

RESEARCH ARTICLE

Vulnerability of Eastern Tropical Pacific chondrichthyan fish to climate change

Florencia Cerutti-Pereyra¹  | Elizabeth J. Drenkard²  | Mario Espinoza^{3,4}  |
 Brittany Finucci⁵  | Felipe Galván-Magaña⁶  | Ana Hacohe-Domené⁷  |
 Alexander Hearn^{4,8}  | Mauricio E. Hoyos-Padilla^{4,9}  | James T. Ketchum^{4,9}  |
 Paola A. Mejía-Falla^{10,11}  | Ana V. Moya-Serrano¹  | Andres F. Navia¹¹  |
 Diana A. Pazmiño^{4,8}  | Deni Ramírez-Macías¹²  | Jodie L. Rummer¹³  |
 Pelayo Salinas-de-León^{1,14}  | Oscar Sosa-Nishizaki¹⁵  | Charles Stock²  | Andrew Chin¹³ 

Correspondence

Florencia Cerutti-Pereyra, Charles Darwin Foundation, Av Charles Darwin s/n, Puerto Ayora, Galápagos, Ecuador.
 Email: florenciacp@gmail.com

Present address

Florencia Cerutti-Pereyra, Délégation Océan Indien, Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) Institute, Le Port, France

Funding information

United States Agency for International Development (USAID); Instituto Politécnico Nacional (COFAA and EDI); Save Our Seas Foundation; Mark and Rachel Rohr Foundation

Abstract

Climate change is an environmental emergency threatening species and ecosystems globally. Oceans have absorbed about 90% of anthropogenic heat and 20%–30% of the carbon emissions, resulting in ocean warming, acidification, deoxygenation, changes in ocean stratification and nutrient availability, and more severe extreme events. Given predictions of further changes, there is a critical need to understand how marine species will be affected. Here, we used an integrated risk assessment framework to evaluate the vulnerability of 132 chondrichthyans in the Eastern Tropical Pacific (ETP) to the impacts of climate change. Taking a precautionary view, we found that almost a quarter (23%) of the ETP chondrichthyan species evaluated were *highly* vulnerable to climate change, and much of the rest (76%) were *moderately* vulnerable. Most of the *highly* vulnerable species are batoids (77%), and a large proportion (90%) are coastal or pelagic species that use coastal habitats as nurseries. Six species of batoids were *highly* vulnerable in all three components of the assessment (exposure, sensitivity and adaptive capacity). This assessment indicates that coastal species, particularly those relying on inshore nursery areas are the most vulnerable to climate change. Ocean warming, in combination with acidification and potential deoxygenation, will likely have widespread effects on ETP chondrichthyan species, but coastal species may also contend with changes in freshwater inputs, salinity, and sea level rise. This climate-related vulnerability is compounded by other anthropogenic factors, such as overfishing and habitat degradation already occurring in the region. Mitigating the impacts of climate change on ETP chondrichthyans involves a range of approaches that include addressing habitat degradation, sustainability of exploitation, and species-specific actions may be required for species at higher risk. The assessment also highlighted the

For affiliations refer to page 15.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2024 The Author(s). *Global Change Biology* published by John Wiley & Sons Ltd.

need to further understand climate change's impacts on key ETP habitats and processes and identified knowledge gaps on ETP chondrichthyan species.

KEYWORDS

batoid, chimaera, ecological risk assessment, elasmobranch, ETP, shark

1 | INTRODUCTION

Climate change is now recognized as an urgent global environmental issue impacting many marine biodiversity hotspots and economically important marine resources (Pörtner et al., 2019). The earth's surface has warmed by 0.6°C over the past 100 years and a further 1.0–3.7°C increase is expected by 2100, with larger changes projected under high carbon dioxide (CO₂) emissions scenarios (Cheng et al., 2020; IPCC, 2018). Ocean warming has been identified as a primary determinant of species range shifts (e.g., Pinsky et al., 2020) and, in combination with oxygen, constrains the metabolic limits of marine organisms (Deutsch et al., 2015). Warming strengthens upper ocean stratification, inhibiting the supply of nutrients to the euphotic zone as well as the resupply of oxygen to deeper waters (Capotondi et al., 2012; Kwiatkowski et al., 2020). The accumulation of atmospheric CO₂ underlying much of observed global warming also acidifies the ocean (Orr et al., 2005), which can have detrimental effects on shell-forming species and other organisms (Kroeker et al., 2013). Changes in upwelling and nutrient availability will impact primary productivity, resulting in productivity declines that may threaten food availability (Kislik et al., 2017; Rykaczewski et al., 2015). Projections of these potential “ocean stressors” for the end of the 21st century suggest that they will continue to pose challenges, even under aggressive mitigation strategies (John et al., 2015; Kwiatkowski et al., 2020) and these effects would continue beyond 2100. There is therefore an urgent need to better understand the impact of such stressors on marine species and key habitats to inform adaptive management strategies.

The Eastern Tropical Pacific (ETP) is located between the subtropical gyres of the North and South Pacific; eastern boundary currents flow into the ETP from the north (California Current) and south (Peru or Humboldt Current), while also containing the eastern end of the Pacific equatorial current system and the eastern Pacific warm pool (Lavín et al., 2006). It has a frontal zone over the Pacific Ocean, and many upwellings zones throughout the region (Forryan et al., 2021; Lluch-Cota, 1999; Willett et al., 2006). The upwelling off the Baja peninsula spans almost one quarter of the equatorial circumference generating the highest average air-to sea heat fluxes and one quarter of global new primary production (Eisele et al., 2021; Lavín et al., 2006; Ryan et al., 2017). Additionally, the Humboldt current reaches close to the equator, where persistent upwelling also results in higher fish production (Ryan et al., 2017). The oceanography of ETP is also characterized by a shallow thermocline (at around 25 m), high surface chlorophyll concentrations (down to about 50 m)

and oxygenation profiles showing hypoxic conditions below the thermocline (Prince & Goodyear, 2006). These features are strongly impacted by the El Niño Southern Oscillation (ENSO), which generates large-scale fluctuations in temperature and other ocean properties in the ETP every 5–10 years (Mantua et al., 1997; Newman et al., 2016; Wang & Fiedler, 2006). Changes in the strength and frequency of ENSO events are uncertain but possible under climate change (McPhaden et al., 2020).

The ETP has geological structures such as oceanic islands and seamounts that interact with ocean circulation and migratory species are known to regularly move among them and mainland creating marine corridors throughout the ETP (Cerutti-Pereyra et al., 2022; Klimley et al., 2022; Lara-Lizardi et al., 2020). Furthermore, the ETP coast includes sandy flats, coastal bays, estuaries, and mangrove forests that provide nursery areas for many species (Castellanos-Galindo et al., 2013; López-Angarita et al., 2016; Miloslavich et al., 2011). Such variety of oceanic features, geological structures, and coastal habitats, results in a highly productive region that provides the basis for a complex marine food structure and biodiversity hotspots that support artisanal and industrial fisheries (Hearn et al., 2010; Klimley et al., 2022; Ryan et al., 2017).

Notably, the ETP also has one of the highest levels of endemism and significant concentrations of marine megafauna biodiversity worldwide, including chondrichthyans (sharks, batoids, and chimaeras) which play key ecological roles in marine ecosystems as one of the largest groups of predatory species connecting food webs across ecosystems (Heithaus et al., 2008; Heupel et al., 2014). Notably, this group is economically important globally through fisheries and tourism (Dent & Clarke, 2015; Gallagher & Hammerslag, 2011). It is a key component of targeted and non-targeted catch in both artisanal and industrial fisheries in the ETP (Cerutti-Pereyra et al., 2019; Croll et al., 2016; Martínez-Ortiz et al., 2015) and they have become an important economic tourism activity (Cisneros-Montemayor et al., 2020; Lynham et al., 2015; Topelko & Dearden, 2005). Notably, chondrichthyans are one of the most threatened marine groups globally due to overfishing (Dulvy et al., 2021; Pacoureau et al., 2021; Sherman et al., 2023) and other threats such as climate change may aggravate the status of their depleted populations (Carrier et al., 2022; Hazen et al., 2013; Pereira Santos et al., 2021). Despite the important ecological and economic roles, little is known about the impacts of climate change on chondrichthyans and how they may respond to such changes.

Ecological risk assessments (ERAs) investigate the effects of ‘ecological hazards’ and determine how an ecological asset will be affected by the identified threat (Hobday, Smith, et al., 2011). Such

assessments are helpful to evaluate the overall risk and impacts faced particularly by data-poor species, such as many chondrichthyan species (Chin et al., 2010; McClure et al., 2023; Walker et al., 2021). This risk assessment has evolved in the last decade into an 'integrated risk assessment' that evaluates climate change vulnerability and predicts species' resilience to inform adaptation policy. For example, suggestions such as protecting spawning biomass or nursery areas, which might increase stock resilience or decrease fishing mortality on high-risk species can contribute to the sustainable management of those species, or managing habitats or areas as refuges for vulnerable (VU) species (Foden et al., 2013; Hare et al., 2016; Quinlan et al., 2023). The integrated risk assessment presented here provides an initial assessment of the vulnerability of ETP chondrichthyans to climate change, a better understanding of the relationship between climate change and its consequences, and a proposed framework for research and management prioritization. This study has also a report in Spanish available on the Charles Foundation website (Cerutti-Pereyra et al., 2024a).

2 | MATERIALS AND METHODS

The integrated risk assessment involves three steps (Table 1): (1) Defining the assessment context, (2) assessing components of vulnerability, and (3) integrating vulnerability components to derive the overall score of vulnerability of each species to the threat of climate change (Chin et al., 2010).

2.1 | Defining the assessment context

2.1.1 | Study region

For the purposes of this study, the ETP was defined as the region from the Gulf of California and the southern tip of the Baja peninsula, Mexico (tropic of Cancer) in the north, to the border between Ecuador and Peru in the south (Figure 1). The westernmost limit is defined at 120°W (western limit of El Niño zone 3, NCAR, 2022). A broad description of the ETP's oceanographic features, geological structures, and coastal habitats is provided in the Section 1.

2.1.2 | Participants

The assessment was conducted by an expert panel of 19 scientists from eight countries (listed as coauthors) that had specific local and regional expertise on regional habitats and ecosystems, chondrichthyan and deep-sea species biology and ecology, shark physiology, risk assessments, and climate change/oceanography. The panel of experts contributed to the data gathering, climate change discussions, and species' assessments through virtual workshops held during 2020 and 2021. Discussion continued until there was a consensus on the assessment for each species.

TABLE 1 Overview of the risk assessment for climate change for chondrichthyans in the Eastern Tropical Pacific.

Step	Procedure
1. Context	<i>Define the entity to be assessed</i> Spatial (study site) and temporal (projections) scope defined. Species lists compiled, species data collected in a database, and species organized into ecological groups <i>Define climate change factors</i> Climate change factors identified for the region. Projections calculated to 2100. Literature review and experts' inputs to identify predicted impacts on the environment, habitats, and processes <i>Define vulnerability attributes</i> Biological and ecological traits defined for each species sensitivity and adaptive capacity
2. Assessment	<i>Ranking exposure</i> Exposure of each species to each climate change factor was ranked as low, medium, or high <i>Ranking sensitivity and adaptive capacity</i> Each attribute of sensitivity (maximum size, size at maturity, productivity, longevity, and rarity) and adaptive capacity (latitudinal range, habitat specificity, mobility, trophic specificity, and physiological tolerance) was ranked as low, medium, or high for each species to derive the overall vulnerability for each component
3. Integration	<i>Integrate vulnerability components</i> Matrix used to integrate the rankings of all components (exposure, sensitivity, and adaptive capacity) to derive overall vulnerability of each species to each climate change driver <i>Collate rankings</i> Species rankings collated to derive the vulnerability of each ecological group to climate change <i>Synergies, interactions, and knowledge gaps</i> Identify potential synergies and interactions with non-climate change issues and identify knowledge gaps arising

2.1.3 | Units of analysis and ecological groups

Information and species profiles for 132 species of chondrichthyans (i.e., 65 sharks, 60 batoids, and 7 chimaeras) were collated from published and unpublished literature/data, the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (<https://www.iucnredlist.org/>) available until 2022, as well as expert panels' inputs. The data used to derive the rankings for this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.11218757> (Cerutti-Pereyra et al., 2024b) and the reference list available in the Supporting Information. To facilitate habitat-specific assessments and the presentation of results, we divided the 132 chondrichthyan species found for the ETP into four discrete ecological groups based on those used by

Chin et al. (2010) and the concept of ecomorphotypes postulated by Compagno (1990) (Table 2). Many species appeared in more than one ecological group and were therefore considered in all ecological groups such species was present.

2.1.4 | Climate change factors

Seven climate change factors were identified by the expert panel: ocean warming, deoxygenation, acidification, changes in primary

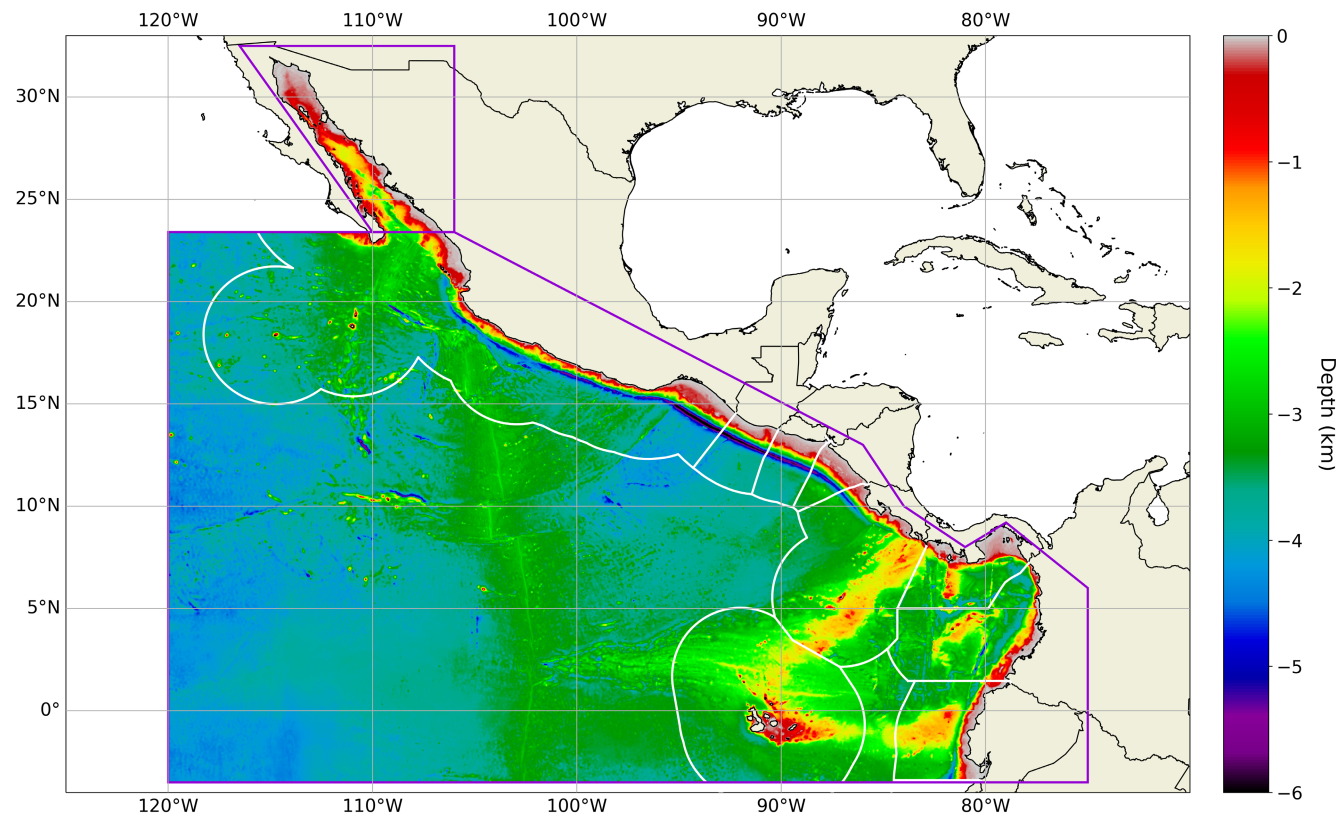


FIGURE 1 Eastern Tropical Pacific study region (outlined in purple and not depicting accepted national boundaries) including oceanic islands, bathymetry, and countries' Exclusive Economic Zone boundaries (white line).

