



Climate change impacts on living marine resources in the Eastern Tropical Pacific

Taylor M. Clarke^{1,2}  | Gabriel Reygondeau¹ | Colette Wabnitz¹  | Ross Robertson³ | Manuel Ixquiac-Cabrera⁴ | Myrna López⁵ | Ana Rosa Ramírez Coghi⁵ | José Luis del Río Iglesias⁶ | Ingo Wehrmann² | William W.L. Cheung¹

¹Changing Ocean Research Unit, Institute for the Oceans and Fisheries, The University of British Columbia, Vancouver, Canada

²Centro de Investigación en Ciencias del Mar y Limnología (CIMAR), Universidad de Costa Rica, San José, Costa Rica

³Smithsonian Tropical Research Institute, Balboa, Panamá

⁴Centro de Estudios del Mar y Acuicultura, Universidad de San Carlos de Guatemala, Guatemala, Guatemala

⁵Museo de Zoología, Escuela de Biología, Universidad de Costa Rica, San José, Costa Rica

⁶Centro Oceanográfico de Vigo, Instituto Español de Oceanografía, Madrid, Spain

Correspondence

Taylor M. Clarke, Changing Ocean Research Unit, The University of British Columbia, Vancouver, Canada.
Email: t.clarke@oceans.ubc.ca

Funding information

Nippon Foundation-the University of British Columbia Nereus Program; Consejo Nacional para Investigaciones Científicas y Tecnológicas (CONICIT) and the Ministerio de Ciencia, Tecnología y Telecomunicaciones (MICITT) of Costa Rica; Natural Sciences and Research Council of Canada

Editor: Yoan Fourcade

Abstract

Aim: Project shifts in the habitat suitability of 505 fish and invertebrate species in the Eastern Tropical Pacific that are likely to occur by the mid-21st century under “high greenhouse gas emissions” (RCP 8.5) and “strong mitigation” (RCP 2.6) scenarios.

Location: The Eastern Tropical Pacific Ocean, a discrete biogeographic region from the Gulf of California to northern Peru.

Methods: Ensemble simulations of climate change effects on fish and invertebrate species caught by four major fisheries in the region, based on four species distribution models and three Earth system models.

Results: Simulation results indicated that species' habitat suitability increased or remained the same in the northern and southern margins of the Eastern Tropical Pacific but decreased by up to 14% in some fisheries along Central America. The largest declines in the average species habitat suitability index were projected for small pelagic fisheries (up to -46%), while the highest local species turnover was projected for coastal small-scale fisheries (up to 80%). Under RCP 8.5, species in the southern half and northern equatorial region of the Eastern Tropical Pacific were projected to shift south-east at a rate of approximately 30–60 km decade⁻¹, respectively. Demersal species were projected to move into shallower, inshore waters with a shift in depth centroids estimated at a rate of around 1 to 13 m decade⁻¹. Range shifts towards the equator reflect movements to cooler habitats that are characteristic of equatorial upwelling systems. Range shifts towards shallower, inshore waters reflect habitat compression associated with the expansion of oxygen minimum zones.

Main conclusions: Our findings highlight the importance of local-scale oceanographic and biological data to elucidate the multidimensional biogeographic shifts of key species, their potential impacts on fisheries in the region and the need to consider such shifts in the design of effective conservation and marine resource management measures.

KEYWORDS

California Current, climate change, deoxygenation, Humboldt Current, large pelagics, shrimp trawl fishery, small pelagics, small-scale fisheries

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Authors. *Diversity and Distributions* published by John Wiley & Sons Ltd.

1 | INTRODUCTION

Climate change is causing a global redistribution of species as they track their shifting environmental niches (Heenan et al., 2015; Jones & Cheung, 2015; Pinsky et al., 2013; Poloczanska et al., 2013). Rapid changes in the ocean are exposing ectotherms to unfavourable conditions (Pauly & Cheung, 2018; Pörtner, 2001) that lower their growth, reproduction and survival rates. These physiological impacts lead to shifts in species biomass and distributions (Cheung et al., 2010; Gattuso et al., 2015; Pörtner et al., 2014). The vulnerability of a species to climate change mainly depends on the scope between current conditions and the species physiological tolerance limits (Pörtner & Peck, 2010).

Tropical species generally exhibit narrow thermal tolerances relative to temperate species and therefore tend to be more sensitive to rapid changes in environmental temperature (Jones & Cheung, 2015; Madeira et al., 2012; Nguyen et al., 2011; Pörtner & Peck, 2010). Under the high-emissions scenario (Representative Concentration Pathway 8.5), species richness in the tropics is projected to decrease by more than 20% by 2050 relative to the 2000s (Jones & Cheung, 2015). Maximum catch potential (a proxy for maximum sustainable yield) is also projected to decrease globally by 3.4 million tonnes per degree Celsius of atmospheric warming, with the tropics being most at risk of such impacts (Cheung et al., 2010, 2016). These climate-driven declines in the availability of tropical living marine resources have the potential to affect national economies and food security, especially in developing countries with low adaptive capacity (Allison et al., 2009; Blasiak et al., 2017; Lam et al., 2016; Lam et al., 2020).

Despite the profound impacts that climate change will have on tropical marine ecosystems, most of the available information is for northern, temperate regions (Poloczanska et al., 2016). Given the widespread lack of access to scientific vessels in tropical countries, fishing vessels represent useful platforms to gain information on species distributions (Wehrtmann et al., 2012). Consequently, patterns in species caught by fisheries over time can help us understand regional biogeographic shifts occurring in response to climate change (Maestri, 2020). Within the Eastern Tropical Ocean (ETP) (Figure 1), climate change effects on fisheries have only been documented for the Gulf of California (Páez-Osuna et al., 2016). However, climate impacts on fishery species may go undetected due to the confounding effects of climate change, climate variability and overfishing (Hsieh et al., 2006), which are hard to disentangle due to the absence of long-term fisheries and oceanographic time series (Pauly & Zeller, 2016). Moreover, while global projections show that, in general, living marine resources will shift polewards (Jones & Cheung, 2015; Poloczanska et al., 2013; Pörtner et al., 2014), observations have underscored the variability in climate change responses across species and space (Lenoir & Svenning, 2015; Morley et al., 2018; Pinsky et al., 2013), with consequences for fisheries management and conservation actions (Arafef-Dalmou et al. 2020; Frazão Santos et al. 2020).

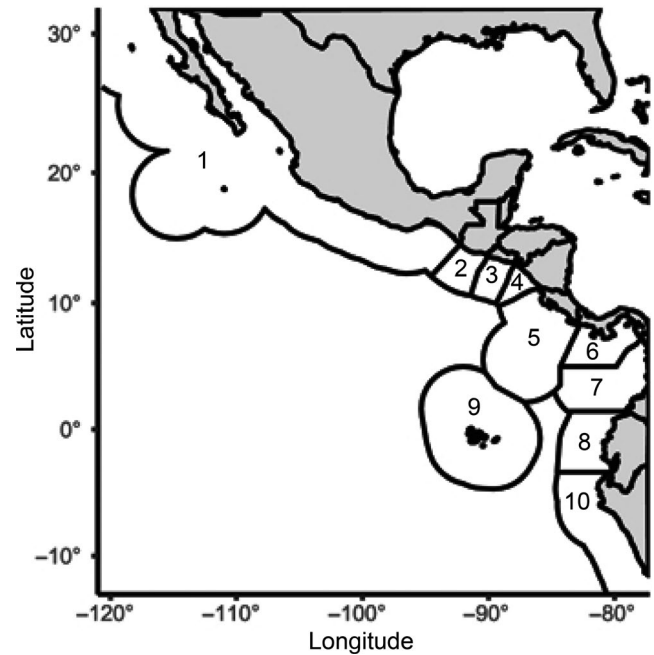


FIGURE 1 Exclusive economic zones in the Eastern Tropical Pacific of interest in this study. 1: Mexico; 2: Guatemala; 3: El Salvador; 4: Nicaragua; 5: Costa Rica; 6: Panama; 7: Colombia; 8: Ecuador; 9: Galapagos; 10: Peru

This study aims to examine the subregional range shift patterns of key fishery species in the ETP and the implications of such shifts for key fisheries and regional biogeography. We hypothesize that climate change will force species to shift towards cooler waters brought up to the surface through upwelling. We use an ensemble of species distribution models to project the future geographic distribution of living marine resources across the ETP under two climate change scenarios. This approach is based on the concept of environmental niche, defined as a set of environmental conditions that allow a species to persist (Hutchinson, 1959). Species distribution models can help elucidate the complexity of biogeographic responses of marine species at subregional scales (Guisan & Thuiller, 2005; Guisan & Zimmermann, 2000) even in data-limited areas such as the ETP (Hernandez et al., 2006; Wisz et al., 2008). Based on the model projections, we discuss the potential impacts of climate change on resource availability and regional marine biogeography.

2 | METHODS

2.1 | Oceanographic setting of the Eastern Tropical Pacific

The Eastern Tropical Pacific Ocean is defined here as the area between 31°N and 5°S, from the northern Gulf of California to northern Peru, with the East Pacific Barrier to the west and the

Central American Isthmus to the east (Figure 1). Upwelling systems within the ETP play an important and complex role in driving the spatial patterns of temperature, primary productivity, pH and oxygen (Fiedler & Lavín, 2017). As such, the ETP is delineated by the California Current eastern boundary upwelling system in the north

and the Humboldt Current eastern boundary upwelling system, South Equatorial Current and equatorial upwelling system to the south (Figure 2; Fiedler & Lavín, 2017). A “warm pool” along Central America separates these cooler regions. This warm pool has three seasonal upwelling systems (Tehuantepec, Papagayo and Panama)

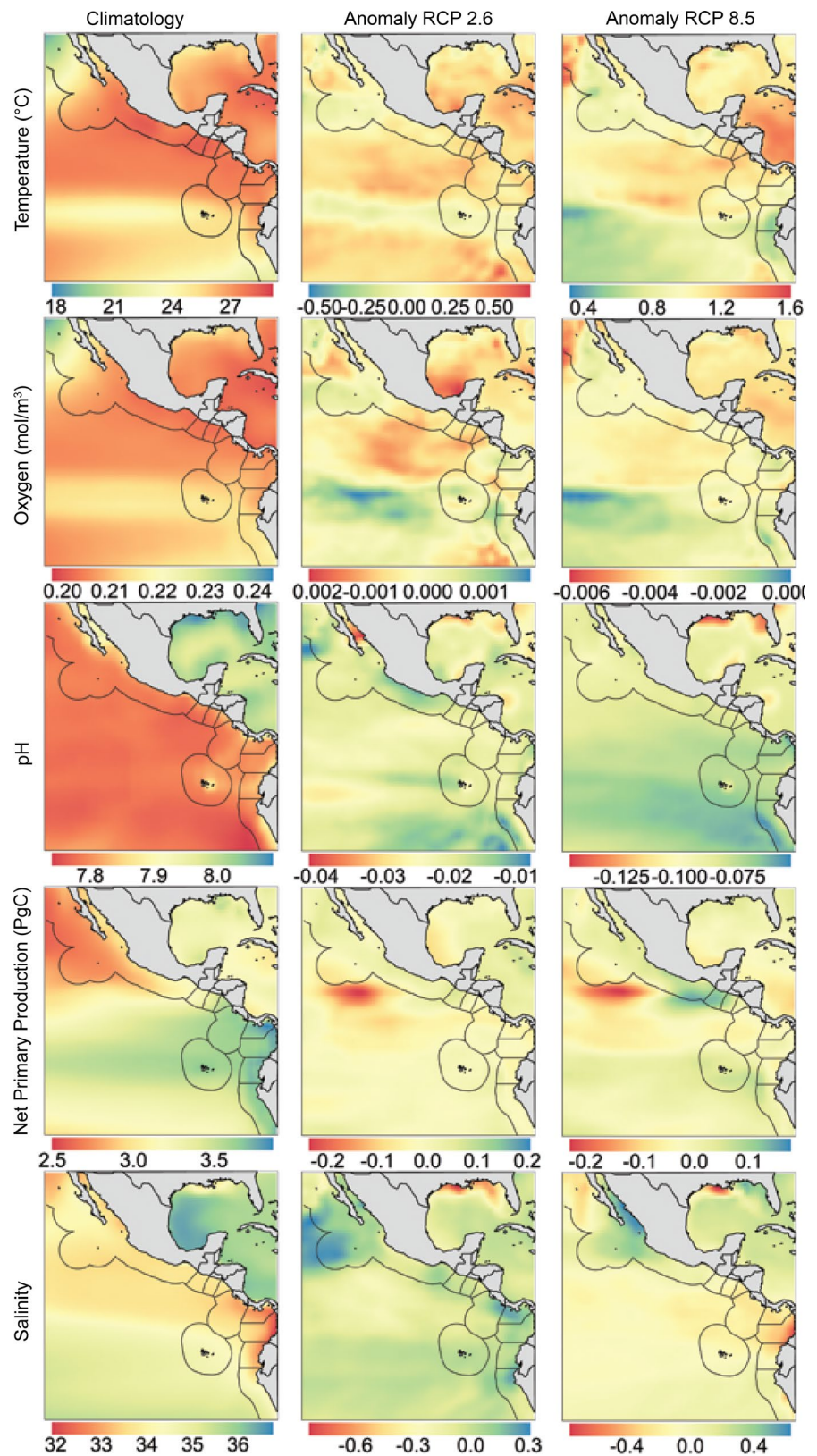


FIGURE 2 Oceanographic conditions (temperature, oxygen, pH, net primary production and salinity) at the ocean surface in 2001–2020 (left-most panel of figures) and environmental variable anomalies by 2041–2060 under RCP 2.6 (middle panel of figures) and RCP 8.5 (right-most panel of figures). For current conditions, lower values are depicted in red and higher values in blue, except for temperature. For anomalies, warmer colours denote declines while cooler colours indicate positive differences, with the exception of temperature and pH where the largest anomaly = 0. Ensembles were created for each variable using the model outputs for the Geophysical Fluid Dynamic Laboratory model (GFDL-ESM-2G), the Institut Pierre Simon Laplace model (IPSL-CM5-MR) and the Max Planck Institute for Meteorology model (MPI-ESM-MR)

