circulation patterns due to ENSO and climate change are expected to affect tuna larval dispersal and habitat preferences, potentially reshaping tuna distribution in the ETP (Arrizabalaga et al., 2015; Erauskin-Extramiana et al., 2019; Ganachaud et al., 2013; Wexler et al., 2011). Yellowfin tuna, bonito (*Sarda chilensis*), and dolphin fish (*Coryphaena hippurus*) may migrate toward coastal waters from northern Chile to southern Ecuador (Bertrand et al., 2020). This could lead to a decline in yellowfin tuna abundance within the Galapagos Marine Reserve. Conversely, projections by Erauskin-Extramiana et al. (2019) and Senina et al. (2018) anticipate an increase in skipjack (*Katsuwonus pelamis*) and yellowfin tuna populations in tropical areas and most coastal EEZs by the century's end, with a notable biomass increase in the Central and Eastern Pacific. Considering fishing effects under RCP 8.5 scenario, yellowfin tuna catches in the ETP could rise by up to 107% by the century's end. However, ocean acidification may reduce larval survival, leading to a 20% decline in biomass by 2100 (Senina et al., 2018). Ramírez-González et al. (2020b) challenged these optimistic projections, finding a significant negative correlation between SST and the biomass of yellowfin tuna associated with Fish Aggregation Devices (FADs) in the GMR. They indicated that higher SST could lead to a decreased presence and reduced biomass of yellowfin tuna near FADs. This discrepancy highlights the complex effects of climate variability on marine ecosystems and stresses the necessity of integrating empirical data with model projections. Such an approach is critical to formulating effective management and adaptation strategies tailored to the specific needs and challenges of the Galapagos small-scale tuna fishery in the face of climate change.

2.3. Socioeconomic impacts and adaptive capacity

ENSO and climate change research in the Galapagos have shifted gradually from analyzing direct impacts on marine ecosystems and fishery resources to understanding broader social-ecological effects (Table 1). Castrejón and Charles (2020) assessed the spatiotemporal distribution of fishing effort in the Galapagos spiny lobster fishery from 1997 to 2011, focusing on the impact of human and climatic drivers. They found that the boom-and-bust cycle of the sea cucumber fishery and the 2007-09 global financial crisis were the most significant factors affecting how fishing effort was distributed over time and space. They identified six key predictor variables that influenced fishing effort distribution, ranked in order of importance: distance from homeport, latitude and longitude, the anthropogenic and climatic driver evaluated, the Oceanic Niño Index (ONI), and the lobster catch from previous fishing trips. Notably, fishing effort increased during the El Niño periods. This pattern is attributed to the redistribution of spiny lobsters from coastal to deeper waters during the El Niño events, making them less accessible to hookah divers. As a result, divers likely increased their search times and diving hours per trip. A similar trend was observed by Robinson and del Pino (1985) and Nicolaides and Murillo (2001) for adult sailfin groupers, during the 1982/83 and 1997/98 El Niño events (see Section 2.2.2). In contrast, Marin and Salinas-de-León (2018) reported that the catchability of sailfin grouper, and other demersal finfish species increased during the 2015/16 El Niño event, likely due to reduced primary productivity, which led to diminished prey biomass and subsequent starvation of demersal predatory fish. This starvation likely made these predators more aggressive in pursuing bait, making them more susceptible to being caught.

Bucaram et al. (2013), using an econometric model, showed that fishers traveled to fishing grounds with high spiny lobster abundance and consequently high expected revenues. They also found that fishing location decisions were sensitive to changes in wave intensity and air temperature. On the other hand, Murillo-Posada et al. (2019) found an inverse relationship between CPUE and SST for *P. penicillatus* and *P. gracilis*: mean CPUE was higher at SST values lower than 22 °C. Both studies highlight the significant influence of SST, wave intensity, and air temperature on fishing effort and catch rates in the Galapagos small-scale fisheries.

Rodríguez-Jácome et al. (2019) and Cavole et al. (2020) assessed the socioeconomic impacts of the El Niño events on small-scale fishers' well-being and livelihoods, based on the local ecological knowledge provided by fishers from San Cristóbal, Santa Cruz, and Isabela. They found that the El Niño events led to significant reductions in fish availability due to warmer SST and the suppression of nutrient-rich upwelling currents, particularly during 1982/83, 1997/98, and 2015/16 El Niño events. These changes forced fish to migrate to deeper or more distant waters, making them less accessible and increasing the difficulty and fishing costs. As a result, fishers experienced decreased catch volumes and income, which negatively impacted their livelihoods and the food security of local communities (Rodríguez-Jácome et al., 2019). Fishers reported altered distribution patterns of fish, mostly small pelagic species, and increased mortality rates among sea lions during the El Niño. Some fishers also identified the north side of Isabela and Fernandina Islands, and the Bolívar Channel, between the west coast of Isabela and the east of Fernandina Islands, as marine refuge sites for corals, fish, and sea cucumbers, which remain cooler and concentrate more fish and invertebrates than the rest of the archipelago during strong the El Niño events (Cavole et al., 2020).