TABLE 2 Description of the four ecological groups of Eastern Tropical Pacific (ETP) chondrichthyans used in the integrated risk assessment. Some species are in more than one ecological group.

Ecological group	Definition	Number of species	Examples of species
Coastal (freshwater, estuarine, and inshore)	Include species that are commonly found in freshwater (e.g., rivers), estuaries, shallow bays, mangroves, intertidal seagrass beds, foreshores, and mudflats, inshore fringing reefs, shallow coastal waters, rocky shoals, sponge gardens and habitats extending from coastal inter-tidal habitats to the mid-shelf platform or ribbon reefs to 40m depth	98	Pacific Eagle Ray (<i>Aetobatus laticeps</i>), bull shark (<i>Carcharhinus leucas</i>)
Shelf	Include species that use deeper water and seabed habitats, extending to the continental slope edge. For the ETP, it will include waters from the surface to the isobath of 500m, including deep-water benthic habitats and the platform around oceanic islands of the ETP	90	Arctic skate (<i>Amblyraja hyperborea</i>), prickly shark (<i>Echinorhinus cookei</i>)
Bathyal	Include species that use benthic habitats of the continental slope and beyond, extending down to 2000m depth	42	Deepsea skate (<i>Bathyraja abyssicola</i>), whitespot ghostshark (<i>Hydrolagus albus</i>)
Pelagic	Include species generally found in depths less than 200m above continental slope and plain, the water column, and open ocean waters	52	Spinetail mobula (<i>Mobula japanica</i>), blue shark (<i>Prionace glauca</i>)

productivity, changes in freshwater inputs, changes in salinity, and sea level rise. These factors, which are similar to those considered in risk assessments (e.g., Chin et al., 2010), may impact chondrichthyan physiology, habitat use, ecological interactions, and the food webs directly linked to them (Table S1). We anticipated that the last three factors (changes in freshwater inputs, salinity, and sea level rise) were only relevant for coastal ecosystems.

Projections for changes in ETP ocean temperature, salinity, dissolved oxygen concentration, pH, and productivity were calculated from earth system model (ESM) contributions to the Sixth Coupled Model Intercomparison Project (Eyring et al., 2016), specifically those for the highest greenhouse gas emissions and radiative forcing scenario, SSP5-8.5 (O'Neill et al., 2014). While a net increase in radiative forcing of 8.5 watts m⁻² would be achieved through emissions of a combination of multiple greenhouse gases (e.g., CO₂, methane, nitrous oxide, fluorinated gases) and aerosol emissions (Pathak et al., 2022), the SSP5-8.5 marker is generally associated with CO₂ emissions of ~120 GtCO₂ by the end of the century and atmospheric CO₂ levels ~1000 ppm (O'Neill et al., 2016; Riahi et al., 2017). Changes were calculated as the difference between 30-year mean climatological states: future (2071–2100)–historical (1985–2014), in the Pacific region bounded by 23.5°N to 3°S and 120°W to 75°W. These calculations did not include the Gulf of California, which is not adequately resolved in coarse resolution ESMs (Asch et al., 2016). We report the range of model mean changes across models in S1, along with the associated level of confidence/consensus in sign and magnitude of the change (see Table S1). Projections of change in precipitation and sea level over the study area and adjacent South and Central American landmasses were taken from Oppenheimer et al. (2019) and Tebaldi et al. (2021), respectively.

2.1.5 | Vulnerability components and attributes

The risk assessment used three components to evaluate climate change vulnerability: *exposure*, *sensitivity*, and *adaptive capacity* (Chin et al., 2010; Jones & Cheung, 2017; Walker et al., 2021).

Exposure was assessed by comparing the overlap of a species' distribution and habitat use within the study area (i.e., coastal vs. offshore, pelagic vs. bathyal) with projected changes in each climate change factor. *Exposure* thus aligns primarily with coast to open ocean and surface to depth gradients in projected changes. For example, exposure to ocean warming attenuates in deeper habitats where less warming is projected to penetrate over the next century and exposure to changes in salinity, freshwater inputs, and sea level are expected to be most acute in coastal regions and attenuated offshore. *Exposure* is considered a 'negative' component: the higher the exposure, the greater the species' vulnerability to climate change. The evaluation of *Exposure* included all habitats within the distribution of each species.

Sensitivity included inherent life-history traits that an individual cannot alter through behavioral or physiological adaptation, and

comprised five attributes: maximum size, size at maturity, productivity (litter size divided into pups and eggs), longevity, and rarity. Chondrichthyan biology suggests that large sizes, low productivity, long life spans, and rarity confer higher sensitivity to a threat (Cailliet et al., 2005; Field et al., 2010; Musick et al., 2000). Just as the component of *exposure*, *sensitivity* is also a 'negative' component where high sensitivity equates to increased potential impact from the threat. Sizes (maximum and at maturity) of sharks and shark-like bodied batoids (e.g., guitarfish) were defined using total length (TL, measured from the snout to the tip of the caudal fin); for the rest of batoids it was based on disc width (DW, measured between the furthest points of the pectoral fins). Size at maturity was calculated as a proportion of maximum size rather than an absolute value (Mejía-Falla et al., 2019). The attribute of rarity encompasses the species, population the size, and rebound potential (see Chin et al., 2010).

Adaptive capacity is considered a 'positive' component. High adaptive capacity means that a species can change its behavior to accommodate changing environmental conditions as a result of acclimation or compensation allowing a species to survive in new conditions. This component comprised five attributes: latitudinal range, habitat specificity, mobility (or immobility), trophic specificity (diet), and physiological tolerance. Larger ranges, generalist habitat use and diet, mobility and physiological tolerance confer higher adaptability. Latitudinal range included the central and eastern Pacific Ocean (distributions in the Western Pacific Ocean were not included in the analysis). Habitat specificity included the records of coastal nurseries for each species; if a species was recorded to use coastal nurseries, its sensitivity was increased (i.e., habitat requirements were more rigid). Mobility included records of both horizontal and vertical movements and migrations.

2.2 | Assessment and integration

The level of *exposure*, *sensitivity*, and *adaptive capacity* were ranked as *low*, *moderate*, or *high*, based on the information available and experts' judgement for each species for each attribute. After ranking all attributes for all species, a logic rule of the majority (hereafter referred to as the majority rule) was used to derive the final rank for each component: the ranking held by most attributes was taken as the final rank for that component while *moderate* was assigned in case of a tie. For example, if the five attributes of *sensitivity* were ranked as H, H, L, L, H, this component would be ranked as H, which reflects the ranking of the majority of these attributes. Instead, if it had a tie of H, H, L, L, M, this component then would be ranked as M, which reflects the variety of rankings without a majority. Because *adaptive capacity* is a positive component, we defined "*rigidity*" as the inverse of adaptive capacity for purposes of the vulnerability calculation, that is, species with low *adaptive capacity* are assigned a high *rigidity*, which favors a high vulnerability ranking. The term *rigidity* is used from now onwards for this component.

Once all attributes and components for each species were ranked (Tables S2–S4), the rankings were combined using the 'majority rule'

to produce a matrix integrating the three components and calculating the overall vulnerability of each chondrichthyan species (Table S5). Once all vulnerability components for the 132 species were assessed, they were collated in ecological groups to determine the relative vulnerability of each group. Rankings for all species were reviewed by the expert panel individually and during online workshops held in 2021. We also present results of species' vulnerability in relation to the IUCN categories. Tables S2–S6 are openly available in Zenodo at <https://doi.org/10.5281/zenodo.11278035> (Cerutti-Pereyra et al., 2024c).

2.2.1 | Uncertainty and the precautionary principle

Uncertainty in the information needed to rank each attribute was managed through two approaches. First, when species-specific data were not found for a given species, we used information from a 'sister species' (same genus). This was noted throughout the database because assessing a species' vulnerability based on sister species data may lower the confidence in the results. Therefore, those species where $\geq 50\%$ of the information used for the assessment was sourced from a sister species are considered to have 'low' confidence. The second approach invoked the precautionary principle: if there was no information available at all for a particular attribute, it was ranked as *high*, which is consistent with the precautionary principle widely used in ERAs to recognize that lack of information increases risk (Chin et al., 2010; Hobday, Game, et al., 2011).

3 | RESULTS

Through the risk assessment, we identified (1) the vulnerability of 132 species of chondrichthyan to climate change in the ETP, and (2) the linkages between exposure of these species and ecological groups to climate change factors. We then suggest management actions addressing the risks identified.

3.1 | Vulnerability of ETP chondrichthyan

From the total number of *sharks* ($n=65$), 11% had an overall *high* vulnerability to climate change, 88% had *moderate* vulnerability, and 1% had *low* vulnerability (Figure 2a). From the total number of *batoids* ($n=60$), 38% had an overall *high* vulnerability and 62% had *moderate* vulnerability (Figure 2a). All *chimaeras* ($n=7$) had *moderate* vulnerability to climate change (Figure 2a). Overall, 23% ($n=30$) of ETP chondrichthyan were ranked with *high* vulnerability (Table 3), most of which were batoids (24 batoids and 6 sharks), and five of these species with *high* vulnerability also had low confidence. Meanwhile, 76% ($n=101$) of ETP chondrichthyan were ranked with *moderate* vulnerability (57 sharks, 37 batoids, 7 chimaeras), over half of which were sharks, and 11 of these 101 species had lower confidence.

Only 1% (one species of shark, *Isistius brasiliensis*) was ranked with *low* vulnerability, but had high confidence (Table S5). Six species of batoids (*Aetomylaeus asperimus*, *Beringraja cortezensis*, *Hypanus longus*, *Pristis pristis*, *Styracura pacifica*, and *Urotrygon simulatrix*) had *high* vulnerability in all three components and only one species of shark (*Isistius brasiliensis*) had an overall *low* vulnerability in all three components (Table S5).

3.2 | Rankings of components

Of those species with *high* vulnerability ($n=30$), 20% had *high* ranks on all three components, 87% had *high* exposure, 60% had *high* sensitivity, and 73% had *high* Rigidity (i.e., low adaptive capacity). Of the 101 species with *moderate* vulnerability to climate change, 11% were had *moderate* ranking on all three components, 54% had *high* exposure to climate change, 11% had *high* sensitivity, and 3% had *high* rigidity (Table S5).

The component of exposure had the highest number of ETP chondrichthyan species with a *high* ranking (H: 62%, M: 24%, L: 14%). The primary component that increased a species' exposure ranking was the use of coastal habitats and nurseries, where exposure to widespread climate drivers such as ocean warming, acidification, and changing oxygen was compounded by the exposure to changes in salinity, freshwater inputs, and sea level rise (Figure 3). The component of sensitivity (H: 22%, M: 74%, L: 4%) had the highest number of species with a *moderate* ranking. From the *low* rankings, rigidity had the highest number of all three components (Figures 2b and 4).

Over 60% of species were found to have *high* exposure on five of the seven climate change factors used in this assessment. For the factor of 'changes in productivity', most species (95%) were ranked with *moderate* exposure, and for three factors (changes in freshwater inputs, changes in salinity, and sea level) 29% of species ranked with *low* exposure. When examining how the ranking of individual climate change factors contribute to a species' vulnerability, 69% of 132 ETP chondrichthyan species were ranked with *high* exposure to 'ocean warming' (Figures 2c and 4). Meanwhile, 'deoxygenation' and 'acidification' were also assessed as affecting a large number of species, with 64% of species ranked with *high* exposure to the former and 61% of species were ranked with *high* exposure to the latter. Only, 5% of species were ranked with *high* exposure to 'changes in productivity' and 95% with *moderate* exposure to this factor. For coastal species, both factors 'changes in freshwater inputs' and 'changes in salinity' had 61% species ranked with *high* exposure, while 59% were ranked with *high* exposure to 'sea level rise' (Figures 2c and 3; Table S6).

3.3 | Vulnerability of threatened ETP chondrichthyan to climate change

According to the IUCN Red List of Threatened Species (<https://www.iucnredlist.org/>), of the 132 ETP chondrichthyan species, 9%

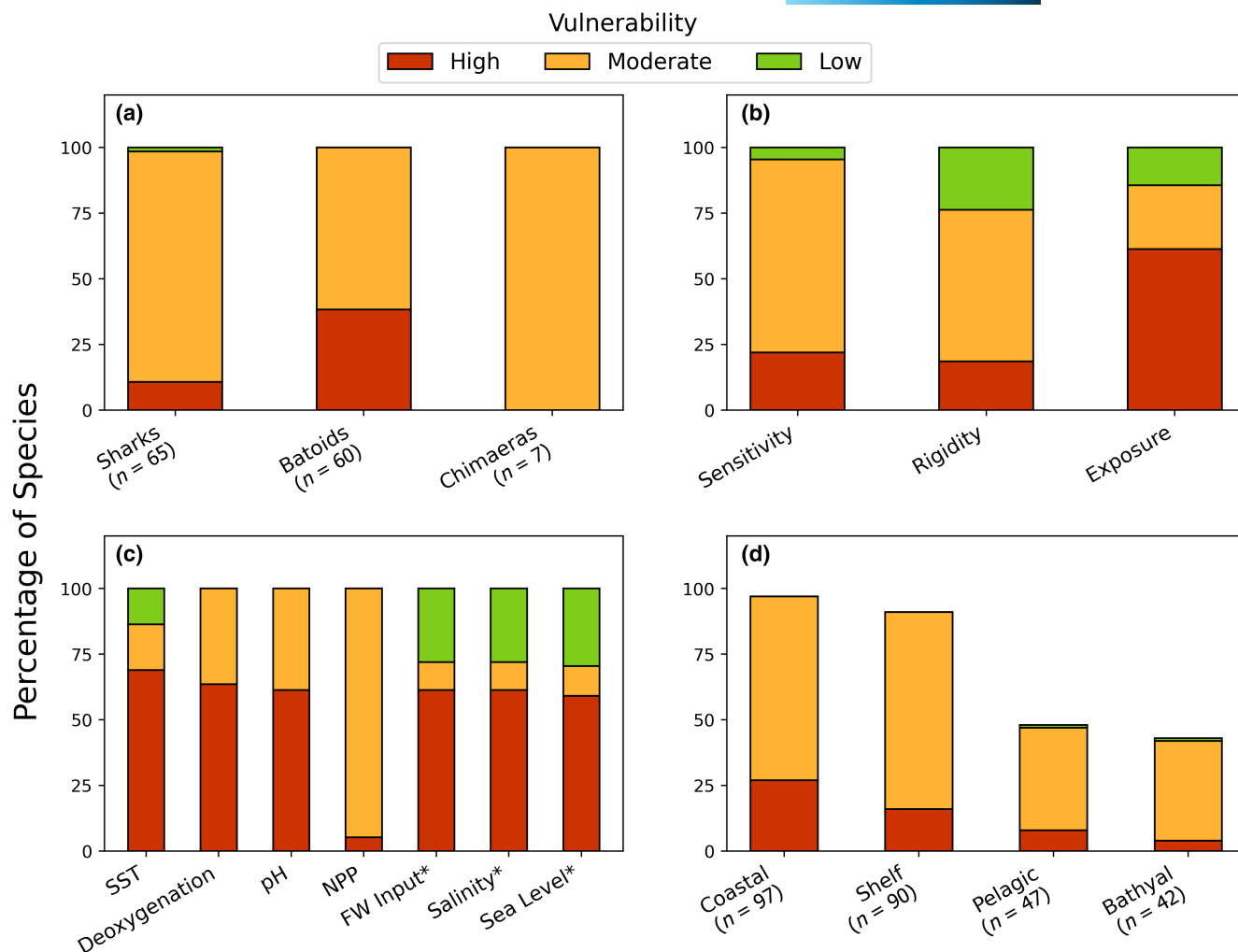


FIGURE 2 Proportion of sharks, batoids, and chimaeras by vulnerability (a), proportion of overall vulnerability by component (b), by climate change factor (c) (*only assessed for coastal ecological group, NPP, Net primary productivity, FW, Freshwater; SST, Sea surface temperature), and by ecological group (d).

are listed as Critically Endangered (CR), 11% as Endangered (EN), 27% as Vulnerable (VU), 14% as Near Threatened (NT), 32% as Least Concern (LC), and 7% as Data Deficient (DD) (Figure S1; Table S5).