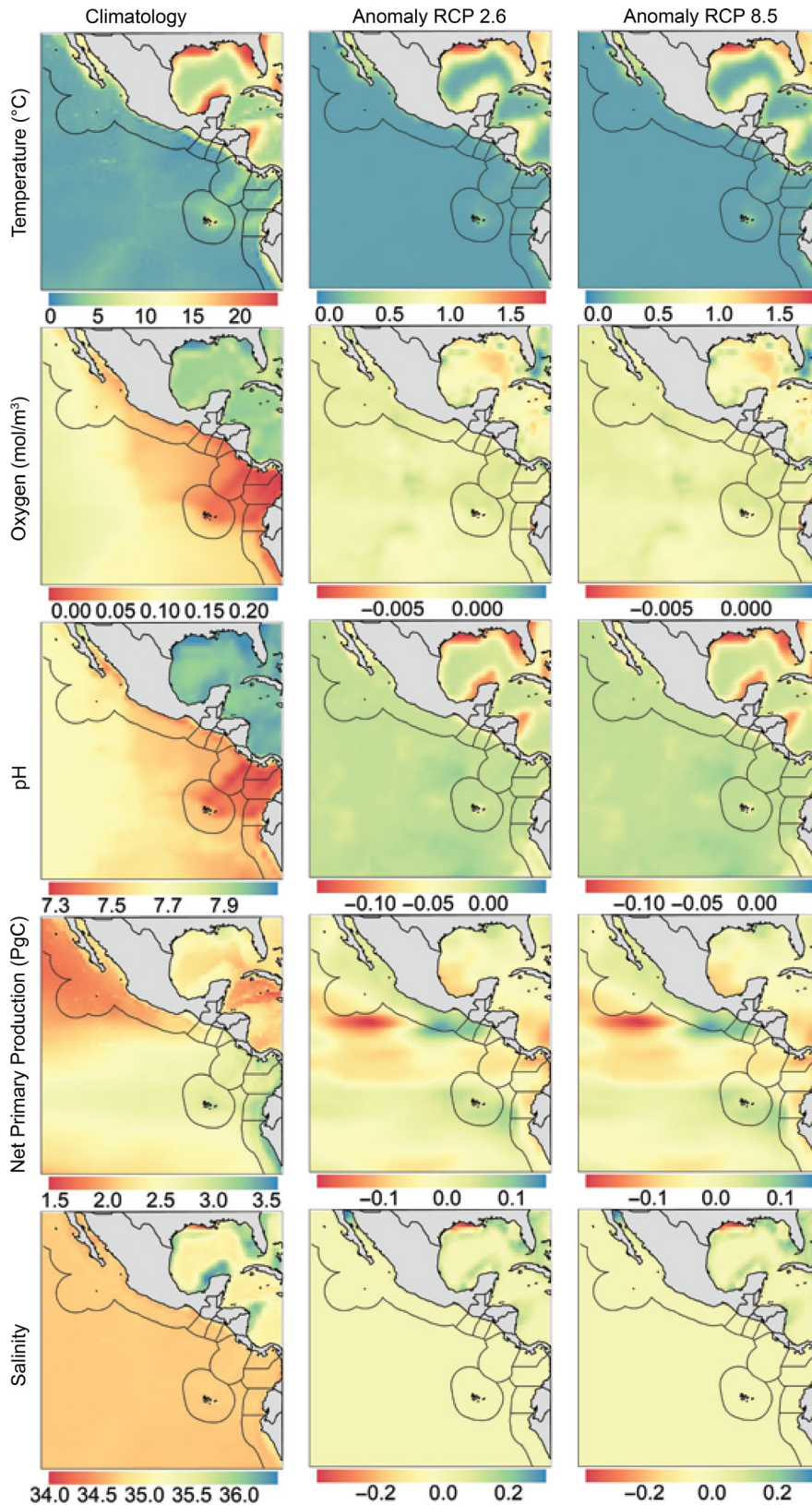


FIGURE 3 Oceanographic conditions at the ocean seafloor in 2001–2020 and anomalies by 2041–2060 under RCP 2.6 and RCP 8.5. Ensembles were created for each variable using the model outputs for the Geophysical Fluid Dynamic Laboratory model (GFDL-ESM-2G), the Institut Pierre Simon Laplace model (IPSL-CM5-MR) and the Max Planck Institute for Meteorology model (MPI-ESM-MR)

produced by wind jets across Central America (Fiedler & Lavín, 2017). Oxygen minimum zones (OMZs) are formed below the shallow thermocline (<80 m) as a result of the high primary productivity in upwelling systems, strong stratification and sluggish circulation

(Figure 3). The southern ETP is characterized by low salinity (<34 psu), while the northern limits are characterized by high salinity (>34 psu), except for an area off Baja California with low-salinity waters transported by the California Current (Fiedler & Lavín, 2017).

2.2 | Fisheries of the ETP

Commercial fisheries catches in the region averaged 11 million tonnes per year during 2005–2014, contributing to approximately 10% of global catches (based on Sea Around Us catch database, Pauly & Zeller, 2015). Marine fisheries in the ETP are diverse in terms of species caught, gears used and fleet sizes (Lluch-Cota et al., 2018). This study focused on species caught by four key fisheries in the ETP: small-scale fisheries, shrimp trawl fisheries, small pelagic fisheries and large pelagic fisheries. Small-scale fisheries generally operate in coastal areas within the continental platform, using a wide variety of gears to capture a large diversity of species. In contrast, the fisheries for shrimp, as well as small and large pelagics, are predominantly large scale. Shrimp trawl fisheries mainly target penaeid, pandalid and solenocerid shrimp species. The small pelagic fisheries mainly operate within the continental shelf and target engraulids and clupeids. Large pelagic fisheries generally operate in more offshore oceanic waters and target tuna, mahi mahi, swordfish and sharks (Cisneros-Montemayor et al., 2013; Donadi et al., 2015; Haas et al., 2015; Harper et al., 2014; Lindop et al., 2015; Lluch-Cota et al., 2018; Schiller et al., 2014; Trujillo et al., 2015).

2.3 | Biotic data

We modelled species caught by the four major fisheries in the ETP, irrespective of the species commercial value. While all fisheries within the region catch a wide variety of species, only a subset of them is landed and sold (Appendix S1: Suppl. 1). Landings records have a low degree of taxonomic resolution and do not include discards. To obtain an accurate representation of species caught by fisheries in the region, inclusive of bycatch and discards, we conducted a thorough scientific literature review that yielded a list of 652 species, comprised of 512 bony fish, 74 elasmobranch species, 47 crustacean species, 16 mollusc species and three echinoderm species. In this study, we attempted to model all species caught by these fisheries, as low-valued species may become valuable in the future.

We compiled global species occurrence data for all species on this list (Appendix S1: Suppl. 2, 3; latitude, longitude and, when available, sampling date) from online databases, museum collections and reports (Angulo et al., 2016; Centro Interdisciplinario de Ciencias Marinas, 2002; Facultad de Ciencias Biológicas, 2001; Froese & Pauly, 2018; GBIF, 2017; Gutiérrez García, 2003, 2004, 2006; Instituto de Biología, 2003; Instituto de Ciencias del Mar y Limnología, 2001a, 2001b; INVEMAR, 2017; IUCN, 2018; Ixquiac, 1998; OBIS, 2017; Robertson & Allen, 2015; Tapia García, 1997). In addition, data from the following databases were accessed through the FishNet2 Portal (www.fishnet2.net, 2017-01-14): Australian Museum, California Academy of Sciences, Cornell University Museum of Vertebrates, Florida Fish and Wildlife Conservation Commission, Universidad Nacional Autónoma de México, IBiología—CNPE/Colección Nacional de Peces, Los Angeles County Museum of Natural History, UNELLEZ

Museo de Zoología, Colección de Peces, MCZ—Harvard University, Oregon State University, Texas Natural History Science Center—Texas Natural History Collections, Tulane University Museum of Natural History—Royal D. Suttkus Fish Collection, University of Arkansas Collections Facility and Yale University Peabody Museum.

We eliminated duplicates, points on land and points outside of the known species biome from the compiled species occurrence data set (Froese & Pauly, 2018; Robertson & Allen, 2015). The data were then gridded into a raster of the global oceans (0.5° of longitude per 0.5° degree of latitude) indicating historical presence of each species. The 547 species with occurrence records in more than 30 cells were selected for further analysis (Hernandez et al., 2006).

2.4 | Abiotic data

We applied generalized linear models (GLM—identity link, Gaussian distribution) to statistically bias-correct (Wilby et al., 1998) average annual climatologies for bottom and surface temperature, oxygen, salinity, pH, primary productivity and mixed layer depth for the ETP (Appendix S1: Suppl. 4). Earth system models (ESMs) account for processes in coarse-grid cells that lead to biases at the local scale. Here, we attempt to correct these biases by modelling the relationship between ESM output and observed climatologies. The dependent variables for each GLM were the annual climatology of observed surface and bottom temperature, salinity, dissolved oxygen concentration (1955–2012) (World Ocean Atlas 2013, <http://www.nodc.noaa.gov/OC5/woa13/>), chlorophyll-*a* concentration (1998 to 2012) (<http://oceancolor.gsfc.nasa.gov>) and mixed layer depth (1998 to 2012) (<http://oceancolor.gsfc.nasa.gov>). The independent variables for each GLM were the annual climatology (1970–2000) of modelled surface and bottom temperature, salinity, dissolved oxygen concentration, chlorophyll-*a* concentration and mixed layer depth from three different commonly used ESM: Geophysical Fluid Dynamic Laboratory model (GFDL-ESM-2G) (Dunne et al. 2013), the Institut Pierre Simon Laplace model (IPSL-CM5A-MR) (Dufresne et al. 2013) and the Max Planck Institute for Meteorology model (MPI-ESM-MR) (Giorgetta et al. 2013). The performance of these ESMs has been extensively examined and tested for applications to the marine realm (Kwiatkowski et al. 2017; Laufkötter et al. 2015). All environmental parameters were regridded and interpolated on to a global 0.5° longitude × 0.5 latitude raster using the bilinear interpolation method, before the bias correction (see Lam et al., 2016).

To account for spatial autocorrelation, we also included the interaction between latitude and longitude as an independent variable in all models. Depth was included as an independent parameter for models of bottom environmental conditions. We did not bias-correct pH, because time series for observed pH data do not exist.

We used the models to produce a regional annual climatology for each parameter based on outputs for each ESM. The global climatologies used to train the species distribution models include the regional bias correction. We assumed the statistical

relationships between ESM and observed climatology will hold in the future and, therefore, used them to project future observed environmental conditions given a set of ESM projections (annual averages of each environmental parameter for RCP 2.6 and RCP 8.5 from 2001 to 2060).