Researchers are increasingly exploring the adaptive capacity of small-scale fishers to enhance sustainability and resilience in the face of environmental uncertainty. Quiroga et al. (2010) focused on the general impacts of climate change on Galapagos small-scale fishers, identifying moderate adaptive capacity hindered by low education, limited computational skills, and language barriers. While their study primarily addressed the broader impacts of climate change, the challenges identified are likely relevant to other stressors, including ENSO events. Rodríguez-Jácome (2019) also investigated Galapagos fishers' perceptions regarding their capacity to face climate change and the adaptive strategies they believe should be implemented by governmental and non-governmental institutions. Most small-scale fishers (56%) felt unprepared to adapt to climate change due to a lack of knowledge, reduced catches from warming waters, and a lack of alternative livelihoods. Fishers proposed several climate change adaptation measures, including awareness campaigns and training for fishers, research on adaptation technologies, community engagement, and training in local tourism and hospitality. They also suggested diversifying fisheries, upgrading personal and boat equipment, adopting climate-adaptive fishing technologies, considering weather factors in fishing plans, and promoting seafood marketing focusing on value-added products to reduce fishing effort and increase economic returns. Value-added products in the Galapagos could involve processing locally caught tuna into high-quality, sustainably branded tuna steaks or producing ready-to-eat meals like tuna burgers and sausages, which could be sold to premium markets (Castrejón et al., 2024b). This strategy could enhance the quality of Galapagos seafood products rather than increasing their quantity. It could also help reduce the pressure on overfished coastal resources while transferring fishing effort toward healthier oceanic pelagic species, boosting economic returns for fishers by increasing tuna quality and value (Castrejón and Defeo, 2024).

Given their experience with extreme ENSO events, Galapagos fishing communities may perceive environmental changes as cyclical rather than permanent, which could diminish the perceived urgency to adapt to long-term climate change. This perception, influenced by existing beliefs and expectations, may hinder effective strategies for addressing the broader social-ecological impacts of climate change (Weber, 2010). While familiarity with ENSO-related variability could enhance preparedness and decision-making, it also risks underestimating the unprecedented and severe impacts of sustained climate change (Finucane, 2009). Future research should examine how these perceptions shape adaptation efforts and whether the adaptive capacity developed for ENSO events can effectively address the more persistent challenges of climate change.

3. Challenges in advancing ENSO and climate change research

In response to growing global concern over climate change in the mid-2000s, efforts to address its impacts in the Galapagos intensified, involving management authorities, NGOs, and academic institutions. A key initiative led by Conservation International and the World Wildlife Fund, assessed the archipelago's vulnerability to climate change, resulting in the "Declaration of Santa Cruz" in 2009 (Larrea and Di Carlo, 2010). This declaration represented a significant commitment to enhancing the resilience of Galapagos biodiversity. However, the progress of climate change research in the Galapagos has been hampered by various institutional challenges. Shifting political priorities often redirects focus and funding away from climate research to address immediate economic and social concerns. For example, following the Declaration of Santa Cruz, research and management priorities shifted to more pressing issues, such as evaluating the effectiveness of the Galapagos National Park (GNP) and the GMR, integrating their management plans, amending the Galapagos Special Law, and creating a unified zoning system for protected areas (Castrejón et al., 2014, 2024a). Additionally, conducting long-term research in the geographically isolated Galapagos Islands requires substantial investment, which is often constrained by reliance on external grants and donations (Castrejón et al., 2014). Despite these challenges, research on ENSO and climate change impacts on Galapagos fisheries has increased gradually (Tables 1 and 2), although progress continues to be hindered by weak governance.