From those ETP chondrichthyan species listed as CR and EN ($n=27$), 26% (five batoids, two sharks) had an overall *high* vulnerability to climate change, while 74% (six batoids, 14 sharks) had an overall *moderate* vulnerability. From those 36 ETP chondrichthyan species listed as VU, 27% (six batoids, four sharks) had an overall *high* vulnerability to climate change, while 69% (12 batoids, 12 sharks, one chimaeras) had *moderate* vulnerability, and 2.7% (one shark) had *low* vulnerability.

From 18 ETP chondrichthyan species listed as NT, 28% (five batoids) had an overall *high* vulnerability to climate change, while 72% (seven batoids, four sharks, and two chimaeras) had *moderate* vulnerability. From 42 ETP chondrichthyan species listed as LC, 14% (five batoids, one shark) had an overall *high* vulnerability to climate change, while 86% (nine batoids, 23 sharks, and four chimaeras) had *moderate* vulnerability.

Finally, of the nine ETP chondrichthyan species listed as DD, 22% (two batoids) had an overall *high* vulnerability and 78% (three batoids and four sharks) had *moderate* vulnerability to climate change (Table S5; Figure S1).

4 | DISCUSSION

This integrated risk assessment provides an important reference point for the vulnerability of 132 chondrichthyans in the ETP to climate change based on current understanding of each species' attributes, the projected changes in the ETP to the end of the 21st century, and the exposure of each species. Overall, our results indicate that 23% of ETP chondrichthyan species exhibit *high* vulnerability and 76% exhibit *moderate* vulnerability to climate change. Importantly, we found that 77% of ETP chondrichthyans exhibiting *high* vulnerability to climate change are batoids. Understanding the extent to which climate change can affect a species and the factors

TABLE 3 Eastern Tropical Pacific chondrichthyan species most vulnerable to climate change (have *high* overall vulnerability).

Ecological group(s)	Family	Species name	Common name	IUCN
Coastal	Aetobatidae	<i>Aetomylaeus (Pteromylaeus) asperrimus</i>	Roughskin bull ray	DD
Coastal	Narcinidae	<i>Diplobatis ommata</i>	Pacific dwarf numbfish	LC
Coastal	Narcinidae	<i>Narcine leoparda</i>	Leopard numbfish	VU
Coastal	Pristidae	<i>Pristis pristis</i>	Large-tooth sawfish	CR
Coastal	Potamotrygonidae	<i>Styracura pacifica</i>	Pacific chupare	VU
Coastal	Urotrygonidae	<i>Urobatis tumbesensis</i>	Tumbes round stingray	LC
Coastal	Urotrygonidae	<i>Urotrygon nana</i>	Dwarf round ray	CR
Coastal	Urotrygonidae	<i>Urotrygon reticulata</i>	Reticulate round ray	NT
Coastal	Urotrygonidae	<i>Urotrygon rogersi</i>	Roger's round ray	VU
Coastal	Urotrygonidae	<i>Urotrygon simulatrix</i>	Fake round ray	DD
Coastal, Shelf	Rajidae	<i>Beringraja (Raja) cortezensis</i>	Cortez skate	NT
Coastal, Shelf	Carcharhinidae	<i>Carcharhinus porosus (cerdale)</i>	Smalltail shark	EN
Coastal, Shelf	Pentanchidae	<i>Cephaloscyllium ventriosum</i>	Swell shark	DD
Coastal, Shelf	Narcinidae	<i>Narcine vermiculata (vermiculatus)</i>	Vermiculate numbfish	LC
Coastal, Shelf	Rhinobatidae	<i>Pseudobatos prahli</i>	Gorgona guitarfish	NT
Coastal, Shelf	Arhynchobatidae	<i>Sympterygia brevicaudata</i>	Shorttail fanskate	NT
Coastal, Shelf	Carcharhinidae	<i>Triaenodon obesus</i>	Whitetip reef shark	EN
Coastal, Shelf	Urotrygonidae	<i>Urobatis pardalis</i>	Leopard round ray	NT
Coastal, Shelf	Urotrygonidae	<i>Urotrygon cimar</i>	Cimar round ray	NT
Coastal, Pelagic	Alopiidae	<i>Alopias vulpinus</i>	Common thresher shark	VU
Coastal, Shelf, Pelagic	Carcharhinidae	<i>Carcharhinus albimarginatus</i>	Silvertip shark	VU
Coastal, Shelf, Pelagic	Dasyatidae	<i>Hypanus (Dasyatis) longus (longa)</i>	Longtail stingray	VU
Coastal, Shelf, Pelagic	Mobulidae	<i>Mobula birostris</i>	Giant manta	EN
Coastal, Shelf, Pelagic	Mobulidae	<i>Mobula tarapacana</i>	Sicklefin devil ray	EN
Coastal, Shelf, Pelagic	Mobulidae	<i>Mobula thurstoni</i>	Bentfin mobula	EN
Coastal, Shelf, Pelagic	Sphyrnidae	<i>Sphyrna mokarran</i>	Great hammerhead shark	CR
Coastal, Shelf, Pelagic, Bathyal	Lamnidae	<i>Carcharodon carcharias</i>	White shark	VU
Bathyal	Rajidae	<i>Dipturus ecuadoriensis</i>	Ecuador skate	DD
Bathyal	Arhynchobatidae	<i>Notoraja martinezi</i>	Barbedwire-tailed skate	LC
Bathyal	Rajidae	<i>Rajella eisenhardti</i>	Galapagos skate	LC

underpinning its vulnerability is essential for designing adaptive management strategies.

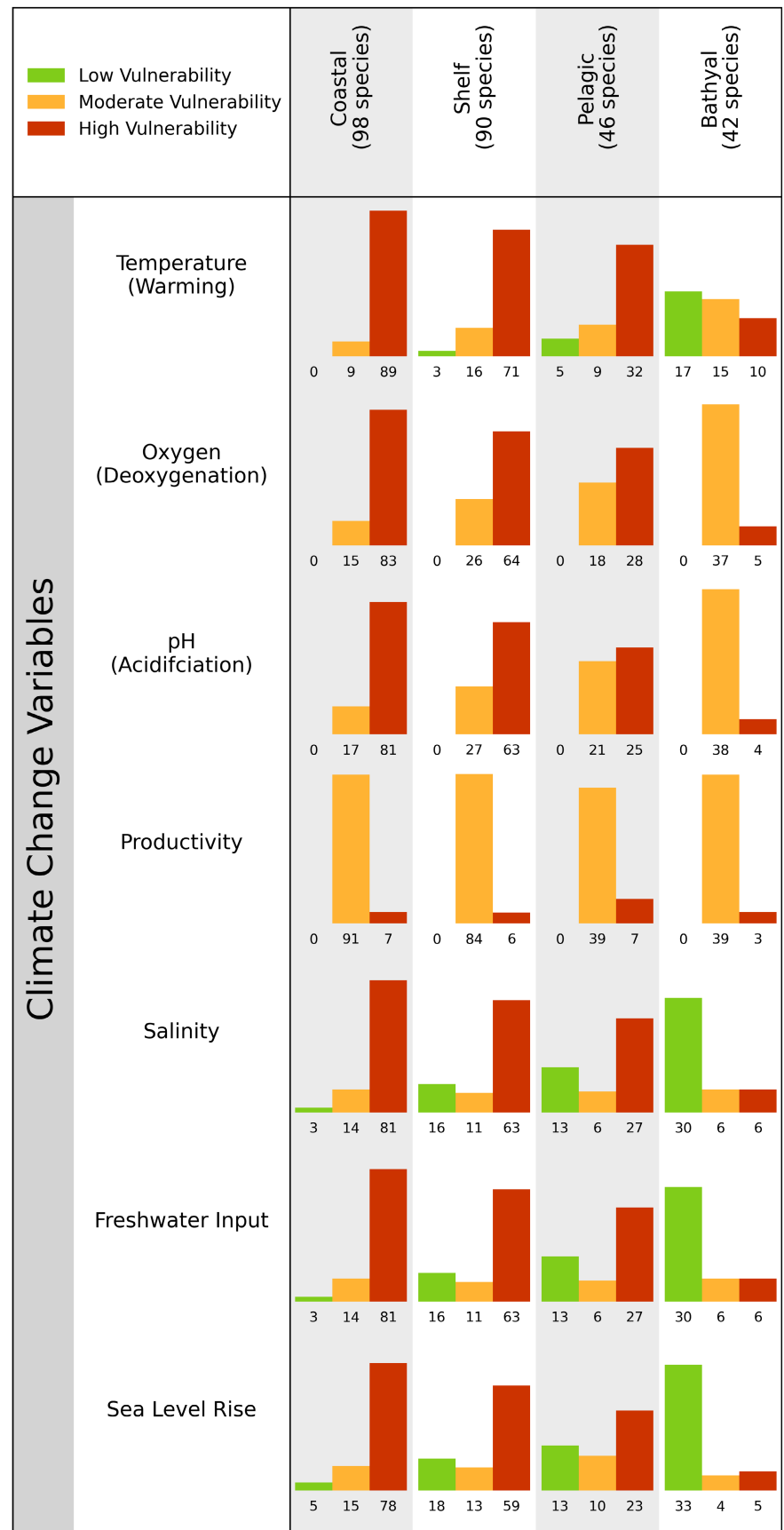
4.1 | Climate change factors affecting ETP chondrichthyans

A large fraction (>60%) of ETP chondrichthyans were rated with *high* exposure to climate change impacts. As described in the results, this reflects the widespread imprint of several climate change factors (ocean warming, acidification, and changing oxygen levels), and the large number of coastal species that are exposed to additional potential stressors from salinity and sea level changes. It should be recognized, however, that the climate change factors used in this assessment differ in consensus on their projected changes and in the degree to which their impacts on chondrichthyans are understood (Table S1). The precautionary approach and resulting vulnerabilities

derived herein did not attempt to deconstruct these differences, but we discuss them here.

Among the climate factors used for this assessment, ocean warming is distinguished by the high degree of certainty in its projected changes (Table S1), its biological effects that are relatively well understood, and its widespread imprint on the ETP. Projections of ocean warming in the ETP (Table S1) under a high emissions Representative Concentration Pathways (RCP) 8.5 scenario (IPCC, 2018) predict increases in the upper ocean (0–200m) ocean temperatures of up to 3.6°C by 2100, with lesser but still significant trends at depth (200–600 and >600m). While species' responses may vary, they frequently include shifts in their distributional range likely related to temperature changes affecting physiology and prey distribution (Chin et al., 2010; Hammerschlag et al., 2022). Such shifts have been reported for large wide-ranging chondrichthyans such as white sharks (*Carcharodon carcharias*) (Tanaka et al., 2021) and tiger sharks (*Galeocerdo cuvier*) (Birkmanis et al., 2020; Hammerschlag et al., 2022). Importantly, while

FIGURE 3 Vulnerability of Eastern Tropical Pacific chondrichthyan ecological groups to climate change factors (number of species on the x-axis).



some endothermic species like the white shark are able to regulate their internal body temperature and can accommodate a wide range of temperatures, changes beyond an optimal temperature range can

compromise muscular, cardiac, and neural functions for other species (Nasby-Lucas et al., 2009; Ripley et al., 2021; Wheeler et al., 2020). Moreover, ocean warming may be making equatorial waters less

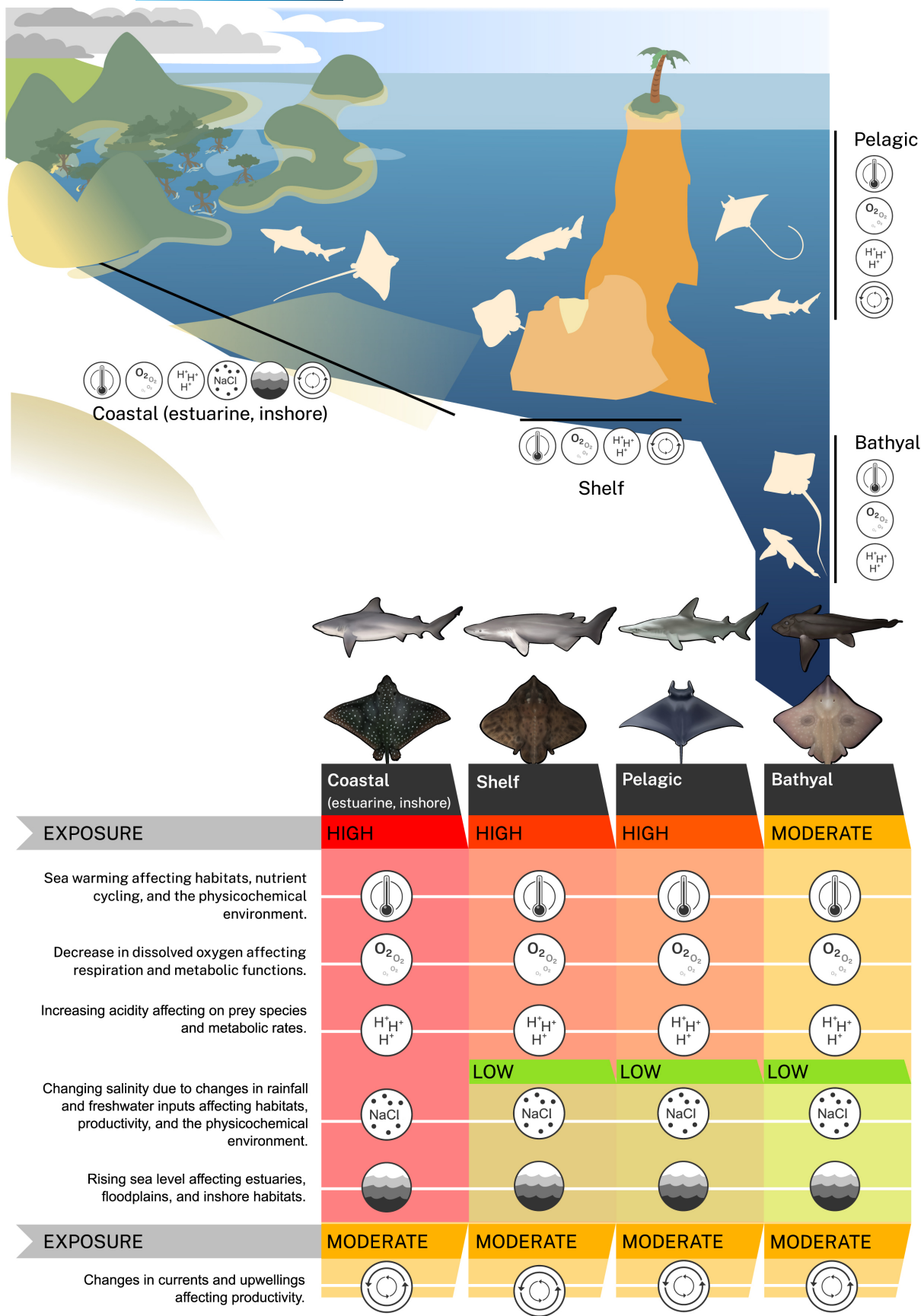


FIGURE 4 Exposure of Eastern Tropical Pacific chondrichthyans ecological groups to climate change factors.

suitable even for tropical and subtropical marine species already adapted to the relatively warm temperatures (Dale et al., 2022). Distribution shifts may be possible only for those species or life stages with high mobility, while species with limited mobility or those that rely on specific habitats may be more greatly impacted (Bangley et al., 2018). In the particular case of juvenile sharks and batoids restricted to coastal nursery habitats, changes in behavior to adapt to different conditions may reduce fitness, affecting the adult population viability for those species (Bouyoucos et al., 2022; Lear et al., 2019).