2.5 | Species distribution models

The current and future distributions of the 547 focal species were projected using species distribution models (SDMs). We used a multimodel approach (Jones & Cheung, 2015) to account for the variability across different Earth system models and SDM outputs and increase the accuracy of the projections (Guo et al., 2015; Jones & Cheung, 2015). We applied four SDMs to quantify the environmental niche of each species: Surface Range Envelope (Araújo & Peterson, 2012), maximum entropy method (Maxent) (Elith et al., 2011), generalized boosting model (Elith et al., 2008) and artificial neural networks (Lek & Guégan, 1999). The input data for each SDM were the species occurrence raster (75% of the original presence data were used to train the model) and the global climatology of the environmental conditions. We selected variables representing bottom water conditions for benthic and demersal species, and surface water conditions for pelagic or coastal species (Froese & Pauly, 2018; Robertson & Allen, 2015). We avoided overparameterization by selecting the subset of the environmental parameters that resulted in the highest specialization (narrowness of the niche) and marginality (difference between the niche and the available environment) values (Appendix S1: Suppl. 5) produced by the ecological-niche factor analysis (ENFA, Basille et al., 2008; Calenge, 2006).

For each species, we ran the four SDMs using the three global climatologies (GFDL-ESM-2G, IPSL-CM5-MR and MPI-ESM-MR), resulting in outputs from a total of 12 models per species. All SDMs were run with the Biomod2 package in R (Thuiller et al., 2016). Each SDM calculated a Habitat Suitability Index (HSI) value for each spatial cell in the ETP region, ranging between 0 (not suitable) and 1 (very suitable).

We evaluated the accuracy of each model using an area under the curve (AUC) analysis of the receiver operating characteristic (ROC). We used the ROC to compare the fitted HSI with the species occurrence raster reserved for testing the model fit (25% of the original presences). Models with an AUC below 0.5 were eliminated, as predictions were worse than random (Sing et al., 2005). This analysis was performed with the pROC package in R (Robin et al., 2011). To be consistent with the approximate time frame represented by the occurrence records and for the development of the models, we used the average SDM predictions for 1970 to 2000.

We then projected changes in the geographic distribution of the species environmental niche for each year between 2001 and 2060 under the "high emission" (RCP 8.5) and "strong mitigation" (RCP 2.6) scenarios. We built an ensemble of model outputs for

each species and climate change scenario. Specifically, for each ESM, we first calculated the average HSI weighted by the AUC values of each species distribution model and then averaged HSI values across ESMs, to produce one HSI value per cell. If the habitat suitability was higher than the species prevalence (i.e. the fraction of cells in which the species was present), we considered the species to be present in the cell (Phillips et al., 2009). We averaged projections over a 20-year time frame to reduce the effect of interannual variability of climatic conditions on species distributions (Stock et al., 2011).

We calculated indicators of biogeographic shifts for the species assemblages caught by each of the four fisheries. We present the results for the shrimp trawl fishery separated in target and bycatch species. These indicators include the shift in geographic and depth centroids, local species loss rates, local invasion rates, species turnover (Cheung et al., 2009) and change in habitat suitability for 2041–2060 relative to 2001–2020. Centroids were defined as

$$C = \frac{\sum_{i=1}^n X_i * HSI_i}{\sum_{i=1}^n HSI_i}$$

where C is a latitudinal, longitudinal or depth centroid, X_i is latitude, longitude or depth in each cell, and HSI_i is the HSI for the ensemble model in each cell.

Depth shifts were calculated as the difference between the depth centroid in 2041–2060 and the depth centroid in 2001–2020. Latitudinal and longitudinal shifts were estimated as the shortest distances between the centroids according to the Haversine method (Hijmans et al., 2018), which assumes a spherical earth. Local invasion and local loss rates were estimated as

$$LI_{i,y} = \frac{n_{i,y}^I}{n_i + 1}$$

$$LL_{i,y} = \frac{n_{i,y}^E}{n_i + 1}$$

where n is the number of species per cell at the beginning of the century, and $n_{i,y}^I$ and $n_{i,y}^E$ are the number of species invading or going extinct in each cell, respectively, by the end of the study's time frame. Finally, species turnover is the sum of invasion and extinction rates.

3 | RESULTS

3.1 | Oceanographic section

The bias-corrected surface-level projections show that anomalies by the mid-21st century are larger under RCP 8.5 than RCP 2.6 for surface temperature, oxygen and pH. Differences between RCPs are much lower for seafloor conditions (Figures 2 and 3). Present (2001–2020) temperatures at depth remained between 0°C and 5°C throughout most of the region, bordered by warmer waters of

6–10°C in the narrow shallow areas along the coastline (Figure 3). By the mid-21st century, surface temperatures are projected to increase by 0.96°C, on average, relative to the present, under RCP 8.5, except in upwelling regions. Surface oxygen follows the same spatial patterns, which is not surprising considering the negative correlation between temperature and oxygen solubility.

Amongst the 547 species with sufficient data for species distribution modelling, 505 species were used for further analysis because at least three of the four species distributions models had AUCs above 0.5 (Appendix S1: Suppl. 6). Variability in AUC values was high across SDMs and low across Earth system models (Appendix S1: Suppl. 7). There was a high overlap between species caught by coastal small-scale fisheries (371 spp.) and shrimp trawl fisheries (441 spp. of bycatch, 19 spp. of shrimp; Appendix S1: Suppl. 1). The environmental variables used to model most species distributions were temperature (505 spp.), oxygen (473 spp.), salinity (358 spp.) and pH (356 spp.), due to their high marginality and specificity values estimated from ENFA (Appendix S1: Suppl. 5).

3.2 | Species shifts

In the northern region (>15° N), the centroids of species distributions were projected to shift towards the north-west at an average rate of 71 km decade⁻¹, while in the northern equatorial region (0° to 15° N) and the southern ETP (0° to 20° S), species were projected to shift south-east at an average rate of 59 and 30 km decade⁻¹, respectively (Figure 4). The direction of projected species geographic shifts was similar across fisheries. Demersal species in most countries were found to move towards shallower waters by an average rate of approximately 1–13 m decade⁻¹; however, there was considerable

variability in the direction and magnitude of depth shifts across species (Figure 5).

3.3 | Habitat suitability

The spatial patterns of changes in habitat suitability by 2041–2060 were similar between RCP 2.6 and RCP 8.5, although in most cases the magnitude of change was greater for RCP 8.5 (Table 1). The habitat suitability of all species was projected to increase or remain the same by 2041–2060 relative to present in the northern and southern limits of the study area (northern Mexico, southern Ecuador and Peru), while it was projected to decrease in southern Mexico, Guatemala, El Salvador, Nicaragua and northern Costa Rica (Figure 6). Consequently, the habitat suitability for all species combined is projected to decrease on average in all EEZs except Peru, with the largest declines from Guatemala to Costa Rica (Table 1). The lowest species turnover rates across all species are also expected in Peru and Mexico (Table 2). Models projected high rates of local loss across all species throughout the study region, except along the northern and southern limits (Figure 7), and high local invasion rates for Panama, Colombia and Ecuador (Figure 8).

Projections of habitat suitability for species caught by small-scale fisheries indicated declines would be strongest from Guatemala to Nicaragua (–16%). In contrast, species habitat suitability was projected to increase in Galapagos and Peru (Table 1; Figure 6). Rates of local loss for species caught by small-scale fisheries were projected to be higher further from the coasts along Costa Rica, Panama, Colombia, Ecuador and Galapagos (Figure 7). The highest local invasion rates were projected for northern Mexico and throughout Costa Rica, Panama, Colombia and

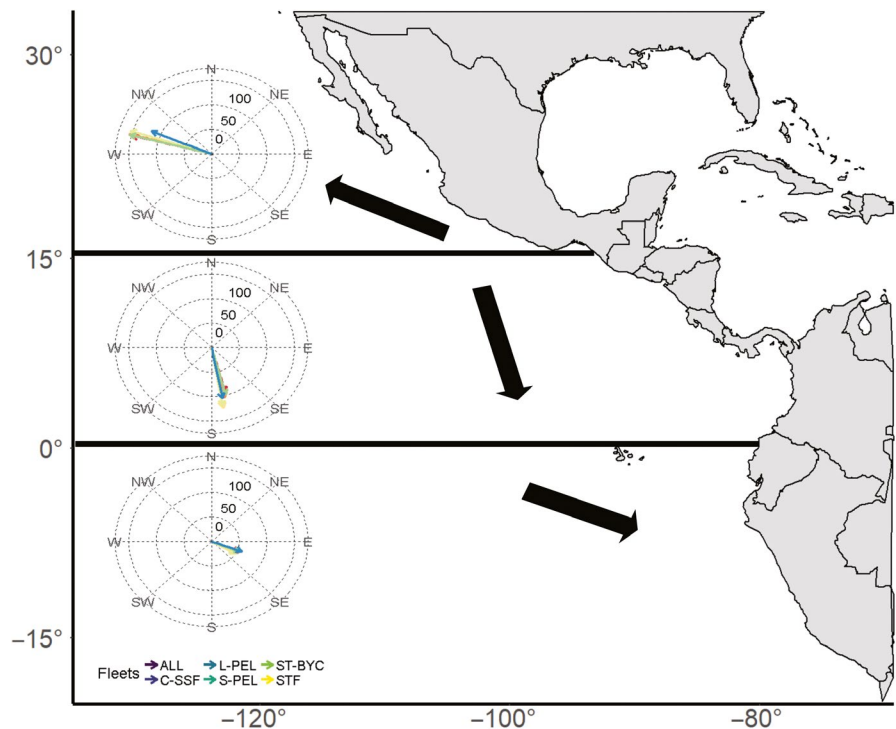


FIGURE 4 Direction and distance (km) of geographic shifts undergone by species groups (classified according to fisheries) by 2041–2060 relative to 2001–2020 under RCP 8.5. L-PEL: large pelagics; STF: shrimp trawl target fishery; ST-BYC: shrimp trawl bycatch; C-SSF: coastal small-scale fisheries; S-PEL: small pelagics

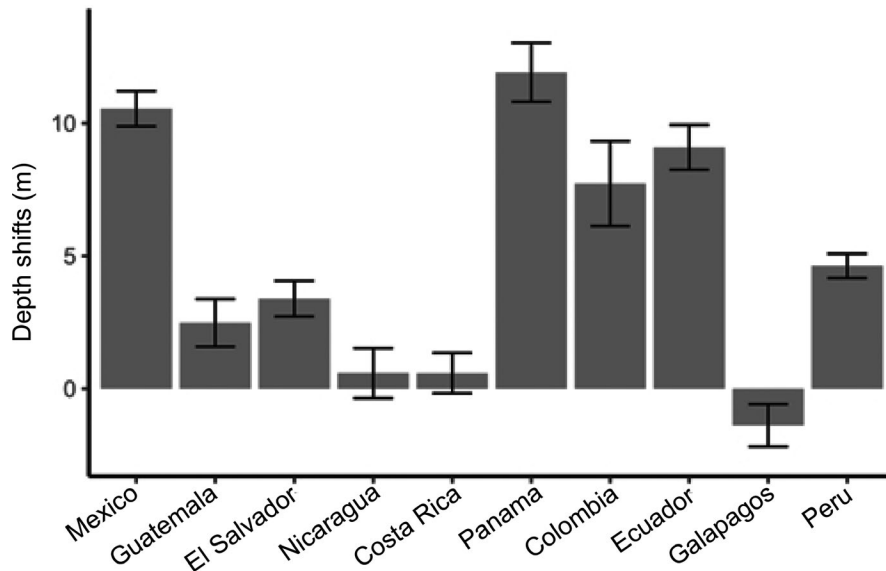


FIGURE 5 Mean and standard deviation of shifts in depth centroids (average depth weighted by the Habitat Suitability Index) for demersal species by 2041–2060 relative to 2001–2020 under RCP 8.5. Positive changes indicate species are shifting towards shallower waters

TABLE 1 Per cent change in the habitat suitability projected by 2041–2060 relative to 2001–2020 for species groups caught in the four main fisheries (large pelagics, small pelagics, shrimp trawl (incl. of bycatch) and small scale) in the Pacific Exclusive Economic Zones from Mexico to Peru.