Research priorities are often influenced by short-term political agendas rather than long-term environmental and socioeconomic needs, resulting in inconsistent funding allocations that leave climate change research underfunded. Additionally, the current research landscape is often siloed, characterized by the absence of collaborative partnerships among key stakeholders, including government agencies, NGOs, and local fishing communities. This social fragmentation has resulted in ineffective data sharing among institutions and stakeholders (Mora and Castrejón, 2024). The absence of a centralized data repository or standardized data-sharing protocols has hindered the ability to conduct comprehensive, interdisciplinary research, preventing researchers from accessing a broader and updated range of datasets necessary for understanding the complex interactions between marine ecosystems, human activities, ENSO, and climate change. Moreover, inadequate economic and human resources have undermined the enforcement of policies and regulations, making it challenging to sustain long-term monitoring and data collection efforts essential for tracking environmental and socioeconomic changes (Castrejón et al., 2014, 2021). Social fragmentation within fishing communities and differing perceptions about fisheries and climate change further complicate the development of cohesive, scientifically informed adaptation strategies. Consequently, the potential for effective research and management to mitigate the growing threats of ENSO and climate events in the Galapagos remains largely unutilized.

4. Recommendations

Future projections indicate that Galapagos marine ecosystems and fisheries will become increasingly vulnerable to ENSO events and climate change (Table 2). Species such as lobsters and demersal finfish, vital for local tourism; export-driven sea cucumbers; and locally consumed tuna, face risks due to climate and human-induced shifts in their abundance and distribution. These changes pose significant threats to Galapagos residents' food security and economic sustainability. Limited by knowledge, resources, and weak governance, small-scale fishers are unprepared to respond. To address these challenges, an ecosystem-based fisheries management approach should be developed using integrated models that combine physical ecosystem dynamics with socio-economic factors, supported by long-term monitoring and scenario planning.

Effective ENSO and climate change research requires interdisciplinary collaboration and robust data sharing. Centralizing data in repositories like Pangaea or the World Data Center for Climate, or leveraging existing databases, can enhance access, transparency, and reproducibility. The main challenge is ensuring consistent data submission and maintenance, supported by clear policies and incentives for standardizing formats and updating data. Linking research grants to mandatory data sharing could incentivize participation (Tedersoo et al., 2021).

Addressing governance challenges in the Galapagos, which have hindered ENSO and climate change research, will require coordinated efforts from governments, NGOs, scientific institutions, and the local community, supported by strategic investments in research infrastructure and local expertise. Engaging local communities through transdisciplinary research offers ground-level insights into the socio-economic impacts of climate and human stressors. This approach will bridge the gap between research and practical adaptation strategies, making findings more relevant and culturally sensitive, and leading to more effective mitigation and adaptation efforts.

Interdisciplinary and transdisciplinary research should guide ecosystem-based adaptation measures that leverage biodiversity to address climate change (Scarano, 2017). Key adaptations include updating the GMR's no-take zones to protect high-ecological value areas, alongside co-managed areas that grant exclusive fishing rights to local communities. Offshore fishing can aid the recovery of overfished coastal species by promoting the sustainable development of the Galapagos small-scale tuna fishery (Castrejón and Defeo, 2023a,b). This strategy should be integrated into a broader ecosystem-based management framework. Additional measures include establishing a robust, long-term, ecosystem-based monitoring program; implementing Fishery Improvement Projects to recover sailfin grouper and white-spotted sand bass stocks; small-scale mariculture to rebuild sea cucumber populations; and market-based incentives such as eco-labeling. These efforts must be supported by capacity-building programs, the adoption of bycatch mitigation methods, and the implementation of electronic monitoring and traceability systems to ensure sustainable fishing practices.

5. Conclusions

Small-scale fisheries in the GMR are vital for local communities' economy and food security. However, they are increasingly threatened by climatic and anthropogenic factors, with ENSO and climate change posing significant risks. This overview emphasizes the profound impacts of climate variability, particularly extreme El Niño events, on marine ecosystems and the communities that rely on them, underscoring the need to develop adaptive strategies to strengthen resilience.

Extreme El Niño events and climate change have already caused, or could potentially cause, significant shifts in marine ecosystems, including changes in species distribution, biomass, and productivity. Overfishing and weak governance have exacerbated the vulnerability of small-scale fisheries. To address these challenges, interdisciplinary collaboration, enhanced data sharing, and the integration of socio-economic factors into research are essential. International cooperation, coupled with adequate local resources and expertise, is equally vital. An ecosystem-based fisheries management approach should be developed to mitigate the combined threats of ENSO, climate change, and human-induced pressures such as overfishing and illegal, unreported, and unregulated fishing. Ultimately, it is imperative to build local scientific capacity, strengthen institutional frameworks, foster community engagement, and integrate scientific insights into policy-making to safeguard the unique social-ecological integrity of the Galapagos Islands in the face of imminent and future climate-related adversities.

CRediT authorship contribution statement

Mauricio Castrejón: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization. **Jeremy Pittman:** Writing – review & editing, Funding acquisition. **Jorge Ramírez-González:** Writing – review & editing, Investigation. **Omar Defeo:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT- 4o to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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