Similar to ocean temperature, there is broad agreement across ESMs also on ocean acidification trends (OA) over the next century and its impact on the ETP will be widespread in upper ocean layers. While the effects of OA on chondrichthyans are still poorly understood (Carrier et al., 2022), studies suggest impacts on the duration of embryonic development, hatching success, hunting behavior, food consumption, growth rates, locomotion, swimming activity, skeletal and denticle demineralization, and long-term survival (Carrier et al., 2022; Di Santo, 2015; Pistevos et al., 2015; Rosa et al., 2017; Vilmar & Di Santo, 2022; Wheeler et al., 2020). Additionally, such impacts can result in cascading effects on other species through different predator-prey relationships (Heithaus, 2001) as OA can also have impacts on critical habitats and food sources that rely on calcification such as coral reefs or shell-forming invertebrates (Hoegh-Guldberg et al., 2017; Hofmann et al., 2010). It is important to highlight that all studies on the effects of OA on chondrichthyan species to date are on benthic pump-breathing sharks and a small number of batoids (Rosa et al., 2017). Thus, there is a considerable lack of knowledge to predict the effects of OA or deoxygenation on ram-ventilating sharks, pelagic batoids, chimaeras, and deep-water species.

Dissolved oxygen differs from acidification because its impact on chondrichthyan physiology and habitats are relatively clear, although consensus on changes in future dissolved oxygen is limited. The ETP has the largest oxygen minimum zone (OMZ) in the world with prevalent hypoxia and anoxia conditions at near-surface and mid-water depths. This limits the vertical extent of pelagic species, thereby reducing the availability of suitable habitat (Abascal et al., 2011; Gilkinson et al., 2007; Vedor et al., 2021) which can considerably increase their exposure to surface fisheries (Prince & Goodyear, 2006; Vedor et al., 2021). Hypoxia, especially in combination with ocean warming and/or OA, can influence respiratory rates and ventilator repression, reduce activity and metabolic rates, and limit the vertical extent of migrations (Carrier et al., 2022; Prince & Goodyear, 2006; Sampaio et al., 2021; Vedor et al., 2021). Despite uncertainties about OMZ expansions, the prevalence of hypoxic and anoxic conditions in the ETP and observational evidence of climate-driven dissolved oxygen changes underlies high exposure, particularly for those species relying on mid-water below the well-oxygenated surface layer. While deoxygenation seems to be the most overlooked factor in chondrichthyan physiology studies, particularly within a climate change context, negative physiological responses to deoxygenation are expected for all aerobic biota (Sampaio et al., 2021).

The combination of ocean warming, acidification, and deoxygenation are known to have compounding effects on species and ecosystems, thus it is becoming urgent to understand how marine organisms will respond to these drivers (Carrier et al., 2022; Di Santo, 2016). The potential of ETP chondrichthyans to survive local population-level extinctions resulting from these combined stressors may depend on their capacity to change their physiological responses and acclimatize at a similar timescale to the changes on these major environmental stressors (Carrier et al., 2022; Di Santo, 2016).

Unlike most risk assessments, we have included changes in primary productivity in our analysis. While the literature suggests that low latitude areas such as the ETP may experience a decline in productivity with ongoing climate change (Doney, 2006), considerable disagreement between model projections remain (Bopp et al., 2013; Kwiatkowski et al., 2020) and the mechanisms and relationships driving these projections have been left unresolved by many ESMs. Importantly, while primary production provides the foundation for marine foodwebs, the relationship between primary production and higher trophic level productivity can be complex (Friedland et al., 2012; Stock et al., 2017). However, projections of climate change impact on fisheries suggest that primary productivity changes may be amplified at higher trophic levels (Lotze et al., 2019). In this assessment, limited consensus on the directionality and magnitude of the expected changes led to *moderate* exposure ratings for all but the most plankton-dependent species. Further research is required to better understand primary productivity changes (e.g., Kwiatkowski et al., 2020) and to comprehend the sensitivity of chondrichthyans' trophic dynamic.

Finally, the exposure of coastal environments to changes in sea level and freshwater inputs/salinity, were a primary factor contributing to the overall *high* vulnerability of coastal species. While there is considerable uncertainty surrounding the magnitude of sea level rise, particularly associated with ice sheet responses, increases in global mean sea level are projected over multiple RCPs and time horizons, with end-of-21st century RCP8.5 projections ranging from 0.61–1.10m at medium confidence level (Oppenheimer et al., 2019). Freshwater changes generally reflect robust patterns of increased precipitation near the equator and decreases in subtropical zones (i.e., the wet get wetter and the dry get drier, Feng & Zhang, 2015). As it will be discussed in the next section, the potential impacts of these changes on coastal species and those that use coastal and estuarine areas as nurseries are numerous, though not well understood.

4.2 | Vulnerability of ecological groups to climate change

4.2.1 | Coastal species at high risk

This assessment found that the majority of *highly* vulnerability chondrichthyans were coastal species (Figure 2d). As discussed above, these species have high exposure to large and broad changes such as ocean warming, deoxygenation, and acidification, in addition to

coastal-related factors such as sea level rise and changes in salinity. In particular, shallow coastal habitats are expected to be frequently exposed to extreme events (e.g., hurricanes), which will further increase the thermal stress in these environments (Cabral et al., 2019). The ETP coastline topology of habitats includes mangroves, which function as nurseries for many species of chondrichthyans (Llerena et al., 2015; López-Angarita, Villate-Moreno, et al., 2021; Zanella et al., 2019). However, mangroves are expected to be greatly impacted by climate change-related physical processes in the future due to projections of high incidence of tropical storms, areas of high relative sea level rise, and increases in precipitation (Cabral et al., 2019; Ward et al., 2016).

Panama and Colombia have some of the highest rates of annual rainfall in the world, maintaining many river deltas and estuaries with low salinities (Fiedler & Talley, 2006; López-Angarita, Cubillos-M, et al., 2021), yet Central America is one of the regions where climate change models consistently predict increases in temperature and decreases in precipitation during the wet season (Ward et al., 2016). These changes will alter estuaries and lagoons, with some potentially becoming incorporated into the sea. If coastal development allows it, the emergence of new estuarine zones will appear upstream, with different salinity as freshwater inputs change with increases in upstream rainfall (Martínez-Arroyo et al., 2011). Within the coastal ecological group, there are a few species that may tolerate various levels of salinity (e.g., *C. leucas*) (Martin, 2005). While elasmobranchs' euryhalinity is not yet well understood, studies suggest that this group may have larger tolerance than thought (Wosnick & Freire, 2013), which may confer a level of adaptability when freshwater inputs change.

Importantly, 66% of ETP chondrichthyans use coastal nurseries, and 23% of these species were also found to have *high* vulnerability to climate change. Thus, identifying and protecting key coastal habitats would be critical to inform habitat-focused actions. Moreover, improving our understanding of how reliant ETP chondrichthyans may be to threatened mangrove, coastal, and estuarine habitats during their early-life development would also help to maintain species' resilience to climate change impacts.

4.2.2 | Shelf and pelagic ecological groups

Pelagic and shelf ETP chondrichthyans had an overall *moderate* vulnerability to climate change although many species rely on coastal nursery areas, which increased their vulnerability ranking. In addition to exposure to ocean warming, acidification, and potential oxygen changes, shelf and pelagic ETP chondrichthyans are likely to be affected by changing currents that alter upwelling patterns and nutrient cycling (Fernández-Álamo & Färber-Lorda, 2006). However, some species of pelagic and migratory chondrichthyans may be able to move across different gradients of temperature, dissolved oxygen, and pH and accommodate changing conditions, which led to a *lower* Rigidity ranking (higher adaptability) and an overall *lower* vulnerability.

We note that a number of pelagic sharks that were rated with *moderate* vulnerability in this study were ranked with *low* vulnerability in another recent study in adjacent waters (e.g., McClure et al., 2023). This difference reflects the nature of vulnerability assessments as McClure et al. considered a range of fish groups that includes some extremely long-lived anadromous and rare rockfish species. Pelagic sharks may seem less vulnerable, when viewed relative to this wider range of species. It is important to highlight that the aim of the current study was to assess the vulnerability within the group of chondrichthyans in the ETP. Additionally, the consideration of potentially consequential changes in primary productivity elevated the vulnerability of pelagic species from *low* to *moderate* levels.

Many shelf and pelagic chondrichthyans forage in nutrient-rich oceanic upwelling areas, which may shift location, changes in its strength, or become less predictable (Ryckaczewski et al., 2015; Sydeman et al., 2014). Phytoplankton abundance and biogeochemical patterns, including hypoxia, can result in large-scale shifts in their distribution (Hays et al., 2005), affecting the distribution, abundance, and seasonality of plankton (Robinson et al., 2009). Planktivorous ETP chondrichthyans (devil rays, whale and basking sharks) could face major challenges if changes in wind and ocean currents that alter the frontal zones and upwellings and create high-density patches in tropical waters (Cabral et al., 2023; Fernández-Álamo & Färber-Lorda, 2006; Lezama-Ochoa et al., 2019). Furthermore, the ENSO phenomenon, can alter upwelling events and their seasonality, affecting reef fish composition and ecosystem function (Eisele et al., 2021; Skubel et al., 2018; White et al., 2019).

4.2.3 | Bathyal ecological group

In this assessment, only 13 species were present exclusively in the Bathyal ecological group (four sharks, seven rays, and two chimaerids) and it had an overall *moderate* vulnerability to climate change. Only four species had *high* vulnerability to climate change likely because the depth of bathyal habitats provide partial refuge from some climate change signals (e.g., attenuated warming and acidification). While the projected changes in sea temperature, dissolved oxygen, and pH at >500m depth in this study were minor relative to changes in shallower waters, three bathyal endemic skates (*Dipturus ecuadoriensis*, *Notoraja martinezi*, *Rajella eisenhardti*) that are known to occur in specific locations within the ETP had an overall *high* vulnerability to climate change. A *high* ranking in *sensitivity* and *rigidity*, suggests that these species may be most sensitive to even minimal habitat changes.

Recent advances in technology for marine exploration have increased our knowledge of deep-sea chondrichthyans in the ETP (Buglass et al., 2020; Cerutti-Pereyra et al., 2018; Friedlander et al., 2019), although there is an important lack of data for most deep-sea chondrichthyans (Finucci et al., 2021), which limits our understanding of climate change impacts on such species and ecosystems. Additionally, the impacts of climate change on the

deep ocean have received little attention compared to coastal and pelagic ecosystems (Brito-Morales et al., 2020). Despite a lower vulnerability found for bathyal species compared to coastal species in this study, climate change is expected to change species ranges, decrease food availability, and reduce biodiversity (Doi et al., 2021; Levin et al., 2020), and projected rate of climate warming in the deep sea may exceed the rate at which deep-sea species are able to adapt to (Brito-Morales et al., 2020; Levin & Bris, 2015). Importantly, the deep sea and shallower ocean layers are connected through vertical movement of nutrients, and it is suspected that warming surface waters, increasing thermal stratification, and subsequent reduction of nutrient supply will reduce deep-sea productivity (Sweetman et al., 2017). Some bathyal regions of the world, such as the ETP, are predicted to face a 55% reduction of productivity by 2100, while the OMZ expansion in parts of the ETP is projected to exceed physiological limits of many species leading to reduced biodiversity resulting in a cascade of effects at depths over 500 m (Sweetman et al., 2017). Deep-sea chondrichthyans cannot be ignored given their limited ability to recover from overexploitation as they are highly sensitive to fishing pressure (Georgeson et al., 2020; Simpfendorfer & Kyne, 2009) and climate change may further increase their susceptibility to human-induced pressure.

4.3 | Special cases

4.3.1 | Batoids—endangered and understudied

This assessment found that 73% of ETP chondrichthyan species with *high* vulnerability to climate change were batoids, although a considerable knowledge gap still exists for this subgroup, which hampers management and conservation efforts. Importantly, six batoids species that had all three components ranked as *high* are rare within the ETP, mostly coastal, and have a high dependency on specific habitats. Specialization alongside rarity is a combination considered to increase extinction risk and vulnerability to climate change, thus species that are ecologically dependent on specific habitats are more susceptible than those that can use different habitat types (Chin et al., 2010; Davies et al., 2004).

Five batoids with *high* overall vulnerability to climate change are also considered EN or CR by the IUCN Red List (*Pristis pristis* (CR), *Urotrygon reticulata* (CR), *Mobula birostris* (EN), *M. tarapacana* (EN), and *M. thurstoni* (EN); Table 3). The higher numbers of batoids with *high* vulnerability to climate change found in this study highlights a critical need to include this group in management efforts throughout the region while also stressing the lack of information. Importantly, many batoid species sustain fisheries (Croll et al., 2016; Cuevas-Zimbrón et al., 2011; Dulvy et al., 2000; Kyne et al., 2020; Tamini et al., 2006) and some species have replaced sharks in coastal fisheries where sharks or other resources have been depleted (Bizzarro et al., 2009; Feitosa et al., 2021). While some batoids such as mantas, sawfishes, wedgefishes, and guitarfishes have been included in

international treaties to reduce their overexploitation, many other batoids species are also vulnerable to overexploitation and climate change and require management and conservation planning that integrates such vulnerability.