Pacific EEZ	All fisheries		Coastal small-scale fisheries		Large pelagic fisheries		Small pelagic fisheries		Shrimp trawl bycatch		Shrimp trawl fisheries	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
	Mexico	-2.39	-4.41	-2.67	-4.98	-13.74	-14.42	-4.55	-10.00	-1.70	-4.00	9.21
Guatemala	-10.18	-13.59	-12.23	-15.85	-18.25	-25.98	-31.24	-40.19	-9.86	-13.18	4.22	4.08
El Salvador	-11.32	-13.45	-13.33	-15.50	-18.16	-24.61	-35.04	-42.13	-11.12	-13.10	0.21	0.94
Nicaragua	-10.46	-13.94	-11.67	-15.97	-12.44	-20.19	-30.45	-45.69	-10.86	-13.86	-1.09	-2.02
Costa Rica	-12.11	-9.04	-13.46	-10.37	-8.77	-8.80	-32.68	-28.20	-12.65	-9.32	0.68	1.31
Panama	-4.62	-7.15	-5.58	-8.51	-2.99	-9.05	-17.64	-29.06	-4.81	-7.21	2.65	1.28
Colombia	-2.42	-6.55	-3.14	-7.47	-1.62	-5.28	-8.03	-20.20	-2.48	-6.77	4.88	0.89
Ecuador	-1.44	-0.89	-1.54	-1.13	1.57	-0.99	-3.52	-4.69	-1.53	-0.73	3.78	5.17
Galapagos	-0.16	1.24	0.41	1.84	1.73	0.99	2.50	3.11	-0.46	1.25	4.35	5.54
Peru	6.01	4.74	5.91	4.48	3.37	3.44	17.42	13.90	6.63	5.15	13.10	13.08

Galapagos (Figure 8). Projected turnover rates for species caught by small-scale fisheries were higher than for any other fishery, surpassing 38% between Costa Rica and Galapagos, and reaching almost 80% in Colombia (Table 2).

Projected decreases in habitat suitability for species caught by large pelagic fisheries were highest between Guatemala and Nicaragua (–20% to –26%) (Table 1), and projected turnover rates were highest between Guatemala and Ecuador (Table 2). Most invasions were projected to occur from Panama to Peru (Figure 8), while local losses were expected to remain high throughout the study region, except along the northern and southern limits (Figure 7).

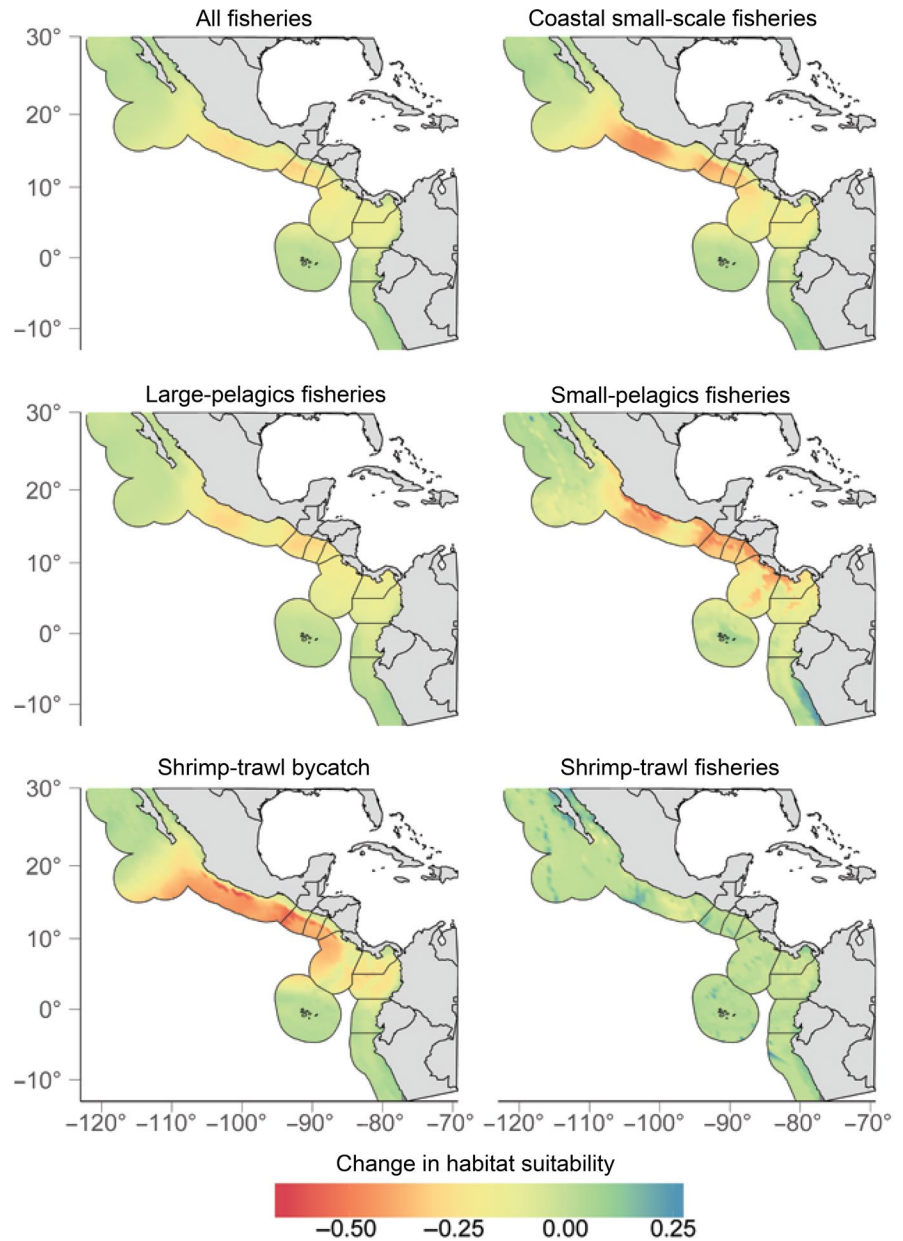
Models projected large declines in habitat suitability for species caught by small pelagic fisheries from Guatemala to Colombia (Table 1) and a 17% increase for Peru (Table 1). Species turnover

projections were below 30% (Table 2), with the highest local losses expected along the continental shelf, especially from Costa Rica to Ecuador (Figure 7). Projected invasion rates were also highest for the continental shelf area (Figure 8).

The habitat suitability of species targeted by the shrimp trawl fishery was projected to increase in all EEZs except Nicaragua, and particularly in Mexico and Peru (Table 1, Figure 6). Local loss rate projections were low throughout the study region apart from small areas in the Gulf of California (Figure 7). Shrimp invasion rates were projected to follow a patchy distribution, mainly along the coastline of northern Mexico and southwards of Panama (Figure 8). Target species in this fishery also showed the lowest turnover rates, with projections below 6% for all EEZs (Table 2).

In contrast to species targeted by the shrimp trawl fishery, the habitat suitability of species caught as bycatch was projected to

FIGURE 6 Projected change in the habitat suitability of species groups caught in the four main fisheries (large pelagics, small pelagics, shrimp trawl (incl. of bycatch) and small scale) by 2041–2060 relative to present (2001–2020) under RCP 8.5. Warm hues in the colour ramp denote losses in habitat suitability, while cool hues denote gains



decrease in all EEZs except the Galapagos and Peru, with the highest impacts estimated for the area between Guatemala and Costa Rica (9%–13%) (Table 1). Patterns of decreasing habitat suitability and local loss mirrored those of small-scale fisheries, but with higher losses spanning further south (Figures 6 and 7). Invasion rates were projected to be much lower than for small-scale fisheries and were limited to the northern and southern limits of the study area (Figure 8).

Most species in each EEZ were not projected to undergo declines in habitat suitability (Appendix S1: Suppl. 8). The changes in habitat suitability of species in the southern EEZs of Peru, Galapagos and Ecuador had narrower frequency distributions, showing smaller changes in habitat suitability. In the remaining EEZs, changes in habitat suitability had skewed distributions, with a small percentage of species decreasing up to 100%. Habitat suitability was projected to increase for a small number of species.

4 | DISCUSSION

Our results provide insights into the expected climate change impacts on regional biogeography and living marine resources in the ETP between now and 2041–2060, a time frame deemed relevant to inform climate change adaptation of fisheries management actions. Results show limited divergence in the projected oceanographic conditions and habitat suitability losses between greenhouse gas emissions scenarios from the present day to 2041–2060 because of lagged responses of some oceanic variables to changes in atmospheric greenhouse gas concentrations.

Two general patterns emerge when examining the oceanographic processes responsible for the distribution of fisheries species: species are shifting towards cooler waters in the northern and southern margins of the ETP and towards more oxygenated, shallower waters. Temperature and oxygen were predicted by our models to be

TABLE 2 Projected species turnover (%) by 2041–2060 relative to 2001–2020 for species groups caught in the four main fisheries (large pelagics, small pelagics, shrimp trawl (incl. of bycatch) and small scale) in the Pacific Exclusive Economic Zones from Mexico to Peru

Pacific EEZ	All fisheries		Coastal small-scale fisheries		Large pelagic fisheries		Small pelagic fisheries		Shrimp trawl bycatch		Shrimp trawl fisheries	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
Mexico	5.78	12.36	8.74	16.60	4.12	9.59	3.06	5.22	7.90	15.33	3.69	5.61
Guatemala	17.27	28.19	1.65	2.42	18.82	30.74	0.00	5.67	1.89	2.38	0.54	0.66
El Salvador	20.06	19.68	3.27	4.06	25.01	24.31	3.99	6.52	2.54	3.20	3.05	3.05
Nicaragua	10.56	11.68	6.22	7.21	14.39	18.56	24.24	30.30	5.87	6.77	3.18	5.45
Costa Rica	17.57	32.27	42.97	48.32	17.48	33.88	8.20	10.14	9.57	27.40	1.20	1.21
Panama	21.64	33.46	41.79	57.70	23.51	39.11	10.25	14.21	18.02	27.23	6.08	4.40
Colombia	22.34	41.12	57.42	79.47	22.23	46.74	7.19	7.55	15.85	32.78	2.05	3.37
Ecuador	10.71	28.89	12.76	38.20	9.48	28.98	5.81	21.00	16.56	45.88	3.53	3.84
Galapagos	5.19	14.88	10.39	38.70	1.82	7.04	5.27	14.83	12.04	38.44	2.79	2.82
Peru	4.37	8.69	4.17	9.38	6.87	10.62	3.71	7.04	3.91	11.15	1.54	1.65

the most important variables shaping the environmental niche of the study species, and therefore, warming and deoxygenation will likely drive the redistribution of species in the ETP. These patterns may be representative of the broader response of marine biodiversity to climate change in the region. Such patterns also agree with expectations from proposed theory explaining the biological responses of marine fishes and invertebrates to changing temperature and oxygen levels. For example, the “oxygen- and capacity-limited thermal tolerance” theory (OCLTT) suggests that temperatures above an organism’s thermal tolerance threshold results in a smaller aerobic scope for physiological functions, like growth and reproduction (Pörtner, 2001). According to the Gill-Oxygen Limitation Theory (GOLT), an increase in oxygen uptake to meet the higher metabolic oxygen demands under ocean warming is limited by the constraints of available area for gaseous exchange in the gill (Pauly & Cheung, 2018). Thus, fish move to waters with temperatures that resemble those of their original habitats to satisfy organisms’ oxygen needs.