4.3.2 | Highly migratory and iconic species

The ETP is home to several highly migratory chondrichthyan species that are also iconic for marine tourism in the ETP (Eckert & Stewart, 2001; Ketchum et al., 2014; Lara-Lizardi et al., 2020). Three out of five species of devil rays (*Mobula birostris*, *M. tarapacana*, *M. thurstoni*) and one out of six species of hammerhead sharks (*Sphyrna mokarran*) occurring in the ETP were found to have *high* vulnerability to climate change in this assessment, while whale sharks (*Rhincodon typus*) had a *moderate* vulnerability.

While the capacity of migratory species to move across gradients of environmental cues may confer adaptability and potentially enable them to adjust to new conditions, highly migratory species have complex migration patterns and depend on the availability of suitable habitat in many locations. The *high* vulnerability of highly migratory species to climate change found in this study highlights the many threats that these species face as they encounter multiple pressures throughout their range, leading to cumulative and synergistic impacts over their lifespan (Robinson et al., 2009). Additionally, changes in frequency, abundance, route, or timing of migrations and aggregations of these species may have substantial economic consequences for the marine-based tourism they sustain in the ETP and the efficacy of marine protected areas.

4.4 | Caution due to uncertainty and low confidence

Of the 132 ETP chondrichthyan species assessed, 12% ($n=16$) had low confidence because $\geq 50\%$ of the information used for the assessment was sourced from a sister species, thus, the assessments of those 16 species should be considered as preliminary. Notably, half of those 16 species were batoids, all species with the combination of *high* vulnerability and low confidence were also batoids, and 62% of species with low confidence were bathyal species (Table S5). These results suggest an important lack of information about batoids and bathyal chondrichthyans in the ETP (Chin et al., 2010; Finucci et al., 2021).

The assessment framework used in this study accommodates a range of data types and various levels of uncertainty (Chin et al., 2010; Georgeson et al., 2020; Hare et al., 2016). The framework's logic structure is fundamentally precautionary as all three components for all climate change factors are unlikely to be ranked as *high*. While there should be caution in using the assessment for those 16 species with low confidence, it integrates the best available information in a systematic process with experts' judgment, thus representing an important first step in examining climate change risks to these relatively data-poor species.

4.5 | Synergies with other anthropogenic pressures

Understanding the cumulative effects of climate change in combination with other stressors affecting chondrichthyans and their ecosystems is crucial for adaptive management. Human impacts are higher in coastal zones than offshore areas, with fishing, climate change, habitat destruction, and pollution being identified as the most significant pressures (Cabral et al., 2019). Overfishing, however, is the most pervasive threat to chondrichthyans globally, placing this group as one of the most threatened marine groups due to over-exploitation (Dulvy et al., 2014, 2021; Field et al., 2010; Pacoureau et al., 2021). Pelagic species such as silky sharks (*C. falciformis*) and devil rays (Mobulidae) already experienced a considerable reduction in abundance in the ETP (Croll et al., 2016; Villate-Moreno et al., 2022). Climate change projections indicate decreases in suitable habitat for species caught in pelagic fisheries in the ETP, the movement of invasive species from tropical to temperate waters, and an increase in local losses in abundance along the ETP platform due to climate change (Clarke et al., 2021). Areas identified as having more at-risk species to climate change tend to be located in tropical and subtropical oceans, and the combination of climate change and fishing pressure will potentially result in high conservation risk for exploited chondrichthyans targeted in the region (Cheung et al., 2018; Vedor et al., 2021).

Human activities on land have also affected coastal habitats through urbanization, agriculture, and aquaculture. Second to overfishing, severe coastal and estuarine habitat loss and degradation, alongside land-based sources of pollution, have been highlighted as a significant global threat faced by sharks and rays (Dulvy et al., 2014, 2021; Jorgensen et al., 2022). The cumulative effects of exploitation, pollution, and habitat degradation can exacerbate a species' vulnerability to climate change, particularly in estuarine ecosystems that are disproportionately affected by coastal development (Pratchett et al., 2011). In extreme cases, some endemic, threatened, or rare chondrichthyan species may be eliminated from the ETP if they are unable to adapt to the cumulative effects of coastal fisheries, habitat degradation, and climate change.

5 | CONCLUSIONS AND RECOMMENDATIONS

This risk assessment provided a systematic evaluation of the vulnerability of 132 chondrichthyans to climate change in the ETP and showed that coastal chondrichthyans in the ETP are at highest risk to climate change. By understanding species' vulnerabilities and synergies with other risk factors, research and management can be focused on species and areas that are most vulnerable to multiple stressors.

The information produced in this assessment can be used by managers to inform fishery and spatial management plans, guide the inclusion of climate variables in species and ecosystem models, and

identify species-specific research and management needs. Reducing the impacts of climate change will require a variety of spatially- and non-spatially fixed approaches. For example, coastal habitats that sustain species and species groups at high risk must be protected to maximize their resilience. In the ETP, this means prioritizing protecting mangroves, estuaries, catchments, and intertidal areas from common threats such as coastal urbanization, disruption of water flow, eutrophication, and pollution. Research to resolve the considerable uncertainties surrounding the tolerance of chondrichthyans to climate change is critical for such measures to be effective. Additional pressures, such as fishing, must also be addressed to minimize threats and alterations in species distributions and seasonal cycles resulting from climate change that can lead to changing reference points for management, which can in turn influence management planning. Unfortunately, the understanding of climate change impacts on fisheries management and coastal planning in the ETP is still lacking, as well as policies that support responses or opportunities to finance climate change mitigation measures. To ensure long-term sustainability of chondrichthyans in the ETP, it is crucial to identify and include important stressors into management. High-risk species should be considered for specific conservation actions, and both fisheries management plans and risk assessments should focus on such species to assess sustainability and guide management.

Ocean warming should be included in regional scientific advice and management. For example, thermal performance regimes (Lear et al., 2019) can be used to predict potential changes in migration patterns and predict the temperatures that may trigger shifts in behavioral patterns in species associated with specific habitats (e.g., nurseries). Using climate models to project key species' habitats and mapping their movements into the future could also help understanding the extent of shift ranges (Diaz-Carballido et al., 2022) and interactions with fisheries fleets to inform management policies (Dale et al., 2022).

This assessment also highlights the need for further research to understand those species highly vulnerable to climate change and research should focus on filling in knowledge gaps that can directly guide management. The links between population dynamics and habitat preservation and restoration should be further investigated as preserving these key habitats in the ETP that will contribute to protecting already threatened chondrichthyans species. An international commitment to long-term support for regional monitoring and research programs is crucial to identify areas where action is required and to monitor the effectiveness of management actions. Lastly, reducing anthropogenic climate driving and minimizing greenhouse emissions through internationally co-ordinated and basin-wide strategies in particular key habitats and along migratory corridors will prove beneficial for reducing the vulnerability of chondrichthyans species in the ETP.

AUTHOR CONTRIBUTIONS

Florencia Cerutti-Pereyra: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; supervision; validation; visualization; writing – original draft; writing – review

and editing. **Elizabeth J. Drenkard**: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing – review and editing. **Mario Espinoza**: Data curation; investigation; supervision; validation; writing – review and editing. **Brittany Finucci**: Data curation; investigation; validation; writing – review and editing. **Felipe Galván-Magaña**: Data curation; investigation; validation. **Ana Hacothen-Domené**: Data curation; investigation; validation; writing – review and editing. **Alexander Hearn**: Data curation; investigation; validation; writing – review and editing. **Mauricio E. Hoyos-Padilla**: Validation; writing – review and editing. **James T. Ketchum**: Data curation; investigation; validation; writing – review and editing. **Paola A. Mejía-Falla**: Data curation; investigation; methodology; validation; writing – review and editing. **Ana V. Moya-Serrano**: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; writing – review and editing. **Andres F. Navia**: Data curation; investigation; methodology; validation; writing – review and editing. **Diana A. Pazmiño**: Data curation; investigation; validation; writing – review and editing. **Deni Ramírez-Macías**: Data curation; investigation; validation; writing – review and editing. **Jodie L. Rummer**: Data curation; formal analysis; investigation; methodology; validation; writing – review and editing. **Pelayo Salinas-de-León**: Funding acquisition; investigation; validation; writing – review and editing. **Oscar Sosa-Nishizaki**: Data curation; investigation; methodology; validation; writing – review and editing. **Charles Stock**: Conceptualization; formal analysis; investigation; methodology; supervision; validation; writing – original draft; writing – review and editing. **Andrew Chin**: Conceptualization; formal analysis; funding acquisition; investigation; methodology; supervision; validation; writing – original draft; writing – review and editing.

AFFILIATIONS

¹Charles Darwin Foundation, Galápagos, Ecuador

²NOAA/OAR/GFDL, Princeton, New Jersey, USA

³Centro de Investigación en Ciencias del Mar y Limnología, Universidad de Costa Rica, San José, Costa Rica

⁴MigraMar, Olema, California, USA

⁵National Institute of Water and Atmospheric Research, Wellington, New Zealand

⁶Instituto Politécnico Nacional-Centro Interdisciplinario de Ciencias Marinas, La Paz, Baja California Sur, Mexico

⁷Universidad del Valle de Guatemala, Guatemala City, Guatemala

⁸Universidad San Francisco de Quito, Galápagos, Ecuador

⁹Pelagios-Kakunja A.C., La Paz, Baja California Sur, Mexico

¹⁰Wildlife Conservation Society–WCS Colombia, Cali, Colombia

¹¹Fundación colombiana para la investigación y conservación de tiburones y rayas-SQUALUS, Cali, Colombia

¹²Conexiones Terramar A.C. Whale Shark Mexico, La Paz, Baja California Sur, Mexico

¹³James Cook University, Townsville, Queensland, Australia

¹⁴Save Our Seas Foundation Shark Research Center and Guy Harvey Research Institute, Nova Southeastern University, Dania Beach, Florida, USA

¹⁵Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, Carretera Ensenada-Tijuana, Ensenada, Baja California, Mexico

ACKNOWLEDGEMENTS

We thank the Charles Darwin Foundation and the Galapagos National Park Directorate (GNPD) for their institutional support.

We are grateful to the United States Agency for International Development (USAID), the Mark and Rachel Rohr Foundation, the Save Our Seas Foundation, and the Instituto Politécnico Nacional (COFAA and EDI) for the fellowships and funding. Thank you very much also to Erin Welsh from Australian National University for preparing the infographic shown in [Figure 4](#), as well as Barbara Mulling and Vincent Saba for their comments and suggestions provided through NOAA's GFDL internal science review process. We are most grateful to the reviewers and the editor for their insightful and constructive comments on the manuscript's early drafts. This publication is contribution number 2626 of the Charles Darwin Foundation for the Galapagos Islands.

CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.11218757> and <https://doi.org/10.5281/zenodo.11278035>.

ORCID

Florencia Cerutti-Pereyra  <https://orcid.org/0000-0001-9471-516X>

<https://orcid.org/0000-0001-9471-516X>

Elizabeth J. Drenkard  <https://orcid.org/0000-0002-3817-5717>

Mario Espinoza  <https://orcid.org/0000-0001-7997-311X>

Brittany Finucci  <https://orcid.org/0000-0003-1315-2946>

Felipe Galván-Magaña  <https://orcid.org/0000-0002-7613-4617>

Ana Hacothen-Domené  <https://orcid.org/0000-0002-0155-3518>

Alexander Hearn  <https://orcid.org/0000-0002-4986-098X>

Mauricio E. Hoyos-Padilla  <https://orcid.org/0000-0002-4318-2655>

<https://orcid.org/0000-0002-4318-2655>

James T. Ketchum  <https://orcid.org/0000-0002-7340-4749>

Paola A. Mejía-Falla  <https://orcid.org/0000-0003-2220-6969>

Ana V. Moya-Serrano  <https://orcid.org/0000-0001-6929-2433>

Andres F. Navia  <https://orcid.org/0000-0002-6758-7729>

Diana A. Pazmiño  <https://orcid.org/0000-0001-7082-3254>

Deni Ramírez-Macías  <https://orcid.org/0000-0003-0293-9444>

Jodie L. Rummer  <https://orcid.org/0000-0001-6067-5892>

Pelayo Salinas-de-León  <https://orcid.org/0000-0001-9155-8373>

Oscar Sosa-Nishizaki  <https://orcid.org/0000-0002-3043-768X>

Charles Stock  <https://orcid.org/0000-0001-9549-8013>

Andrew Chin  <https://orcid.org/0000-0003-1813-4042>

REFERENCES

- Abascal, F. J., Quintans, M., Ramos-Cardelle, A., & Mejuto, J. (2011). Movements and environmental preferences of the shortfin mako, *Isurus oxyrinchus*, in the southeastern Pacific Ocean. *Marine Biology*, 158, 1175–1184. <https://doi.org/10.1007/s00227-011-1639-1>
- Asch, R. G., Pilcher, D. J., Rivero-Calle, S., & Holding, J. M. (2016). Demystifying models: Answers to ten common questions that ecologists have about earth system models. *Limnology and Oceanography Bulletin*, 25, 65–70. <https://doi.org/10.1002/lob.10113>

- Bangley, C. W., Paramore, L., Shiffman, D. S., & Rulifson, R. A. (2018). Increased abundance and nursery habitat use of the bull shark (*Carcharhinus leucas*) in response to a changing environment in a warm-temperate estuary. *Scientific Reports*, 8, 6018. <https://doi.org/10.1038/s41598-018-24510-z>
- Birkmanis, C. A., Freer, J. J., Simmons, L. W., Partridge, J. C., & Sequeira, A. M. M. (2020). Future distribution of suitable habitat for pelagic sharks in Australia under climate change models. *Frontiers in Marine Science*, 7, 1–11. <https://doi.org/10.3389/fmars.2020.00570>
- Bizzarro, J. J., Smith, W. D., Márquez-Farías, J. F., Tyminski, J., & Hueter, R. E. (2009). Temporal variation in the artisanal elasmobranch fishery of Sonora, Mexico. *Fisheries Research*, 97, 103–117. <https://doi.org/10.1016/j.fishres.2009.01.009>
- Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., & Vichi, M. (2013). Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences*, 10, 6225–6245. <https://doi.org/10.5194/bg-10-6225-2013>
- Bouyoucos, I., Simpfendorfer, C., Planes, S., Schwieterman, G. D., Weideli, O. C., & Rummer, J. L. (2022). Thermally insensitive physiological performance allows neonatal sharks to use coastal habitats as nursery areas. *Marine Ecology Progress Series*, 682, 137–152.
- Brito-Morales, I., Schoeman, D. S., Molinos, J. G., Burrows, M. T., Klein, C. J., Arafeh-Dalmau, N., Kaschner, K., Garilao, C., Kesner-Reyes, K., & Richardson, A. J. (2020). Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. *Nature Climate Change*, 10, 576–581. <https://doi.org/10.1038/s41558-020-0773-5>
- Buglass, S., Nagy, S., Ebert, D., Sepa, P., Turchik, A., Bell, K. L. C., Rivera, F., & Giddens, J. (2020). First records of the seven-gilled *Notorynchus cepedianus* and six-gilled *Hexanchus griseus* sharks (Chondrichthyes: Hexanchiformes: Hexanchidae) found in the Galápagos Marine Reserve. *Journal of Fish Biology*, 97, 926–929. <https://doi.org/10.1111/jfb.14447>
- Cabral, H., Fonseca, V., Sousa, T., & Leal, M. C. (2019). Synergistic effects of climate change and marine pollution: An overlooked interaction in coastal and estuarine areas. *International Journal of Environmental Research and Public Health*, 16, 1–17. <https://doi.org/10.3390/ijerph16152737>
- Cabral, M. M. P., Stewart, J. D., Marques, T. A., Ketchum, J. T., Ayala-Bocos, A., Hoyos-Padilla, E. M., & Reyes-Bonilla, H. (2023). The influence of El Niño Southern Oscillation on the population dynamics of oceanic manta rays in the Mexican Pacific. *Hydrobiologia*, 850, 257–267.
- Cailliet, G. M., Musick, J. A., Simpfendorfer, C. A., & Stevens, J. D. (2005). Ecology and life history characteristics of chondrichthyan fish. In S. L. Fowler, R. D. Cavanagh, M. Camhi, G. H. Burgess, G. M. Cailliet, S. V. Fordham, C. A. Simpfendorfer, & J. A. Musick (Eds.), *Sharks, rays and chimaeras: The status of the chondrichthyan fishes* (pp. 12–18). IUCN.
- Capotondi, A., Alexander, M. A., Bond, N. A., Curchitser, E. N., & Scott, J. D. (2012). Enhanced upper ocean stratification with climate change in the CMIP3 models. *Journal of Geophysical Research: Oceans*, 117, C04031. <https://doi.org/10.1029/2011JC007409>
- Carrier, J. C., Simpfendorfer, C. A., Heithaus, M. R., Yopak, K. E., Rummer, J. L., Bouyoucos, I. A., Wheeler, C. R., Santos, C. P., & Rosa, R. (2022). Climate change and sharks. In J. Carrier, C. Simpfendorfer, M. R. Heithaus, & K. E. Yopak (Eds.), *Biology of sharks and their relatives* (3rd ed., pp. 767–793). CRC Press.
- Castellanos-Galindo, G. A., Krumme, U., Rubio, E. A., & Saint-Paul, U. (2013). Spatial variability of mangrove fish assemblage composition in the tropical eastern Pacific Ocean. *Reviews in Fish Biology and Fisheries*, 23, 69–86. <https://doi.org/10.1007/s11160-012-9276-4>
- Cerutti-Pereyra, F., Denkard, E. J., Espinoza, M., Finucci, B., Galván-Magaña, F., Hacohe-Domené, A., Hearn, A., Hoyos-Padilla, M. E., Ketchum, J. T., Mejía-Falla, P. A., Moya-Serrano, A. V., Navia, A. F., Pazmiño, D. A., Ramírez-Macías, D., Rummer, J. L., Salinas-de-León, P., Sosa-Nishizaki, O., Stock, C., & Chin, A. (2024a). *Vulnerabilidad de condricios al cambio climático en la región del Pacífico Oriental Tropical*. Puerto Ayora, Galápagos, Ecuador. Reporte final. 136 pp.
- Cerutti-Pereyra, F., Denkard, E. J., Espinoza, M., Finucci, B., Galván-Magaña, F., Hacohe-Domené, A., Hearn, A., Hoyos-Padilla, M. E., Ketchum, J. T., Mejía-Falla, P. A., Moya-Serrano, A. V., Navia, A. F., Pazmiño, D. A., Ramírez-Macías, D., Rummer, J. L., Salinas-de-León, P., Sosa-Nishizaki, O., Stock, C., & Chin, A. (2024b). Dataset used to assess the vulnerability of chondrichthyan fishes of the Eastern Tropical Pacific to climate change openly available in Zenodo. <https://doi.org/10.5281/zenodo.11218757>
- Cerutti-Pereyra, F., Denkard, E. J., Espinoza, M., Finucci, B., Galván-Magaña, F., Hacohe-Domené, A., Hearn, A., Hoyos-Padilla, M. E., Ketchum, J. T., Mejía-Falla, P. A., Moya-Serrano, A. V., Navia, A. F., Pazmiño, D. A., Ramírez-Macías, D., Rummer, J. L., Salinas-de-León, P., Sosa-Nishizaki, O., Stock, C., & Chin, A. (2024c). Supplementary materials Tables 2–6: Ranking of each attribute and vulnerability of chondrichthyan fishes of the Eastern Tropical Pacific to climate change openly available in Zenodo. <https://doi.org/10.5281/zenodo.11278035>
- Cerutti-Pereyra, F., Moity, N., Dureuil, M., Ramírez-González, J., Reyes, H., Budd, K., Jarrín, M., & Salinas-de-León, P. (2019). Artisanal longline fishing the Galapagos Islands – effects on vulnerable megafauna in a UNESCO World Heritage site. *Ocean and Coastal Management*, 183, 104995. <https://doi.org/10.1016/j.ocecoaman.2019.104995>
- Cerutti-Pereyra, F., Salinas-De-León, P., Arnés-Urgellés, C., Suarez-Moncada, J., Espinoza, E., Vaca, L., & Páez-Rosas, D. (2022). Using stable isotopes analysis to understand ontogenetic trophic variations of the scalloped hammerhead shark at the Galapagos Marine Reserve. *PLoS One*, 17(6), e0268736. <https://doi.org/10.1371/journal.pone.0268736>
- Cerutti-Pereyra, F., Yáñez, A. B., Ebert, D. A., Arnés-Urgellés, C., & Salinas-De-León, P. (2018). New record and range extension of the Deepsea Skate, *Bathyraja abyssicola* (Chondrichthyes: Arhynchobatidae), in the Galapagos Islands. *Journal of the Ocean Science Foundation*, 30, 85–89. <https://doi.org/10.5281/zenodo.1400829>
- Cheng, L., Trenberth, K. E., Gruber, N., Abraham, J. P., Fasullo, J. T., Li, G., Mann, M. E., Zhao, X., & Zhu, J. (2020). Improved estimates of changes in upper ocean salinity and the hydrological cycle. *Journal of Climate*, 33, 10357–10381. <https://doi.org/10.1175/JCLI-D-20-0366.1>
- Cheung, W., Jones, M. C., Reygondeau, G., & Frölicher, T. L. (2018). Opportunities for climate-risk reduction through effective fisheries management. *Global Change Biology*, 24, 5149–5163. <https://doi.org/10.1111/gcb.14390>
- Chin, A., Kyne, P. M., Walker, T. I., & McAuley, R. B. (2010). An integrated risk assessment for climate change: Analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology*, 16, 1936–1953. <https://doi.org/10.1111/j.1365-2486.2009.02128.x>
- Cisneros-Montemayor, A. M., Becerril-García, E. E., Berdeja-Zavala, O., & Ayala-Bocos, A. (2020). *Shark ecotourism in Mexico: Scientific research, conservation, and contribution to a Blue Economy* (1st ed.). Elsevier Ltd.
- Clarke, T. M., Reygondeau, G., Wabnitz, C., Robertson, R., Ixquiac-Cabrera, M., López, M., Ramírez Coghi, A. R., del Río Iglesias, J. L., Wehrtmann, I., & Cheung, W. W. L. (2021). Climate change impacts on living marine resources in the Eastern Tropical Pacific. *Diversity and Distributions*, 27, 65–81. <https://doi.org/10.1111/ddi.13181>
- Compagno, L. J. V. (1990). Alternative life-history styles of cartilaginous fishes in time and space. *Environmental Biology of Fishes*, 28, 33–75.
- Croll, D. A., Dewar, H., Dulvy, N. K., Fernando, D., Francis, M. P., Galván-Magaña, F., Hall, M., Heinrichs, S., Marshall, A., McCauley, D.,

- Newton, K. M., Notarbartolo-di-Sciara, G., O'Malley, M., O'Sullivan, J., Poortvliet, M., Roman, M., Stevens, G., Tershy, B. R., & White, W. T. (2016). Vulnerabilities and fisheries impacts: The uncertain future of manta and devil rays. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26, 562–575. <https://doi.org/10.1002/aqc.2591>
- Cuevas-Zimbrón, E., Pérez-Jiménez, J. C., & Méndez-Loeza, I. (2011). Spatial and seasonal variation in a target fishery for spotted eagle ray *Aetobatus narinari* in the southern Gulf of Mexico. *Fisheries Science*, 77, 723–730. <https://doi.org/10.1007/s12562-011-0389-9>
- Dale, J. J., Brodie, S., Carlisle, A. B., Castleton, M., Hazen, E. L., Bograd, S. J., & Block, B. A. (2022). Global habitat loss of a highly migratory predator, the blue marlin (*Makaira nigricans*). *Diversity and Distributions*, 28, 2020–2034. <https://doi.org/10.1111/ddi.13606>
- Davies, K. F., Margules, C. R., & Lawrence, J. F. (2004). A synergistic effect puts rare, specialized species at greater risk of extinction. *Ecology*, 85, 265–271. <https://doi.org/10.1890/03-0110>
- Dent, F., & Clarke, S. C. (2015). *State of the global market for shark products* (Vol. 590). FAO Fisheries and Aquaculture.
- Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H. O., & Huey, R. B. (2015). Climate change tightens a metabolic constraint on marine habitats. *Science*, 348, 1132–1135. <https://doi.org/10.1126/science.aaa1605>
- Di Santo, V. (2015). Ocean acidification exacerbates the impacts of global warming on embryonic little skate, *Leucoraja erinacea* (Mitchill). *Journal of Experimental Marine Biology and Ecology*, 463, 72–78. <https://doi.org/10.1016/j.jembe.2014.11.006>
- Di Santo, V. (2016). Intraspecific variation in physiological performance of a benthic elasmobranch challenged by ocean acidification and warming. *The Journal of Experimental Biology*, 219, 1725–1733. <https://doi.org/10.1242/jeb.139204>
- Díaz-Carballido, P. L., Mendoza-González, G., Yañez-Arenas, C. A., & Chiappa-Carrara, X. (2022). Evaluation of shifts in the potential future distributions of carcharhinid sharks under different climate change scenarios. *Frontiers in Marine Science*, 8, 8.
- Doi, H., Yasuhara, M., & Ushio, M. (2021). Causal analysis of the temperature impact on deep-sea biodiversity. *Biology Letters*, 17, 2–7. <https://doi.org/10.1098/rsbl.2020.0666>
- Doney, S. C. (2006). Plankton in a warmer world. *Nature*, 444, 695–696. <https://doi.org/10.1038/444695a>
- Dulvy, N. K., Fowler, S. L., Musick, J. A., Cavanagh, R. D., Kyne, P. M., Harrison, L. R., Carlson, J. K., Davidson, L. N. K., Fordham, S. V., Francis, M. P., Pollock, C. M., Simpfendorfer, C. A., Burgess, G. H., Carpenter, K. E., Compagno, L. J. V., Ebert, D. A., Gibson, C., Heupel, M. R., Livingstone, S. R., ... White, W. T. (2014). Extinction risk and conservation of the world's sharks and rays. *eLife*, 3, e00590. <https://doi.org/10.7554/eLife.00590.001>
- Dulvy, N. K., Metcalfe, J. D., Glanville, J., Pawson, M. G., & Reynolds, J. D. (2000). Fishery stability, local extinctions, and shifts in community structure in skates. *Conservation Biology*, 14, 283–293. <https://doi.org/10.1046/j.1523-1739.2000.98540.x>
- Dulvy, N. K., Pacoureau, N., Rigby, C. L., Pollom, R. A., Jabado, R. W., Ebert, D. A., Finucci, B., Pollock, C. M., Cheok, J., Derrick, D. H., Herman, K. B., Sherman, C. S., VanderWright, W. J., Lawson, J. M., Walls, R. H. L., Carlson, J. K., Charvet, P., Bineesh, K. K., Fernando, D., ... Simpfendorfer, C. A. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology*, 31, 4773–4787.e8. <https://doi.org/10.1016/j.cub.2021.08.062>
- Eckert, S. A., & Stewart, B. S. (2001). Telemetry and satellite tracking of whale sharks, *Rhincodon typus*, in the Sea of Cortez, Mexico, and the north Pacific Ocean. *Environmental Biology of Fishes*, 60, 299–308. <https://doi.org/10.1023/A:1007674716437>
- Eisele, M. H., Madrigal-Mora, S., & Espinoza, M. (2021). Drivers of reef fish assemblages in an upwelling region from the Eastern Tropical Pacific Ocean. *Journal of Fish Biology*, 98, 1074–1090. <https://doi.org/10.1111/jfb.14639>
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9, 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- Feitosa, L. M., Queiroz, A. P. N., Labonne, M., Dressler, V. L., & Lessa, R. P. (2021). Habitat use and nursery evaluation for the longnose stingray *Hypanus guttatus* (Bloch & Schneider, 1801) using vertebral microchemistry. *Journal of Fish Biology*, 99, 1538–1549. <https://doi.org/10.1111/jfb.14858>
- Feng, H., & Zhang, M. (2015). Global land moisture trends: Drier in dry and wetter in wet over land. *Scientific Reports*, 5, 18018. <https://doi.org/10.1038/srep18018>
- Fernández-Álamo, M. A., & Färber-Lorda, J. (2006). Zooplankton and the oceanography of the Eastern Tropical Pacific: A review. *Progress in Oceanography*, 69, 318–359. <https://doi.org/10.1016/j.pocean.2006.03.003>
- Fiedler, P. C., & Talley, L. D. (2006). Hydrography of the Eastern Tropical Pacific: A review. *Progress in Oceanography*, 69, 143–180. <https://doi.org/10.1016/j.pocean.2006.03.008>
- Field, I. C., Meekan, M. G., Buckworth, R. C., & Bradshaw, C. J. A. (2010). Susceptibility of sharks, rays and chimaeras to global extinction. *Advances in Marine Biology*, 56, 275–363. [https://doi.org/10.1016/S0065-2881\(09\)56004-X](https://doi.org/10.1016/S0065-2881(09)56004-X)
- Finucci, B., Cheok, J., Ebert, D. A., Herman, K., Kyne, P. M., & Dulvy, N. K. (2021). Ghosts of the deep—Biodiversity, fisheries, and extinction risk of ghost sharks. *Fish and Fisheries*, 22, 391–412. <https://doi.org/10.1111/faf.12526>
- Foden, W. B., Butchart, S. H. M., Stuart, S. N., Vié, J. C., Akçakaya, H. R., Angulo, A., DeVantier, L. M., Gutsche, A., Turak, E., Cao, L., Donner, S. D., Kataria, V., Bernard, R., Holland, R. A., Hughes, A. F., O'Hanlon, S. E., Garnett, S. T., Şekercioğlu, Ç. H., & Mace, G. M. (2013). Identifying the World's Most climate change vulnerable species: A systematic trait-based assessment of all birds, amphibians and corals. *PLoS One*, 8, e65427.
- Forryan, A., Naveira Garabato, A. C., Vic, C., Nurser, A. J. G., & Hearn, A. R. (2021). Galápagos upwelling driven by localized wind-front interactions. *Scientific Reports*, 11, 1–12. <https://doi.org/10.1038/s41598-020-80609-2>
- Friedland, K. D., Stock, C., Drinkwater, K. F., Link, J. S., Leaf, R. T., Shank, B. V., Rose, J. M., Pilskaln, C. H., & Fogarty, M. J. (2012). Pathways between primary production and fisheries yields of large marine ecosystems. *PLoS One*, 7, e28945.
- Friedlander, A. M., Giddens, J., Ballesteros, E., Blum, S., Brown, E. K., Caselle, J. E., Henning, B., Jost, C., Salinas-de-León, P., & Sala, E. (2019). Marine biodiversity from zero to a thousand meters at Clipperton Atoll (Île de La Passion), Tropical Eastern Pacific. *PeerJ*, 7, e7279. <https://doi.org/10.7717/peerj.7279>
- Gallagher, A. J., & Hammerschlag, N. (2011). Global shark currency: The distribution frequency and economic value of shark ecotourism. *Current Issues in Tourism*, 14, 797–812. <https://doi.org/10.1080/13683500.2011.585227>
- Georgeson, L., Rigby, C. L., Emery, T. J., Fuller, M., Hartog, J., Williams, A. J., Hobday, A. J., Duffy, C. A. J., Simpfendorfer, C. A., Okuda, T., Stobutzki, I. C., & Nicol, S. J. (2020). Ecological risks of demersal fishing on deepwater chondrichthyan populations in the Southern Indian and South Pacific Oceans. *ICES Journal of Marine Science*, 77, 1711–1727. <https://doi.org/10.1093/icesjms/fsaa019>
- Gilkinson, A. K., Pearson, H. C., Weltz, F., & Davis, R. W. (2007). Photo-identification of sea otters using nose scars. *Journal of Wildlife Management*, 71, 2045–2051. <https://doi.org/10.2193/2006-410>
- Hammerschlag, N., McDonnell, L. H., Rider, M. J., Street, G. M., Hazen, E. L., Natanson, L. J., McCandless, C. T., Boudreau, M. R., Gallagher, A. J., Pinsky, M. L., & Kirtman, B. (2022). Ocean warming alters the distributional range, migratory timing, and spatial protections of an apex predator, the tiger shark (*Galeocerdo*