4.1 | Species shifts

The Humboldt Current and California Current eastern boundary upwelling systems (produced by alongshore winds in Peru and northern Mexico) and the equatorial upwelling systems (near the equator produced by the Coriolis force) have a cooling effect along the northern and southern limits of the ETP (Fiedler & Lavín, 2017). These upwelling systems are separated by the eastern Pacific warm pool along Central America, resulting in an inverse temperature gradient in the Northern Hemisphere (Fiedler & Lavín, 2017). Consequently, between 0° N and 15° N species are moving towards the equator instead of the poles (Fiedler & Lavín, 2017; Pörtner et al., 2014). As expected, species are shifting at a faster rate in tropical areas with weaker latitudinal temperature gradients, where their preferred temperature has shifted further away. In contrast,

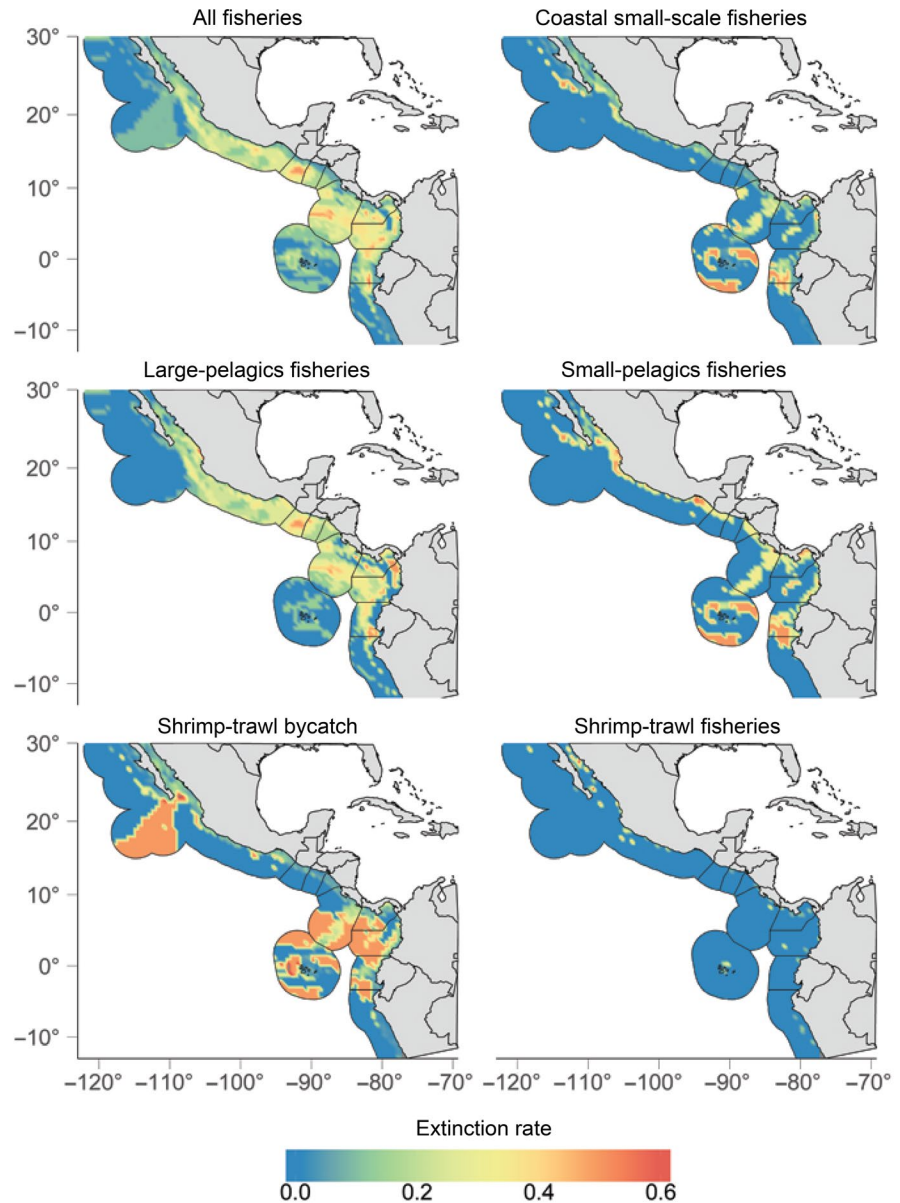
the steeper temperature gradient along the Humboldt Current allows for species to find their preferred temperature within shorter distances (Robinson et al., 2015).

Species within the ETP shift towards the equator when waters warm during El Niño events (Sielfeld et al., 2010), further supporting the projected equatorwards shift of tropical species. Local losses, population recoveries and range extensions are common responses to El Niño–Southern Oscillation-related interannual temperature variability in the ETP (Mora & Robertson, 2005). Reports from as early as 1982 show that tropical shrimp shift southwards towards Peru during El Niño (Barber & Chavez, 1983). A more recent study identified 100 tropical species in Chilean waters (with subtropical and temperate climatic conditions) during El Niño years (Sielfeld et al., 2010).

In contrast to observed range shifts elsewhere (Dulvy et al., 2008; Poloczanska et al., 2013), our findings show that species are projected to shift towards shallower instead of deeper waters. This shoaling of species can be attributed to the expansion of oxygen minimum zones (OMZs), which drive most organisms into shallower and more oxygenated waters (Stramma et al., 2008, 2010, 2012). These shallower waters are also warmer, which increases the energy required to meet basic metabolic demands and may require organisms to compensate for temperatures outside their tolerance range (Gallo & Levin, 2016; Pörtner et al., 2014). OMZs are known to compress the habitats of both benthic and pelagic species (Gallo & Levin, 2016). For example, OMZs have been shown to compress the habitat of billfish in the eastern Pacific warm pool (Prince and Goodyear 2007) and of small pelagics in Peru (Bertrand et al., 2011). The expansion of OMZ was also found to force echinoderms in the California Current to shoal, while the contraction of OMZ during El Niño temporarily expanded the habitat of demersal fish towards deeper waters in Peru (Arntz et al., 2006; Keller et al., 2015; Sato, Levin, and Schiff, 2017).

Decreases in the habitat suitability and local losses of the living marine resources focused on in this study mainly occurred across the EEZs of Central America and Colombia, coinciding with the

FIGURE 7 Projected local extinction rate of species groups caught in the four main fisheries (large pelagics, small pelagics, shrimp trawl (incl. of bycatch) and small scale) for 2041–2060 relative to 2001–2020 under RCP 8.5. The larger the extinction rate, the warmer the colour



warming and expansion of the eastern Pacific warm pool (Fiedler & Lavín, 2017). High invasion rates along the northern limits of the study area and south of 10°N could be caused by species shifting towards the cooler waters of the upwelling systems. Projections for upwelling systems under climate change, however, are uncertain as Earth system models do not resolve upwelling processes well (Lluch-Cota et al., 2014). The potential increase in upwelling intensity could affect species biogeography. For example, enhanced hypoxia and acidification associated with upwelling activity could limit the beneficial effects of cooling and higher primary productivities on habitat suitability (Bakun, 2017; Bakun et al., 2015; Fiedler & Lavín, 2017).

4.2 | Implications for fisheries and conservation

Our findings highlight the importance of local-scale oceanographic and biological data to elucidate the multidimensional biogeographic

shifts on fishery species and their potential impacts on fisheries in the region. Overall, changes in the habitat suitability, and therefore composition of species caught by the four main fisheries, are expected to be most severe along Central America, with substantial variations in the magnitude of impacts across fisheries.

The results suggest that shrimp fisheries may benefit from the impacts of climate change in the ETP because of the increase in habitat suitability of its target species. Shrimp in general may be less vulnerable to climate change because of their fast population growth rates, high larval dispersal rates and low ecological specificity (Hsieh et al., 2006). Nevertheless, many shrimp stocks throughout the region are overfished (Cisneros-Montemayor et al., 2013; Donadi et al., 2015; Haas et al., 2015; Harper et al., 2014; Lindop et al., 2015; Schiller et al., 2014; Trujillo et al., 2015). In addition, shrimp catches are correlated with El Niño, suggesting climate variability may strongly influence interannual stock dynamics (Arreguín-Sánchez et al., 2015; Diop et al., 2007; López-Martínez et al., 2002).

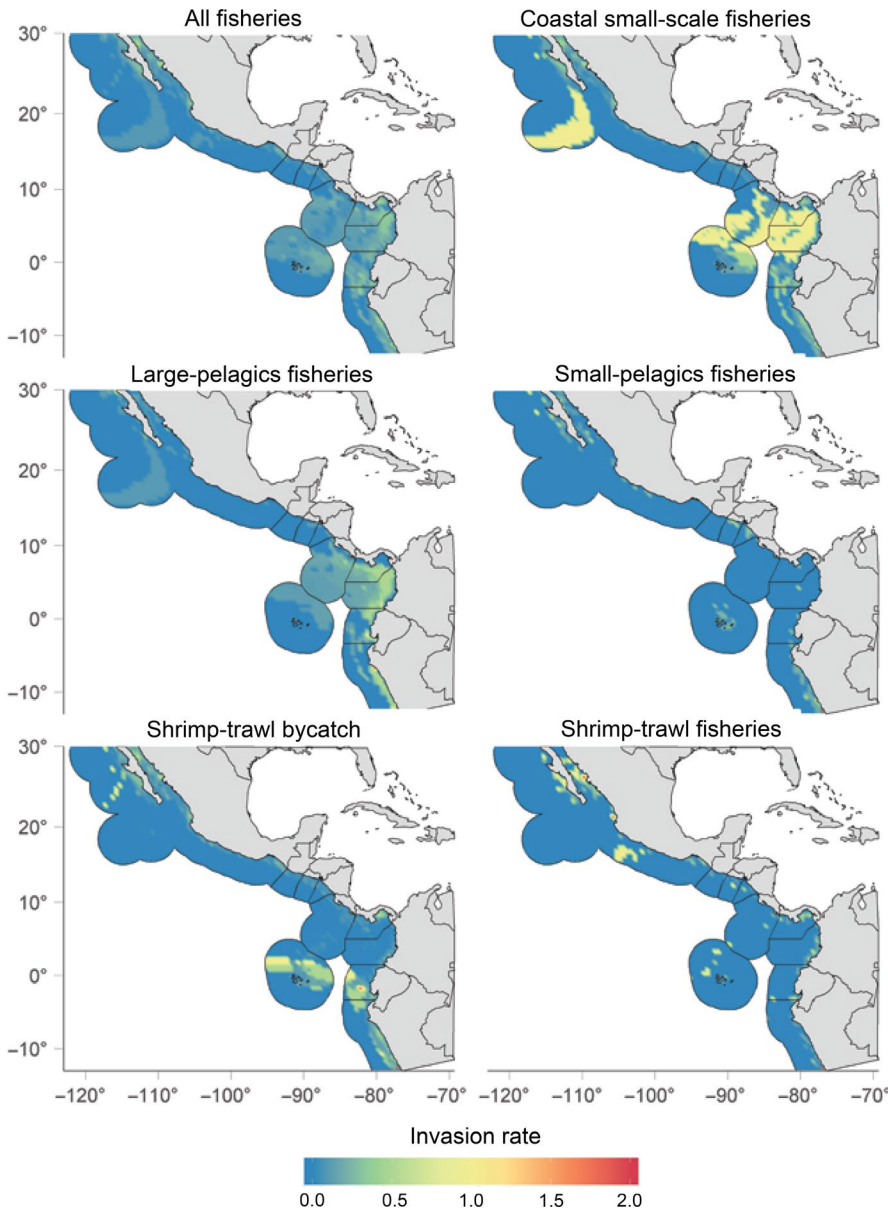


FIGURE 8 Projected local invasion rate of species groups caught in the four main fisheries (large pelagics, small pelagics, shrimp trawl (incl. of bycatch) and small scale) for 2041–2060 relative to 2001–2020 under RCP 8.5. The larger the invasion rate, the warmer the colour

Overall, the shrimp fishery's environmental impacts would increase, as it would continue to put additional pressure on shrimp bycatch species, which are projected to undergo strong declines in habitat suitability.

In contrast, small-scale fisheries are at high risk of impacts under climate change, with findings showing strong declines in habitat suitability and high local losses. However, such risk may be mitigated by fisheries catching species projected to move into their fishing grounds and therefore likely replacing a proportion of foregone catches. For example, despite projected declines in habitat suitability for species caught by small-scale fisheries in Costa Rica, Panama, Colombia, Ecuador and Galapagos, their waters will become more suitable for a large number of species currently not caught by the fisheries. If these species are able to colonize and establish populations in the newly available habitats, without causing local losses of traditional target species, "invaders" may help compensate for the

decrease in traditionally targeted species. The flexibility granted by the multigear, multispecies approach of small-scale fisheries may allow them to seize the opportunity of catching these new species on their fishing grounds (Lluch-Cota et al., 2018). On the other hand, small-scale fishing communities may be highly vulnerable to climate change impacts, because they do not have the vessels to chase stocks on the move, many of their stocks are already overfished, they are highly dependent on short-term income (Lluch-Cota et al., 2018), and "invading" species may not contribute to food security and livelihood opportunities in the same way. Any impact on the small-scale fishing sector is likely to affect food security and local economies to a much larger extent than official statistics would indicate, because their catches, employment and income are widely under-reported (Pauly & Zeller, 2016). Findings from this study can help inform stewardship and sustainable fishing practices local communities need to adopt to support their needs in the future.

4.3 | Model robustness and uncertainty

While the regional geographic patterns of projected changes are considered reliable, the specific magnitude of projected changes is affected by model and scenario uncertainties (Cheung, et al., 2016; Wabnitz et al., 2018). While the multimodel approach accounts for uncertainties associated with future emissions, species distribution models' and Earth system models' structures, several additional sources of uncertainty remain (Peterson & Soberón, 2012; Stock et al., 2011). First, the results depend on the accuracy of the bias-corrected ESM projections (Cheung, et al., 2016) and the assumption that the correlation between the ESMs and the observed climatology will hold in the future. In addition, model outputs rely on ESMs, which exclude small-scale processes that would allow to better resolve regional upwelling dynamics and coastal processes. Second, the species distribution modelling approach applied here focuses on habitat suitability in a single-species context. Therefore, the method does not account for ecosystem effects, such as interspecies dynamics, the ability of invading species to establish themselves in new habitats, or the possible biodiversity and habitat loss that invading species may cause (Pecl et al., 2017). Local losses and invasions have the potential to modify ecosystem structure and function (Marzloff et al., 2016; Pecl et al., 2017). Third, we may have underestimated the declines in habitat suitability by modelling the realized niches of species rather than populations, for which there are little data available. The average niche breadth of a species is much wider than that of a population and therefore will be less sensitive to projected changes in environmental conditions. Fourth, several tropical species are already close to their thermal limits, likely increasing their vulnerability to further warming (Sunday, Bates, and Dulvy 2011). Fifth, we do not consider other human stressors that have and will continue to drive impacts on living marine resources (Galbraith et al., 2017; Peterson & Soberón, 2012; Polidoro et al., 2012). For example, our models do not account for the environmental impacts of shrimp fisheries, nor for the effects of overfishing of large pelagics in the ETP (Dent & Clarke, 2015; Espinoza et al., 2018). Therefore, billfish, tunas and other large pelagics are probably even more vulnerable to climate change than our results indicate. Moreover, local losses or invasions of top predators may trigger trophic cascades that cause disproportionate impacts on marine ecosystems (Heupel et al., 2014). Sixth, the possibility of genetic and phenotypic plasticity that determine potential acclimation and rapid evolution of marine species may reduce their sensitivity to climate change (Calosi et al., 2016; Quintero and Wiens, 2013). Evidence of evolutionary responses of marine fishes and invertebrates to climate change is still limited and is an important area for further exploration in future studies. Overall, most of these sources of uncertainty would likely produce stronger declines in habitat suitability, while incorporating the potential adaptation responses of species may result in more optimistic projections.

Our findings contribute to the understanding of species responses to the growing threat of climate change in a complex oceanographic region, in support of efforts to implement management and

conservation actions. This study can help identify which species may need greater protection in the future and identify areas that would support greater resilience in the face of climate change, such as biodiversity refuges (Hoffmann, Irl, and Beierkuhnlein, 2019; Kujala et al., 2013). The identification of areas that may be particularly vulnerable to climate change may also be used to inform marine spatial planning for climate adaptation initiatives in the ETP). Thus, species projections can inform policy decisions and conservation strategies that ensure the protection and sustainable use of living marine resources (Wilson et al., 2020).

ACKNOWLEDGEMENTS

TMC acknowledges the Fondo de Incentivos of the Consejo Nacional para Investigaciones Científicas y Tecnológicas (CONICIT) and the Ministerio de Ciencia, Tecnología y Telecomunicaciones (MICITT) of Costa Rica, for a scholarship. WLC acknowledges support from the Nippon Foundation—the University of British Columbia Nereus Program. TMC and WLC acknowledge funding support from the Natural Sciences and Research Council of Canada (Discovery Grant).

DATA AVAILABILITY STATEMENT

We used open access data sources for the analysis in this manuscript and have included them in the references and supplements.

ORCID

Taylor M. Clarke  <https://orcid.org/0000-0002-9438-5794>

Colette Wabnitz  <https://orcid.org/0000-0002-5076-9163>

REFERENCES

- Allison, E. H., Perry, A. L., Badjeck, M.-C., Adger, W. N., Brown, K., Conway, D., Halls, A. S., Pilling, G. M., Reynolds, J. D., Andrew, N. L., & Dulvy, N. K. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, 10, 173–196. <https://doi.org/10.1111/j.1467-2979.2008.00310.x>
- Angulo, A., López, M., Bussing, W., & Rosa, A. (2016). Colección ictiológica del Museo de Zoología de la Universidad de Costa Rica. In: Del Moral-Flores, L. F., Ramírez-Villalobos, Á. J., Martínez-Pérez, J. A., González-Acosta, A. F., Franco-López, J. (Eds.), *Colecciones ictiológicas de Latinoamérica. Facultad de Estudios Superiores Iztacala, Universidad Nacional Autónoma de México & Sociedad Mexicana de Ictiología, Mexico*, pp. 56–65.
- Araújo, M. B., & Peterson, A. T. (2012). Uses and misuses of bioclimatic envelope modeling. *Ecology*, 93, 1527–1539. <https://doi.org/10.1890/11-1930.1>
- Arreguín-Sánchez, F., del Monte-Luna, P., & Zetina-Rejón, M. J. (2015). Climate change effects on aquatic ecosystems and the challenge for fishery management: Pink Shrimp of the southern Gulf of Mexico. *Fisheries*, 40, 15–19. <https://doi.org/10.1080/03632415.2015.988075>
- Bakun, A. (2017). Climate change and ocean deoxygenation within intensified surface-driven upwelling circulations. *Philos. Trans. R. Soc. A*, 375, 20160327. <https://doi.org/10.1098/rsta.2016.0327>
- Bakun, A., Black, B. A., Bograd, S. J., García-Reyes, M., Miller, A. J., Rykaczewski, R. R., & Sydeman, W. J. (2015). Anticipated effects of climate change on coastal upwelling ecosystems. *Current Climate Change Reports*, 1, 85–93. <https://doi.org/10.1007/s40641-015-0008-4>
- Barber, R. T., & Chavez, F. P. (1983). Biological consequences of El Niño. *Science*, 222, 1203–1210. <https://doi.org/10.1126/science.222.4629.1203>

- Basille, M., Calenge, C., Marboutin, É., Andersen, R., & Gaillard, J.-M. (2008). Assessing habitat selection using multivariate statistics: Some refinements of the ecological-niche factor analysis. *Ecological Modelling*, 211, 233–240. <https://doi.org/10.1016/j.ecolmodel.2007.09.006>
- Béné, C., Wood, R. G., Newsham, A., & Davies, M. (2012). *Resilience: New Utopia or New Tyranny? Reflection about the potentials and limits of the concept of resilience in relation to vulnerability reduction programmes*. IDS Work. Pap., 2012, 1–61. <https://doi.org/10.1111/j.2040-0209.2012.00405.x>
- Bertrand A., Chaigneau A., Peraltilla S., Ledesma J., Graco M., Monetti F., Chavez F. P. (2011). Oxygen: A Fundamental Property Regulating Pelagic Ecosystem Structure in the Coastal Southeastern Tropical Pacific. *PLoS ONE*, 6(12), e29558. <http://dx.doi.org/10.1371/journal.pone.0029558>
- Blasiak R., Spijkers J., Tokunaga K., Pittman J., Yagi N., Österblom H. (2017). Climate change and marine fisheries: Least developed countries top global index of vulnerability. *PLOS ONE*, 12(6), e0179632. <http://dx.doi.org/10.1371/journal.pone.0179632>
- Buurman, J., & Babovic, V. (2016). Adaptation pathways and real options analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, 35, 137–150. <https://doi.org/10.1016/j.polsoc.2016.05.002>
- Calenge, C. (2006). The package “adehabitat” for the R software: A tool for the analysis of space and habitat use by animals. *Ecological Modelling*, 197, 516–519. <https://doi.org/10.1016/j.ecolmodel.2006.03.017>
- Calosi P., De Wit P., Thor P., Dupont S. (2016). Will life find a way? Evolution of marine species under global change. *Evolutionary Applications*, 9(9), 1035–1042. <http://dx.doi.org/10.1111/eva.12418>
- Centro Interdisciplinario de Ciencias Marinas (2002). *Colección Ictiológica del CICIMAR-IPN (Base de datos REMIB-CONABIO)*. Instituto Politécnico Nacional.
- Chambers, L. E., Barnard, P., Poloczanska, E. S., Hobday, A. J., Keatley, M. R., Allsopp, N., & Underhill, L. G. (2017). Southern Hemisphere biodiversity and global change: Data gaps and strategies: Southern Hemisphere Data Gaps and Strategies. *Austral Ecology*, 42, 20–30. <https://doi.org/10.1111/aec.12391>
- Cheung, W. W. L., Jones, M. C., Reygondeau, G., & Frölicher, T. L. (2018). Opportunities for climate-risk reduction through effective fisheries management. *Global Change Biology*, 24(11), 5149–5163. <https://doi.org/10.1111/gcb.14390>
- Cheung, W. W. L., Jones, M. C., Reygondeau, G., Stock, C. A., Lam, V. W. Y., & Frölicher, T. L. (2016). Structural uncertainty in projecting global fisheries catches under climate change. *Ecological Modelling*, 325, 57–66. <https://doi.org/10.1016/j.ecolmodel.2015.12.018>
- Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., & Pauly, D. (2009). Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, 10, 235–251. <https://doi.org/10.1111/j.1467-2979.2008.00315.x>
- Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16, 24–35. <https://doi.org/10.1111/j.1365-2486.2009.01995.x>
- Cheung, W. W. L., Reygondeau, G., & Frölicher, T. L. (2016). Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science*, 354, 1591–1594. <https://doi.org/10.1126/science.aag2331>
- Cisneros-Montemayor, A. M., Cisneros-Mata, M. A., Harper, S., & Pauly, D. (2013). Extent and implications of IUU catch in Mexico's marine fisheries. *Marine Policy*, 39, 283–288. <https://doi.org/10.1016/j.marpol.2012.12.003>
- Dent, F., & Clarke, S. (2015). *State of the global market for shark products*. FAO fisheries and aquaculture technical paper.
- Diop, H., Keithly, W. R., Kazmierczak, R. F., & Shaw, R. F. (2007). Predicting the abundance of white shrimp (*Litopenaeus setiferus*) from environmental parameters and previous life stages. *Fisheries Research*, 86, 31–41. <https://doi.org/10.1016/j.fishres.2007.04.004>
- Donadi, R., Au, A., Zyllich, K., Harper, S., & Zeller, D. (2015). *Reconstruction of marine fisheries in El Salvador 1950–2010*. Work. Pap., Working Paper Series, Fisheries Centre, The University of British Columbia 2015–35, 1–22.
- Dufresne J.-L., Foujols M.-A., Denvil S., Caubel A., Marti O., Aumont O., Balkanski Y., Bekki S., Bellenger H., Benshila R., Bony S., Bopp L., Braconnot P., Brockmann P., Cadule P., Cheruy F., Codron F., Cozic A., Cugnet D., de Noblet N., Duvel J.-P., Ethé C., Fairhead L., Fichefet T., Flavoni S., Friedlingstein P., Grandpeix J.-Y., Guez L., Guilyardi E., Hauglustaine D., Hourdin F., Idelkadi A., Ghattas J., Joussaume S., Kageyama M., Krinner G., Labetoulle S., Lahellec A., Lefebvre M.-P., Lefevre F., Levy C., Li Z. X., Lloyd J., Lott F., Madec G., Mancip M., Marchand M., Masson S., Meurdesoif Y., Mignot J., Musat I., Parouty S., Polcher J., Rio C., Schulz M., Swingedouw D., Szopa S., Talandier C., Terray P., Viovy N., Vuichard N. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Climate Dynamics*, 40(9–10), 2123–2165. <http://dx.doi.org/10.1007/s00382-012-1636-1>
- Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmüller, V., Dye, S. R., & Skjoldal, H. R. (2008). Climate change and deepening of the north sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, 45, 1029–1039.
- Dunne J. P., John J. G., Shevliakova E., Stouffer R. J., Krasting J. P., Malyshev S. L., Milly P. C. D., Sentman L. T., Adcroft A. J., Cooke W., Dunne K. A., Griffies S. M., Hallberg R. W., Harrison M. J., Levy H., Wittenberg A. T., Phillips P. J., Zadeh N. (2013). GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics*. *Journal of Climate*, 26(7), 2247–2267. <http://dx.doi.org/10.1175/jcli-d-12-00150.1>
- Elith, J., Leathwick, J. R., & Hastie, T. (2008). A working guide to boosted regression trees. *Journal of Animal Ecology*, 77, 802–813. <https://doi.org/10.1111/j.1365-2656.2008.01390.x>
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, 17, 43–57. <https://doi.org/10.1111/j.1472-4642.2010.00725.x>
- Espinoza, M., Díaz, E., Angulo, A., Hernández, S., & Clarke, T. M. (2018). Chondrichthyan diversity, conservation status, and management challenges in Costa Rica. *Frontiers in Marine Science*, 5, <https://doi.org/10.3389/fmars.2018.00085>
- Facultad de Ciencias Biológicas (2001). *Colección de Crustáceos Decápodos Marinos de las Costas Mexicanas (UANL) (Base de datos REMIB-CONABIO)*. Universidad Autónoma de Nuevo León.
- Fiedler, P. C., & Lavín, M. F. (2017). Oceanographic conditions of the Eastern Tropical Pacific. In P. W. Glynn, D. P. Manzanillo, & I. C. Enochs (Eds.), *Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic Environment* (pp. 59–83). Springer. https://doi.org/10.1007/978-94-017-7499-4_3
- Frazão Santos C., Agardy T., Andrade F., Calado H., Crowder L. B., Ehler C. N., García-Morales S., Gissi E., Halpern B. S., Orbach M. K., Pörtner H., Rosa R. (2020). Integrating climate change in ocean planning. *Nature Sustainability*, 3(7), 505–516. <http://dx.doi.org/10.1038/s41893-020-0513-x>
- Froese, R., & Pauly, D. (2018). *FishBase* [WWW Document]. World Wide Web Electron. Publ. URL www.fishbase.org (accessed 9.10.18).
- Galbraith, E. D., Carozza, D. A., & Bianchi, D. (2017). A coupled human-Earth model perspective on long-term trends in the global marine fishery. *Nature Communications*, 8, 14884. <https://doi.org/10.1038/ncomms14884>