- cuvier). *Global Change Biology*, 28, 1990–2005. <https://doi.org/10.1111/gcb.16045>
- Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, E. J., Griffiths, R. B., Alexander, M. A., Scott, J. D., Alade, L., Bell, R. J., Chute, A. S., Curti, K. L., Curtis, T. H., Kircheis, D., Kocik, J. F., Lucey, S. M., McCandless, C. T., Milke, L. M., Richardson, D. E., ... Griswold, C. A. (2016). A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental Shelf. *PLoS One*, 11, e0146756. <https://doi.org/10.1371/journal.pone.0146756>
- Hays, G. C., Richardson, A. J., & Robinson, C. (2005). Climate change and marine plankton. *Trends in Ecology & Evolution*, 20, 337–344. <https://doi.org/10.1016/j.tree.2005.03.004>
- Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., Jonsen, I. D., Shaffer, S. A., Dunne, J. P., Costa, D. P., Crowder, L. B., & Block, B. A. (2013). Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change*, 3, 234–238. <https://doi.org/10.1038/nclimate1686>
- Hearn, A., Ketchum, J., Klimley, A. P., Espinoza, E., & Peñaherrera, C. (2010). Hotspots within hotspots? Hammerhead shark movements around wolf Island, Galapagos Marine Reserve. *Marine Biology*, 157, 1899–1915. <https://doi.org/10.1007/s00227-010-1460-2>
- Heithaus, M. R. (2001). Predator-prey and competitive interactions between sharks (order Selachii) and dolphins (suborder Odontoceti): A review. *Journal of Zoology*, 253, 53–68. <https://doi.org/10.1017/S0952836901000061>
- Heithaus, M. R., Frid, A., Wirsing, A. J., & Worm, B. (2008). Predicting ecological consequences of marine top predator declines. *Trends in Ecology & Evolution*, 23, 202–210. <https://doi.org/10.1016/j.tree.2008.01.003>
- Heupel, M., Knip, D., Simpfendorfer, C., & Dulvy, N. K. (2014). Sizing up the ecological role of sharks as predators. *Marine Ecology Progress Series*, 495, 291–298.
- Hobday, A. J., Game, E. T., Grantham, H. S., & Richardson, A. J. (2011). Conserving the largest habitat on earth: Protected areas in the pelagic ocean. In J. Claudet (Ed.), *Marine protected areas: A multidisciplinary approach* (pp. 347–372). Cambridge University Press.
- Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., Deng, R. A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S. P., Johnson, D., Kenyon, R., Knuckey, I. A., Ling, S. D., Pitcher, R., Sainsbury, K. J., Sporcic, M., Smith, T., ... Zhou, S. (2011). Ecological risk assessment for the effects of fishing. *Fisheries Research*, 108, 372–384. <https://doi.org/10.1016/j.fishres.2011.01.013>
- Hoegh-Guldberg, O., Poloczanska, E. S., Skirving, W., & Dove, S. (2017). Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science*, 4, 4.
- Hofmann, G. E., Barry, J. P., Edmunds, P. J., Gates, R. D., Hutchins, D. A., Klinger, T., & Sewell, M. A. (2010). The effect of ocean acidification on calcifying organisms in marine ecosystems: An organism-to-ecosystem perspective. *Annual Review of Ecology, Evolution, and Systematics*, 41, 127–147.
- IPCC. (2018). *Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. (V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds.).
- John, J. G., Stock, C. A., & Dunne, J. P. (2015). A more productive, but different, ocean after mitigation. *Geophysical Research Letters*, 42, 9836–9845. <https://doi.org/10.1002/2015GL066160>
- Jones, M. C., & Cheung, W. W. L. (2017). Using fuzzy logic to determine the vulnerability of marine species to climate change. *Global Change Biology*, 24, e719–e731. <https://doi.org/10.1111/gcb.13869>
- Jorgensen, S. J., Micheli, F., White, T. D., van Houtan, K., Alfaro-Shigueto, J., Andrzejczek, S., Arnoldi, N. S., Baum, J. K., Block, B., Britten, G. L., Butner, C., Caballero, S., Cardeñoso, D., Chapple, T. K., Clarke, S., Cortés, E., Dulvy, N. K., Fowler, S., Gallagher, A. J., ... Ferretti, F. (2022). Emergent research and priorities for shark and ray conservation. *Endangered Species Research*, 47, 171–203. <https://doi.org/10.3354/ESR01169>
- Ketchum, J. T., Hearn, A., Klimley, A. P., Peñaherrera, C., Espinoza, E., Bessudo, S., Soler, G., & Arauz, R. (2014). Inter-island movements of scalloped hammerhead sharks (*Sphyrna lewini*) and seasonal connectivity in a marine protected area of the Eastern Tropical Pacific. *Marine Biology*, 161, 939–951. <https://doi.org/10.1007/s00227-014-2393-y>
- Kislak, E., Saltos, G. M., Torres, G., & Borbor-Córdova, M. (2017). Biological hotspots in the Galapagos Islands: Exploring seasonal trends of ocean climate drivers to monitor algal blooms. *International Journal of Bioengineering and Life Sciences*, 11, 784–794.
- Klimley, A. P., Arauz, R., Bessudo, S. C., Elpis, J., Chinacalle, N., Espinoza, E., Green, J., Hearn, A. R., Hoyos-Padilla, M. E., Nalesso, E., Ketchum, J. T., & Peñaherrera-Palma, C. (2022). Studies of the movement ecology of sharks justify the existence and expansion of marine protected areas in the Eastern Pacific Ocean. *Environmental Biology of Fishes*, 105, 2133–2153. <https://doi.org/10.1007/s10641-021-01204-6>
- Kroecker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., Duarte, C. M., & Gattuso, J. P. (2013). Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Global Change Biology*, 19, 1884–1896. <https://doi.org/10.1111/gcb.12179>
- Kwiatkowski, L., Torres, O., Bopp, L., Aumont, O., Chamberlain, M., Christian, J. R., Dunne, J. P., Gehlen, M., Ilyina, T., John, J. G., Lenton, A., Li, H., Lovenduski, N. S., Orr, J. C., Palmieri, J., Santana-Falcón, Y., Schwinger, J., Séférian, R., Stock, C. A., ... Ziehn, T. (2020). Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences*, 17, 3439–3470. <https://doi.org/10.5194/bg-17-3439-2020>
- Kyne, P. M., Jabado, R. W., Rigby, C. L., Dharmadi, Gore, M. A., Pollock, C. M., Herman, K. B., Cheok, J., Ebert, D. A., Simpfendorfer, C. A., & Dulvy, N. K. (2020). The thin edge of the wedge: Extremely high extinction risk in wedgefishes and giant guitarfishes. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 30, 1337–1361. <https://doi.org/10.1002/aqc.3331>
- Lara-Lizardi, F., Hoyos-Padilla, M., Alex Hearn, A., Klimley, P., Galván-Magaña, F., Arauz, R., Bessudo, S., Castro, E., Clua, E., Espinoza, E., Fischer, C., Peñaherrera-Palma, C., Steiner, T., & Ketchum, J. T. (2020). Shark movements in the Revillagigedo Archipelago and connectivity with the Eastern Tropical Pacific. *bioRxiv*. <https://doi.org/10.1101/2020.03.02.972844>
- Lavín, M. F., Fiedler, P. C., Amador, J. A., Ballance, L. T., Färber-Lorda, J., & Mestas-Núñez, A. M. (2006). A review of Eastern Tropical Pacific oceanography: Summary. *Progress in Oceanography*, 69, 391–398. <https://doi.org/10.1016/j.pocean.2006.03.005>
- Lear, K. O., Whitney, N. M., Morgan, D. L., Brewster, L. R., Whitty, J. M., Poulakis, G. R., Scharer, R. M., Guttridge, T. L., & Gleiss, A. C. (2019). Thermal performance responses in free-ranging elasmobranchs depend on habitat use and body size. *Oecologia*, 191, 829–842. <https://doi.org/10.1007/s00442-019-04547-1>
- Levin, L. A., & Bris, N. L. (2015). The deep ocean under climate change. *Science*, 350, 766–768. <https://doi.org/10.1126/science.aad0126>
- Levin, L. A., Wei, C. L., Dunn, D. C., Amon, D. J., Ashford, O. S., Cheung, W. W. L., Colaço, A., Dominguez-Carrió, C., Escobar, E. G., Harden-Davies, H. R., Drazen, J. C., Ismail, K., Jones, D. O. B., Johnson, D. E., Ie, J. T., Lejzerowicz, F., Mitarai, S., Morato, T., Mulsow, S., ... Yasuhara, M. (2020). Climate change considerations are fundamental to management of deep-sea resource

- extraction. *Global Change Biology*, 26, 4664–4678. <https://doi.org/10.1111/gcb.15223>
- Lezama-Ochoa, N., Hall, M. A., Pennino, M. G., Stewart, J. D., López, J., & Murua, H. (2019). Environmental characteristics associated with the presence of the Spinetail devil ray (*Mobula mobular*) in the Eastern Tropical Pacific. *PLoS One*, 14, 1–24. <https://doi.org/10.1371/journal.pone.0220854>
- Llerena, Y., Peñaherrera, C., Espinoza, E., Hirschfeld, M., Wolff, M., & Vinuesa, L. (2015). Nursery grounds of blacktip sharks (*Carcharhinus limbatus*) in mangrove-fringed bays in the central part of the Galapagos Archipelago. Galapagos report 2013–2014. GNPD, GCREG, CDF and GC. Puerto Ayora.
- Lluch-Cota, S. E. (1999). Coastal upwelling in the eastern Gulf of California. *Oceanologica Acta*, 23, 731–740.
- López-Angarita, J., Cubillos-M, J. C., Villate-Moreno, M., del Cid, A., Díaz, J. M., Cooke, R., Cagua, E. F., & Tilley, A. (2021). Bright spots for research and conservation of the largetooth sawfish *Pristis pristis* in Colombia and Panamá. *Endangered Species Research*, 46, 147–160. <https://doi.org/10.3354/esr01150>
- López-Angarita, J., Roberts, C. M., Tilley, A., Hawkins, J. P., & Cooke, R. G. (2016). Mangroves and people: Lessons from a history of use and abuse in four Latin American countries. *Forest Ecology and Management*, 368, 151–162. <https://doi.org/10.1016/j.foreco.2016.03.020>
- López-Angarita, J., Villate-Moreno, M., Díaz, J. M., Cubillos-M, J. C., & Tilley, A. (2021). Identifying nearshore nursery habitats for sharks in the Eastern Tropical Pacific from fisheries landings and interviews. *Ocean and Coastal Management*, 213, 1–21. <https://doi.org/10.1016/j.ocecoaman.2021.105825>
- Lotze, H. K., Tittensor, D. P., Bryndum-Buchholz, A., Eddy, T. D., Cheung, W. W. L., Galbraith, E. D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J. L., Bopp, L., Büchner, M., Bulman, C. M., Carozza, D. A., Christensen, V., Coll, M., Dunne, J. P., Fulton, E. A., Jennings, S., ... Worm, B. (2019). Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 116, 12907–12912. <https://doi.org/10.1073/pnas.1900194116>
- Lynham, J., Costello, C., Gaines, S., & Sala, E. (2015). *Economic valuation of marine- and shark-based tourism in the Galapagos Islands: Report to the Galapagos National Park*. National Geographic Pristine Seas.
- Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on Salmon production. *Bulletin of the American Meteorological Society*, 78, 1069–1080. [https://doi.org/10.1175/1520-0477\(1997\)078<1069:APICOW>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2)
- Martin, R. A. (2005). Conservation of freshwater and euryhaline elasmobranchs: A review. *Journal of the Marine Biological Association of the UK*, 85, 1049–1073. <https://doi.org/10.1017/S0025315405012105>
- Martínez-Arroyo, A., Manzanilla-Naim, S., & Zavala-Hidalgo, J. (2011). Vulnerability to climate change of marine and coastal fisheries in México. *Atmosfera*, 24, 103–123.
- Martínez-Ortiz, J., Aires-da-silva, A. M., Lennert-Cody, C. E., & Maunders, M. N. (2015). The ecuadorian artisanal fishery for large pelagics: Species composition and spatio-temporal dynamics. *PLoS One*, 10, 1–29. <https://doi.org/10.1371/journal.pone.0135136>
- McClure, M. M., Haltuch, M. A., Willis-Norton, E., Huff, D. D., Hazen, E. L., Crozier, L. G., Jacox, M. G., Nelson, M. W., Andrews, K. S., Barnett, L. A. K., Berger, A. M., Beyer, S., Bizzarro, J., Boughton, D., Cope, J. M., Carr, M., Dewar, H., Dick, E., Dorval, E., ... Bograd, S. J. (2023). Vulnerability to climate change of managed stocks in the California current large marine ecosystem. *Frontiers in Marine Science*, 10, 1–21. <https://doi.org/10.3389/fmars.2023.1103767>
- McPhaden, M. J., Santoso, A., & Cai, W. (2020). Introduction to El Niño Southern Oscillation in a changing climate. In M. J. McPhaden, A. Santoso, & W. Cai (Eds.), *El Niño Southern Oscillation in a changing climate* (pp. 1–19). <https://doi.org/10.1002/9781119548164.ch1>
- Mejía-Falla, P. A., Castro, E. R., Ballesteros, C. A., Bent-Hooker, H., Caldas, J. P., Rojas, A., & Navia, A. F. (2019). Effect of a precautionary management measure on the vulnerability and ecological risk of elasmobranchs captured as target fisheries. *Regional Studies in Marine Science*, 31, 100779. <https://doi.org/10.1016/j.rsma.2019.100779>
- Miloslavich, P., Klein, E., Díaz, J. M., Hernández, C. E., Bigatti, G., Campos, L., Artigas, F., Castillo, J., Penchaszadeh, P. E., Neill, P. E., Carranza, A., Retana, M. V., Díaz de Astarloa, J. M., Lewis, M., Yorio, P., Piriz, M. L., Rodríguez, D., Yoneshigue-Valentin, Y., Gamboa, L., & Martín, A. (2011). Marine biodiversity in the Atlantic and Pacific coasts of South America: Knowledge and gaps. *PLoS One*, 6, e14631. <https://doi.org/10.1371/journal.pone.0014631>
- Musick, J. A., Burgess, G., Cailliet, G., Camhi, M., & Fordham, S. (2000). Management of sharks and their relatives (*Elasmobranchii*). *Fisheries*, 25, 9–11. [https://doi.org/10.1577/1548-8446\(2000\)025<0009:MOSATR>2.0.CO;2](https://doi.org/10.1577/1548-8446(2000)025<0009:MOSATR>2.0.CO;2)
- Nasby-Lucas, N., Dewar, H., Lam, C. H., Goldman, K. J., & Domeier, M. L. (2009). White shark offshore habitat: A behavioral and environmental characterization of the eastern pacific shared offshore foraging area. *PLoS One*, 4, e8163. <https://doi.org/10.1371/journal.pone.0008163>
- NCAR. (2022). *El Niño zone 3*. <https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-4-oni-and-tni>
- Newman, M., Alexander, M. A., Ault, T. R., Cobb, K. M., Deser, C., di Lorenzo, E., Mantua, N. J., Miller, A. J., Minobe, S., Nakamura, H., Schneider, N., Vimont, D. J., Phillips, A. S., Scott, J. D., & Smith, C. A. (2016). The Pacific decadal oscillation, revisited. *Journal of Climate*, 29, 4399–4427. <https://doi.org/10.1175/JCLI-D-15-0508.1>
- O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & Van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, 122, 387–400. <https://doi.org/10.1007/s10584-013-0905-2>
- O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9, 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
- Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., & Sebesvari, Z. (2019). Sea level rise and implications for low-lying islands, coasts and communities. In H.-O. Pörtner, D. C. Roberts, V. Masson Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 321–445). Cambridge University Press.
- Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R. M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R. G., Plattner, G. K., Rodgers, K. B., ... Yool, A. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437, 681–686. <https://doi.org/10.1038/nature04095>
- Pacoureau, N., Rigby, C. L., Kyne, P. M., Sherley, R. B., Winker, H., Carlson, J. K., Fordham, S. V., Barreto, R., Fernando, D., Francis, M. P., Jabado, R. W., Herman, K. B., Liu, K. M., Marshall, A. D., Pollom, R. A., Romanov, E. V., Simpfendorfer, C. A., Yin, J. S., Kindsvater, H. K., & Dulvy, N. K. (2021). Half a century of global decline in oceanic sharks and rays. *Nature*, 589, 567–571.
- Pathak, M., Slade, R., Shukla, P. R., Skea, J., Pichs-Madruga, R., & Ürges-Vorsatz, D. (2022). Technical summary. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz,

- & J. Malley (Eds.), *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. <https://doi.org/10.1017/9781009157926.002>
- Pereira, S. C., Eduardo, S., Pereira, B. P., Rita, P. M., Borges, F. O., Wheeler, C. R., Bouyoucos, I. A., Rummer, J. L., Catarina, F. S., & Rui, R. (2021). Elasmobranch responses to experimental warming, acidification, and oxygen loss—A meta-analysis. *Frontiers in Marine Science*, 8, 735377.
- Pinsky, M. L., Selden, R. L., & Kitchel, Z. J. (2020). Climate-driven shifts in marine species ranges: Scaling from organisms to communities. *Annual Review of Marine Science*, 12, 153–179. <https://doi.org/10.1146/annurev-marine-010419-010916>
- Pistevos, J. C. A., Nagelkerken, I., Rossi, T., Olmos, M., & Connell, S. D. (2015). Ocean acidification and global warming impair shark hunting behaviour and growth. *Scientific Reports*, 5, 16293. <https://doi.org/10.1038/srep16293>
- Pörtner, H. O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., & Weyer, N. M. (2019). The ocean and cryosphere in a changing climate. IPCC spec report. https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/02_SROCC_FM_FINAL.pdf
- Pratchett, M. S., Bay, L. K., Gehrke, P. C., Koehn, J. D., Osborne, K., Pressey, R. L., Sweatman, H. P. A., & Wachenfeld, D. (2011). Contribution of climate change to degradation and loss of critical fish habitats in Australian marine and freshwater environments. *Marine and Freshwater Research*, 62, 1062–1081.
- Prince, E. D., & Goodyear, C. P. (2006). Hypoxia-based habitat compression of tropical pelagic fishes. *Fisheries Oceanography*, 15, 451–464. <https://doi.org/10.1111/j.1365-2419.2005.00393.x>
- Quinlan, J. A., Nelson, M., Savoia, C., Skubel, R., Scott, J. D., Ailloud, L., Ainsworth, C., Alvarez, D., Bacheler, N. M., Burton, M., Calay, S., Cummings, N., Doerr, J. C., Driggers, W., Erisman, B., Gandy, R., Grove, L. J., Hanisko, D., Heublein, J., ... Griffis, R. (2023). Results from the Gulf of Mexico climate vulnerability analysis. NOAA technical memorandum NMFS-SEFSC-767.
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaserna, J. C., Samir, K. C., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., ... Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Ripley, D. M., de Giorgio, S., Gaffney, K., Thomas, L., & Shiels, H. A. (2021). Ocean warming impairs the predator avoidance behaviour of elasmobranch embryos. *Conservation Physiology*, 9, 1–7. <https://doi.org/10.1093/conphys/coab045>
- Robinson, R. A., Crick, H. Q. P., Learmonth, J. A., Maclean, I. M. D., Thomas, C. D., Bairlein, F., Forchhammer, M. C., Francis, C. M., Gill, J. A., Godley, B. J., Harwood, J., Hays, G. C., Huntley, B., Hutson, A. M., Pierce, G. J., Rehfish, M. M., Sims, D. W., Santos, B. M., Sparks, T. H., ... Visser, M. E. (2009). Travelling through a warming world: Climate change and migratory species. *Endangered Species Research*, 7, 87–99. <https://doi.org/10.3354/esr00095>
- Rosa, R., Rummer, J. L., & Munday, P. L. (2017). Biological responses of sharks to ocean acidification. *Biology Letters*, 13, 20160796. <https://doi.org/10.1098/rsbl.2016.0796>
- Ryan, J. P., Green, J. R., Espinoza, E., & Hearn, A. R. (2017). Association of whale sharks (*Rhincodon typus*) with thermo-biological frontal systems of the Eastern Tropical Pacific. *PLoS One*, 12, e0182599. <https://doi.org/10.1371/journal.pone.0182599>
- Ryckaczewski, R. R., Dunne, J. P., Sydeman, W. J., García-Reyes, M., Black, B. A., & Bograd, S. J. (2015). Poleward displacement of coastal upwelling-favorable winds in the ocean's eastern boundary currents through the 21st century. *Geophysical Research Letters*, 42, 6424–6431. <https://doi.org/10.1002/2015GL064694>
- Sampaio, E., Santos, C., Rosa, I. C., Ferreira, V., Pörtner, H. O., Duarte, C. M., Levin, L. A., & Rosa, R. (2021). Impacts of hypoxic events surpass those of future ocean warming and acidification. *Nature Ecology & Evolution*, 5, 311–321. <https://doi.org/10.1038/s41559-020-01370-3>
- Sherman, C. S., Simpfendorfer, C. A., Pacoureau, N., Matsushiba, J. H., Yan, H. F., Walls, R. H. L., Rigby, C. L., VanderWright, W. J., Jabado, R. W., Pollom, R. A., Carlson, J. K., Charvet, P., Bin Ali, A., Fahmi, Cheok, J., Derrick, D. H., Herman, K. B., Finucci, B., Eddy, T. D., ... Dulvy, N. K. (2023). Half a century of rising extinction risk of coral reef sharks and rays. *Nature Climate Change*, 14, 1–11. <https://doi.org/10.1038/s41467-022-35091-x>
- Simpfendorfer, C. A., & Kyne, P. M. (2009). Limited potential to recover from overfishing raises concerns for deep-sea sharks, rays and chimaeras. *Environmental Conservation*, 36, 97–103. <https://doi.org/10.1017/S0376892909990191>
- Skubel, R., Kirtman, B., Fallows, C., & Hammerschlag, N. (2018). Patterns of long-term climate variability and predation rates by a marine apex predator, the white shark *Carcharodon carcharias*. *Marine Ecology Progress Series*, 587, 129–139.
- Stock, C. A., John, J. G., Ryckaczewski, R. R., Asch, R. G., Cheung, W. W. L., Dunne, J. P., Friedland, K. D., Lam, V. W. Y., Sarmiento, J. L., & Watson, R. A. (2017). Reconciling fisheries catch and ocean productivity. *Proceedings of the National Academy of Sciences of the United States of America*, 114, E1441–E1449. <https://doi.org/10.1073/pnas.1610238114>
- Sweetman, A. K., Thurber, A. R., Smith, C. R., Levin, L. A., Mora, C., Wei, C. L., Gooday, A. J., Jones, D. O. B., Rex, M., Yasuhara, M., Ingels, J., Ruhl, H. A., Frieder, C. A., Danovaro, R., Würzburg, L., Baco, A., Grupe, B. M., Pasulka, A., Meyer, K. S., ... Roberts, J. M. (2017). Major impacts of climate change on deep-sea benthic ecosystems. *Elementa: Science of the Anthropocene*, 5. <https://doi.org/10.1525/elementa.203>
- Sydeman, W. J., García-Reyes, M., Schoeman, D. S., Ryckaczewski, R. R., Thompson, S. A., Black, B. A., & Bograd, S. J. (2014). Climate change and wind intensification in coastal upwelling ecosystems. *Science*, 345, 77–80. <https://doi.org/10.1126/science.1251635>
- Tamini, L. L., Chiaramonte, G. E., Perez, J. E., & Cappozzo, H. L. (2006). Batoids in a coastal trawl fishery of Argentina. *Fisheries Research*, 77, 326–332. <https://doi.org/10.1016/j.fishres.2005.08.013>
- Tanaka, K. R., van Houtan, K. S., Mailander, E., Dias, B. S., Galginitis, C., O'Sullivan, J., Lowe, C. G., & Jorgensen, S. J. (2021). North Pacific warming shifts the juvenile range of a marine apex predator. *Scientific Reports*, 11, 1–9. <https://doi.org/10.1038/s41598-021-82424-9>
- Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O'Neill, B., Sanderson, B., van Vuuren, D., Riahi, K., Meinshausen, M., Nicholls, Z., Tokarska, K. B., Hurtt, G., Kriegler, E., Lamarque, J. F., Meehl, G., ... Ziehn, T. (2021). Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth System Dynamics*, 12, 253–293. <https://doi.org/10.5194/esd-12-253-2021>
- Topelko, K. N., & Dearden, P. (2005). The shark watching industry and its potential contribution to shark conservation. *Journal of Ecotourism*, 4, 108–128. <https://doi.org/10.1080/14724040409480343>
- Vedor, M., Queiroz, N., Mucientes, G., Couto, A., Costa, I., Santos, A., Vandeperre, F., Fontes, J., Afonso, P., Rosa, R., Humphries, N. E., & Sims, D. W. (2021). Climate-driven deoxygenation elevates fishing vulnerability for the ocean's widest ranging shark. *eLife*, 10, 1–29. <https://doi.org/10.7554/eLife.62508>
- Villate-Moreno, M., Cubillos-M, J. C., Stibor, H., Crawford, A. J., & Straube, N. (2022). Molecular identification and first demographic insights of sharks based on artisanal fisheries bycatch in the Pacific Coast of Colombia: implications for conservation. *PeerJ*, 10, e13478. <https://doi.org/10.7717/peerj.13478>
- Vilmar, M., & Di Santo, V. (2022). Swimming performance of sharks and rays under climate change. *Reviews in Fish Biology and Fisheries*, 32, 765–781. <https://doi.org/10.1007/s11160-022-09706-x>

- Walker, T. I., Day, R. W., Awruch, C. A., Bell, J. D., Braccini, J. M., Dapp, D. R., Finotto, L., Frick, L. H., Garcés-García, K. C., Guida, L., Huveneers, C., Martins, C. L., Rochowski, B. E. A., Tovar-Ávila, J., Trinnie, F. I., & Reina, R. D. (2021). Ecological vulnerability of the chondrichthyan fauna of southern Australia to the stressors of climate change, fishing and other anthropogenic hazards. *Fish and Fisheries*, 22, 1105–1135. <https://doi.org/10.1111/faf.12571>
- Wang, C., & Fiedler, P. C. (2006). ENSO variability and the Eastern Tropical Pacific: A review. *Progress in Oceanography*, 69, 239–266. <https://doi.org/10.1016/j.pocean.2006.03.004>
- Ward, R. D., Friess, D. A., Day, R. H., & Mackenzie, R. A. (2016). Impacts of climate change on mangrove ecosystems: A region by region overview. *Ecosystem Health and Sustainability*, 2, e01211. <https://doi.org/10.1002/ehs2.1211>
- Wheeler, C. R., Gervais, C. R., Johnson, M. S., Vance, S., Rosa, R., Mandelman, J. W., & Rummer, J. L. (2020). Anthropogenic stressors influence reproduction and development in elasmobranch fishes. *Reviews in Fish Biology and Fisheries*, 30, 373–386. <https://doi.org/10.1007/s11160-020-09604-0>
- White, C. F., Lyons, K., Jorgensen, S. J., O'Sullivan, J., Winkler, C., Weng, K. C., & Lowe, C. G. (2019). Quantifying habitat selection and variability in habitat suitability for juvenile white sharks. *PLoS One*, 14, e0214642.
- Willett, C. S., Leben, R., & Lavin, M. F. (2006). Eddies and mesoscale processes in the Eastern Tropical Pacific. *Progress in Oceanography*, 69, 218–238.
- Wosnick, N., & Freire, C. A. (2013). Some euryhalinity may be more common than expected in marine elasmobranchs: The example of the South American skate *Zapteryx brevirostris* (Elasmobranchii, Rajiformes, Rhinobatidae). *Comparative Biochemistry and Physiology*

Part A: *Molecular & Integrative Physiology*, 166, 36–43. <https://doi.org/10.1016/j.cbpa.2013.05.002>

Zanella, I., López-Garro, A., & Cure, K. (2019). Golfo Dulce: Critical habitat and nursery area for juvenile scalloped hammerhead sharks *Sphyrna lewini* in the Eastern Tropical Pacific Seascape. *Environmental Biology of Fishes*, 102, 1291–1300. <https://doi.org/10.1007/s10641-019-00907-1>

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Cerutti-Pereyra, F., Drenkard, E. J., Espinoza, M., Finucci, B., Galván-Magaña, F., Hacohe-Domené, A., Hearn, A., Hoyos-Padilla, M. E., Ketchum, J. T., Mejía-Falla, P. A., Moya-Serrano, A. V., Navia, A. F., Pazmiño, D. A., Ramírez-Macías, D., Rummer, J. L., Salinas-de-León, P., Sosa-Nishizaki, O., Stock, C., & Chin, A. (2024). Vulnerability of Eastern Tropical Pacific chondrichthyan fish to climate change. *Global Change Biology*, 30, e17373. <https://doi.org/10.1111/gcb.17373>