- Gallo, N. D., & Levin, L. A. (2016). Fish ecology and evolution in the world's oxygen minimum zones and implications of ocean deoxygenation. In: Curry, B. E. (Ed.), *Advances in Marine Biology*. Elsevier, pp. 117–198. doi: <https://doi.org/10.1016/bs.amb.2016.04.001>
- Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., & Turley, C. (2015). Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios. *Science*, 349, aac4722. <https://doi.org/10.1126/science.aac4722>
- Guo C., Lek S., Ye S., Li W., Liu J., Li Z. (2015). Uncertainty in ensemble modelling of large-scale species distribution: Effects from species characteristics and model techniques. *Ecological Modelling*, 306, 67–75. <http://dx.doi.org/10.1016/j.ecolmodel.2014.08.002>
- GBIF (2017). *GBIF Home Page* [WWW Document]. <https://www.gbif.org>
- Giorgetta M. A., Jungclaus J., Reick C. H., Legutke S., Bader J., Böttinger M., Brovkin V., Crueger T., Esch M., Fieg K., Glushak K., Gayler V., Haak H., Hollweg H.-D., Ilyina T., Kinne S., Kornbluh L., Matei D., Mauritsen T., Mikolajewicz U., Mueller W., Notz D., Pithan F., Raddatz T., Rast S., Redler R., Roeckner E., Schmidt H., Schnur R., Segschneider J., Six K. D., Stockhause M., Timmreck C., Wegner J., Widmann H., Wieners K.-H., Claussen M., Marotzke J., Stevens B. (2013). Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *Journal of Advances in Modeling Earth Systems*, 5(3), 572–597. <http://dx.doi.org/10.1002/jame.20038>
- Guisan, A., & Thuiller, W. (2005). Predicting species distribution: offering more than simple habitat models. *Ecology Letters*, 8, 993–1009. <https://doi.org/10.1111/j.1461-0248.2005.00792.x>
- Guisan, A., & Zimmermann, N. E. (2000). Predictive habitat distribution models in ecology. *Ecological Modelling*, 135, 147–186. [https://doi.org/10.1016/S0304-3800\(00\)00354-9](https://doi.org/10.1016/S0304-3800(00)00354-9)
- Gutiérrez García, R. (2003). *Evaluación del langostino Pleuroncodes planipes en el Pacífico nicaragüense, por el método de área barrida*. Junio 2003. Centro de Investigaciones Pesqueras y Acuicolas, Managua, Nicaragua.
- Gutiérrez García, R. (2004). *Crucero de pesca comercial de camarón de profundidad Heterocarpus affinis, en el Pacífico nicaragüense Enero - febrero 2004*. Centro de Investigaciones Pesqueras y Acuicolas.
- Gutiérrez García, R. (2006). *Evaluación del estado de explotación del camarón costero (Litopenaeus y Farfantepenaeus) del Pacífico de Nicaragua*. Período 2000–2005. Centro de Investigaciones Pesqueras y Acuicolas, Managua, Nicaragua.
- Haas, A., Harper, S., Zyllich, K., & Zeller, D. (2015). *Reconstruction of Nicaragua's fisheries catches: 1950–2010*. Work. Pap., Working Paper Series, Fisheries Centre, The University of British Columbia 2015–23, 1–9.
- Harper, S., Guzman, H. M., Zyllich, K., & Zeller, D. (2014). Reconstructing Panama's total fisheries Catches from 1950 to 2010: Highlighting data deficiencies and management needs. *Marine Fisheries Review*, 76, 51–65. https://doi.org/10.7755/MFR.76.1_2.3
- Heenan, A., Pomeroy, R., Bell, J., Munday, P. L., Cheung, W., Logan, C., Brainard, R., Yang Amri, A., Aliño, P., Armada, N., David, L., Rivera-Guieb, R., Green, S., Jompa, J., Leonardo, T., Mamaug, S., Parker, B., Shackeroff, J., & Yasin, Z. (2015). A climate-informed, ecosystem approach to fisheries management. *Marine Policy*, 57, 182–192. <https://doi.org/10.1016/j.marpol.2015.03.018>
- Hernandez, P. A., Graham, C. H., Master, L. L., & Albert, D. L. (2006). The effect of sample size and species characteristics on performance of different species distribution modeling methods. *Ecography*, 29, 773–785. <https://doi.org/10.1111/j.0906-7590.2006.04700.x>
- Heupel, M., Knip, D., Simpfendorfer, C., & Dulvy, N. (2014). Sizing up the ecological role of sharks as predators. *Marine Ecology Progress Series*, 495, 291–298. <https://doi.org/10.3354/meps10597>
- Hijmans, R. J., Williams, E., & Vennes, C. (2018). *geosphere: Spherical Trigonometry*. R package version 1.5-10. <https://CRAN.R-project.org/package=geosphere>
- Hoffmann, S., Irl, S. D. H., & Beierkuhnlein, C. (2019). Predicted Climate Shifts within Terrestrial Protected Areas Worldwide. *Nature Communications*, 10(1), 4787. <https://doi.org/10.1038/s41467-019-12603-w>
- Hsieh, C., Reiss, C. S., Hunter, J. R., Beddington, J. R., May, R. M., & Sugihara, G. (2006). Fishing elevates variability in the abundance of exploited species. *Nature London*, 443, 859–862. <https://doi.org/10.1038/nature05232>
- Hutchinson, G. E. (1959). Homage to Santa Rosalia or why are there so many kinds of animals? *American Naturalist*, 93, 145–159.
- Instituto de Biología (2003). *Colección Nacional de Peces del Instituto de Biología (IBUNAM) (Base de datos REMIB-CONABIO)*. Universidad Nacional Autónoma de México.
- Instituto de Ciencias del Mar y Limnología (2001a). *Colección de Referencia de Crustáceos del Pacífico Mexicano (ICMyL-MAZ, UNAM) (Base de datos REMIB-CONABIO)*. Universidad Nacional Autónoma de México.
- Instituto de Ciencias del Mar y Limnología (2001b). *Colección de Referencia de Peces del Pacífico Mexicano (ICMyL-MAZ, UNAM) (Base de datos REMIB-CONABIO)*. Universidad Nacional Autónoma de México.
- INVEMAR (2017). *Sistema de Información Ambiental Marina [en línea]*: [WWW Document]. <http://siam.invemar.org.co/sibm-busqueda-avanzada>
- IUCN (2018). *The IUCN Red List of Threatened Species*. Version 2017–1. [WWW Document]. <http://www.iucnredlist.org>
- Ixquiac, M. (1998). *Análisis de la composición y distribución de la fauna de acompañamiento del camarón (FAC) en el Océano Pacífico guatemalteco dentro de las isóbatas de 10 a 100 m durante los cruceros de investigación enero 1996 a febrero 1998 (Tesis de Licenciatura)*. Centro de Estudios del Mar y Acuicultura, Universidad de San Carlos de Guatemala.
- Jones, M. C., & Cheung, W. W. L. (2015). Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES Journal of Marine Science*, 72, 741–752. <https://doi.org/10.1093/icesjms/fsu172>
- Keller A. A., Ciannelli L., Wakefield W. W., Simon V., Barth J. A., Pierce S. D. (2015). Occurrence of demersal fishes in relation to near-bottom oxygen levels within the California Current large marine ecosystem. *Fisheries Oceanography*, 24(2), 162–176. <http://dx.doi.org/10.1111/fog.12100>
- Kujala H., Moilanen A., Araújo M. B., Cabeza M. (2013). Conservation Planning with Uncertain Climate Change Projections. *PLoS ONE*, 8(2), e53315. <http://dx.doi.org/10.1371/journal.pone.0053315>
- Kwiatkowski L., Bopp L., Aumont O., Ciais P., Cox P. M., Laufkötter C., Li Y., Séférian R. (2017). Emergent constraints on projections of declining primary production in the tropical oceans. *Nature Climate Change*, 7(5), 355–358. <http://dx.doi.org/10.1038/nclimate3265>
- Lam, V. W. Y., Allison, E. H., Bell, J. D., Blythe, J., Cheung, W. W. L., Frölicher, T. L., Gasalla, M. A., & Sumaila, U. R. (2020). Climate change, tropical fisheries and prospects for sustainable development. *Nature Reviews Earth & Environment*, 1(9), 440–454.
- Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., & Sumaila, U. R. (2016). Projected change in global fisheries revenues under climate change. *Scientific Reports*, 6, <https://doi.org/10.1038/srep32607>
- Laufkötter C., Vogt M., Gruber N., Aita-Noguchi M., Aumont O., Bopp L., Buitenhuis E., Doney S. C., Dunne J., Hashioka T., Hauck J., Hirata T., John J., Le Quéré C., Lima I. D., Nakano H., Seferian R., Totterdell I., Vichi M., Völker C. (2015). Drivers and uncertainties of future global marine primary production in marine ecosystem models. *Biogeosciences*, 12(23), 6955–6984. <http://dx.doi.org/10.5194/bg-12-6955-2015>
- Lek, S., & Guégan, J. F. (1999). Artificial neural networks as a tool in ecological modelling, an introduction. *Ecological Modelling*, 120, 65–73. [https://doi.org/10.1016/S0304-3800\(99\)00092-7](https://doi.org/10.1016/S0304-3800(99)00092-7)
- Lenoir, J., & Svenning, J.-C. (2015). Climate-related range shifts - a global multidimensional synthesis and new research directions. *Ecography*, 38, 15–28. <https://doi.org/10.1111/ecog.00967>
- Lindop, A. M. M., Chen, T., Zyllich, K., & Zeller, D. (2015). *A reconstruction of Colombia's marine fisheries catches*. Work. Pap., Working Paper

- Series, Fisheries Centre, The University of British Columbia 2015–32, 1–15.
- Lluch-Cota, S., Arreguin-Sanchez, F., Salvadeo, C. J., & Del Monte Luna, P. (2018). Chapter 10: Climate change impacts, vulnerabilities and adaptations: Northeast Tropical Pacific marine fisheries. In M. Barange, T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith, & F. Poulain (Eds.), *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options*, FAO Fisheries and Aquaculture Technical Paper (pp. 207–218). FAO.
- Lluch-Cota, S. E., Hoegh-Guldberg, O., Karl, D. M., Pörtner, H. O., Sundby, S., & Gattuso, J. P. (2014). Cross-chapter box on uncertain trends in major upwelling ecosystems. In Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., et al. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (pp. 149–151). Cambridge University Press.
- López-Martínez, J., Arreguín-Sánchez, F., Hernández-Vázquez, S., Herrera-Valdivia, E., Nevárez-Martínez, M. O., Morales-Azpeitia, R., Lluch-Cota, S., & Lluch-Cota, D. B. (2002). Effects of the El Niño Events on the brown shrimp fishery in the Gulf of California, Mexico. *Investigaciones Marinas*, 30, <https://doi.org/10.4067/S0717-71782002030100081>
- Madeira D., Narciso L., Cabral H. N., Vinagre C. (2012). Thermal tolerance and potential impacts of climate change on coastal and estuarine organisms. *Journal of Sea Research*, 70, 32–41. <http://dx.doi.org/10.1016/j.seares.2012.03.002>
- Maestri R. (2020). A macroecological perspective on Neotropical rodents. *Mastozoología Neotropical*, 27(SI), 24–34. http://dx.doi.org/10.31687/saremmn_si.20.27.1.04
- Marzloff, M. P., Melbourne-Thomas, J., Hamon, K. G., Hoshino, E., Jennings, S., van Putten, I. E., & Pecl, G. T. (2016). Modelling marine community responses to climate-driven species redistribution to guide monitoring and adaptive ecosystem-based management. *Global Change Biology*, 22, 2462–2474. <https://doi.org/10.1111/gcb.13285>
- Mora, C., & Robertson, D. R. (2005). Causes of latitudinal gradients in species richness: a test with fishes. *Ecology*, 86, 1771–1782. <https://doi.org/10.1890/04-0883>
- Morley, J. W., Selden, R. L., Latour, R. J., Frölicher, T. L., Seagraves, R. J., & Pinsky, M. L. (2018). Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLoS One*, 13, e0196127. <https://doi.org/10.1371/journal.pone.0196127>
- Nguyen, K. D. T., Morley, S. A., Lai, C.-H., Clark, M. S., Tan, K. S., Bates, A. E., & Peck, L. S. (2011). Upper temperature limits of tropical marine ectotherms: Global warming implications. *PLoS One*, 6, e29340. <https://doi.org/10.1371/journal.pone.0029340>
- OBIS (2017). *Ocean Biogeographic Information System* [WWW Document]. www.obis.org
- Páez-Osuna, F., Sanchez-Cabeza, J. A., Ruiz-Fernández, A. C., Alonso-Rodríguez, R., Piñón-Gimate, A., Cardoso-Mohedano, J. G., Flores-Verdugo, F. J., Carballo, J. L., Cisneros-Mata, M. A., & Álvarez-Borrego, S. (2016). Environmental status of the Gulf of California: A review of responses to climate change and climate variability. *Earth Science Reviews*, 162, 253–268. <https://doi.org/10.1016/j.earscirev.2016.09.015>
- Pauly, D., & Cheung, W. W. L. (2018). Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. *Global Change Biology*, 24, e15–e26. <https://doi.org/10.1111/gcb.13831>
- Pauly, D., & Zeller, D., (Editors), (2015). *Sea Around Us Concepts, Design and Data* (seararoundus.org).
- Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nature Communications*, 7, 10244. <https://doi.org/10.1038/ncomms10244>
- Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., ... Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355, eaai9214. <https://doi.org/10.1126/science.aai9214>
- Peterson, A. T., & Soberón, J. (2012). Integrating fundamental concepts of ecology, biogeography, and sampling into effective ecological niche modeling and species distribution modeling. *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology*, 146, 789–796. <https://doi.org/10.1080/11263504.2012.740083>
- Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., & Ferrier, S. (2009). Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecological Applications*, 19, 181–197. <https://doi.org/10.1890/07-2153.1>
- Pinsky M. L., Worm B., Fogarty M. J., Sarmiento J. L., Levin S. A. (2013). Marine Taxa Track Local Climate Velocities. *Science*, 341(6151), 1239–1242. <http://dx.doi.org/10.1126/science.1239352>
- Polidoro, B., Brooks, T., Carpenter, K., Edgar, G., Henderson, S., Sanciangco, J., & Robertson, D. (2012). Patterns of extinction risk and threat for marine vertebrates and habitat-forming species in the Tropical Eastern Pacific. *Marine Ecology Progress Series*, 448, 93–104. <https://doi.org/10.3354/meps09545>
- Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., Brander, K., Bruno, J. F., Buckley, L. B., Burrows, M. T., Duarte, C. M., Halpern, B. S., Holding, J., Kappel, C. V., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Schwing, F., Thompson, S. A., & Richardson, A. J. (2013). Global imprint of climate change on marine life. *Nature Climate Change*, 3, 919–925. <https://doi.org/10.1038/nclimate1958>
- Poloczanska, E. S., Burrows, M. T., Brown, C. J., García Molinos, J., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V., Moore, P. J., Richardson, A. J., Schoeman, D. S., & Sydeman, W. J. (2016). Responses of marine organisms to climate change across oceans. *Frontiers in Marine Science*, 3, 62. <https://doi.org/10.3389/fmars.2016.00062>
- Pörtner, H.-O. (2001). Climate change and temperature-dependent biogeography: oxygen limitation of thermal tolerance in animals. *Naturwissenschaften*, 88, 137–146. <https://doi.org/10.1007/s001140100216>
- Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., Zavalov, P. O. (2014). Ocean systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 411–484). Cambridge University Press.
- Pörtner, H. O., & Peck, M. A. (2010). Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. *Journal of Fish Biology*, 77, 1745–1779. <https://doi.org/10.1111/j.1095-8649.2010.02783.x>
- Prince Eric D., Goodyear C. Phillip (2007). Consequences of Ocean Scale Hypoxia Constrained Habitat for Tropical Pelagic Fishes. *Gulf and Caribbean Research*, 19, <http://dx.doi.org/10.18785/gcr.1902.04>
- Quintero I., Wiens J. J. (2013). Rates of projected climate change dramatically exceed past rates of climatic niche evolution among vertebrate species. *Ecology Letters*, 16(8), 1095–1103. <http://dx.doi.org/10.1111/ele.12144>
- Robertson, D. R., & Allen, G. R. (2015). *Shorefishes of the Tropical Eastern Pacific: online information system*. Version 2.0 [WWW Document]. Shorefishes Trop. East. Pac. Online Inf. Syst. Version 20. URL <http://biogeodb.stri.si.edu/sftep/en/pages>
- Robin, X., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J.-C., & Müller, M. (2011). pROC: an open-source package for R and S+

- to analyze and compare ROC curves. *BMC Bioinformatics*, 12, 77. <https://doi.org/10.1186/1471-2105-12-77>
- Robinson, L. M., Hobday, A. J., Possingham, H. P., & Richardson, A. J. (2015). Trailing edges projected to move faster than leading edges for large pelagic fish habitats under climate change. *Deep Sea Research Part II: Topical Studies in Oceanography*, 113, 225–234. <https://doi.org/10.1016/j.dsr2.2014.04.007>
- Sato, K. N., Levin, L. A., & Schiff, K. (2017). Habitat compression and expansion of sea urchins in response to changing climate conditions on the California continental shelf and slope (1994–2013). *Deep Sea Research Part II: Topical Studies in Oceanography*, 137, 377–389. <https://doi.org/10.1016/j.dsr2.2016.08.012>
- Schiller, L., Alava, J. J., Grove, J., Reck, G., & Pauly, D. (2014). The demise of Darwin's fishes: evidence of fishing down and illegal shark finning in the Galápagos Islands. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 25, 431–446. <https://doi.org/10.1002/aqc.2458>
- Sielfeld, W., Laudien, J., Vargas, M., & Villegas, M. (2010). El Niño induced changes of the coastal fish fauna off northern Chile and implications for ichthyogeography. *Revista de biología marina y oceanografía*, 45, 705–722. <https://doi.org/10.4067/S0718-19572010000400014>
- Sing, T., Sander, O., Beerenwinkel, N., & Lengauer, T. (2005). ROCr: visualizing classifier performance in R. *Bioinformatics*, 21, 3940–3941. <https://doi.org/10.1093/bioinformatics/bti623>
- Stock, C. A., Alexander, M. A., Bond, N. A., Brander, K. M., Cheung, W. W. L., Curchitser, E. N., Delworth, T. L., Dunne, J. P., Griffies, S. M., Haltuch, M. A., Hare, J. A., Hollowed, A. B., Lehodey, P., Levin, S. A., Link, J. S., Rose, K. A., Rykaczewski, R. R., Sarmiento, J. L., Stouffer, R. J., ... Werner, F. E. (2011). On the use of IPCC-class models to assess the impact of climate on Living Marine Resources. *Progress in Oceanography*, 88, 1–27. <https://doi.org/10.1016/j.pocean.2010.09.001>
- Stramma, L., Johnson, G. C., Sprintall, J., & Mohrholz, V. (2008). Expanding oxygen-minimum zones in the tropical oceans. *Science*, 320, 655–658.
- Stramma, L., Prince, E. D., Schmidtko, S., Luo, J., Hoolihan, J. P., Visbeck, M., Wallace, D. W. R., Brandt, P., & Körtzinger, A. (2012). Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change*, 2, 33–37. <https://doi.org/10.1038/nclimate1304>
- Stramma, L., Schmidtko, S., Levin, L. A., & Johnson, G. C. (2010). Ocean oxygen minima expansions and their biological impacts. *Deep Sea Research Part I: Oceanographic Research Papers*, 57, 587–595. <https://doi.org/10.1016/j.dsr.2010.01.005>
- Sunday, J. M., Bates, A. E., & Dulvy, N. K. (2011). Global analysis of thermal tolerance and latitude in ectotherms. *Proceedings of the Royal Society B: Biological Sciences*, 278(1713), 1823–1830. <https://doi.org/10.1098/rspb.2010.1295>
- Tapia García, M. (1997). *Diversidad dinámica y patrones reproductivos en la comunidad de peces demersales del Golfo de Tehuantepec (Bases de datos SNIB-CONABIO)*. Unidad Iztapalapa, Universidad Autónoma Metropolitana.
- Thuiller, W., Georges, D., Engler, R., & Breiner, F. (2016). *biomod2: Ensemble Platform for Species Distribution Modeling*, R package.
- Trujillo, P., Cisneros-Montemayor, A. M., Harper, S., Zyllich, K., & Zeller, D. (2015). *Reconstruction of Costa Rica's marine fisheries catches, 1950–2010*. Work. Pap., Working Paper Series, Fisheries Centre, The University of British Columbia 2015–31, 1–16.
- Wabnitz, C. C. C., Lam, V. W. Y., Reygondeau, G., Teh, L. C. L., Al-Abdulrazzak, D., Khalfallah, M., Pauly, D., Palomares, M. L. D., Zeller, D., & Cheung, W. W. L. (2018). Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. *PLoS One*, 13, e0194537. <https://doi.org/10.1371/journal.pone.0194537>
- Wehrtmann, I. S., Arana, P., Barriga, E., Gracia, A., & Paulo Ricardo, P. (2012). Deep-water shrimp fisheries in Latin America: a review. *Latin American Journal of Aquatic Research*, 40(3), 497–535. <https://scielo.conicyt.cl/pdf/lajar/v40nSpecIssue/art02.pdf>
- Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J., & Wilks, D. S. (1998). Statistical downscaling of general circulation model output: A comparison of methods. *Water Resources Research*, 34, 2995–3008. <https://doi.org/10.1029/98WR02577>
- Wilson K. L., Tittensor D. P., Worm B., Lotze H. K. (2020). Incorporating climate change adaptation into marine protected area planning. *Global Change Biology*, 26(6), 3251–3267. <http://dx.doi.org/10.1111/gcb.15094>
- Wisz, M. S., Hijmans, R. J., Li, J., Peterson, A. T., Graham, C. H., Guisan, A., NCEAS Predicting Species Distributions Working Group† (2008). Effects of sample size on the performance of species distribution models. *Diversity and Distributions*, 14, 763–773. <https://doi.org/10.1111/j.1472-4642.2008.00482.x>

BIOSKETCH

Taylor Clarke's main research interests are data-deficient fisheries in the tropical Eastern Pacific and how they may be affected by climate change. Taylor began working with fisheries in 2007, when she became a researcher for the Fisheries and Aquaculture Unit of the University of Costa Rica. There, she gained experience in field biology working with shrimp trawl fisheries and small-scale fisheries in Costa Rica. She is now a PhD candidate at the Changing Oceans Research Unit of the Institute of the Oceans and Fisheries at the University of British Columbia. Under the mentorship of Dr. William Cheung, Taylor aims to understand how environmental change may transform the biogeography of living marine resources, using empirical data and model simulations. She is also developing a new method that will allow us to understand and project the impacts of warming and deoxygenation on data-deficient fisheries resources.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Clarke TM, Reygondeau G, Wabnitz C, et al. Climate change impacts on living marine resources in the Eastern Tropical Pacific. *Divers Distrib*. 2021;27:65–81. <https://doi.org/10.1111/ddi.13181>