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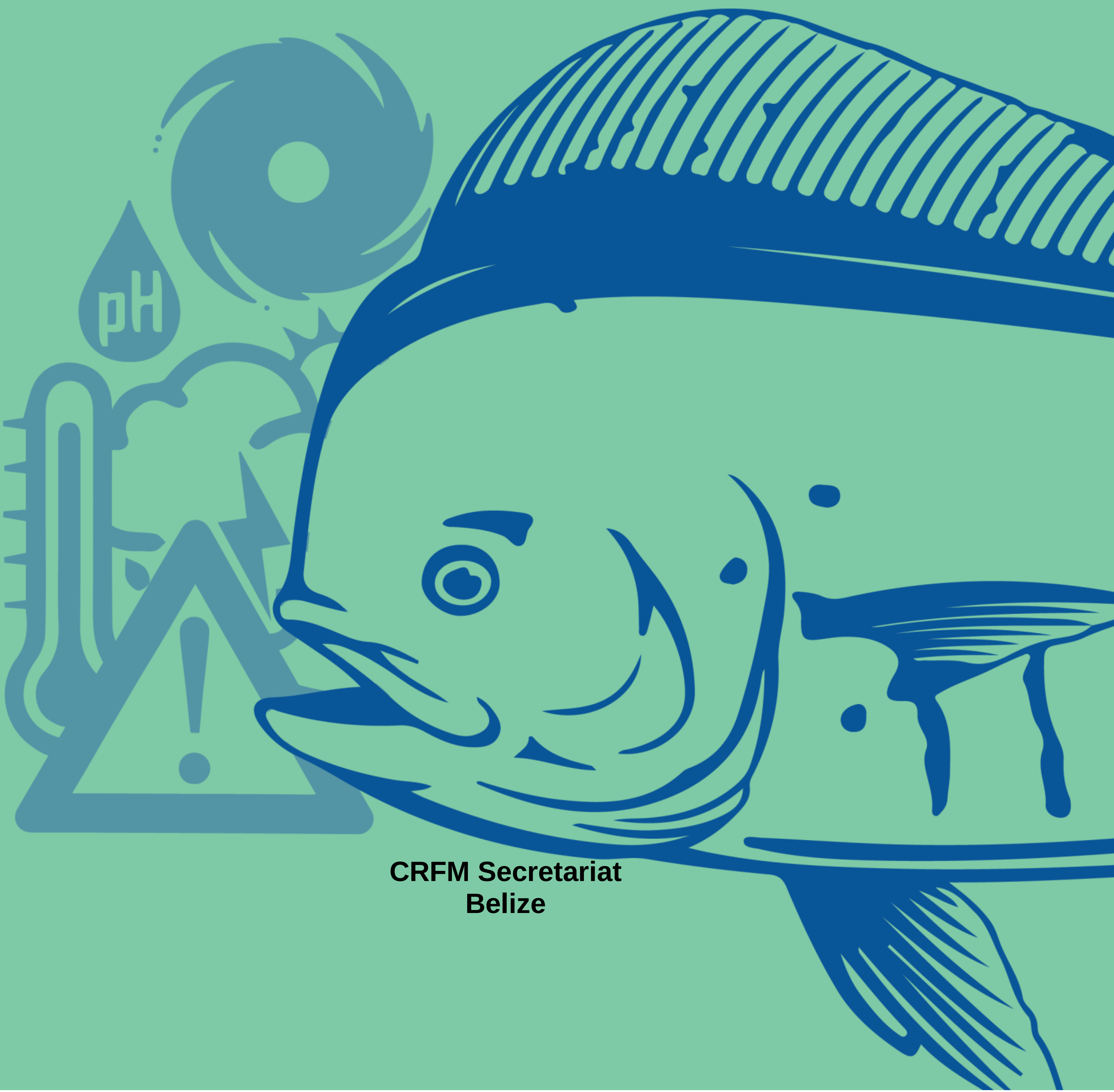

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SYNTHESIS

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Abstract

As part of the Caribbean Track of the Pilot Programme for Climate Resilience a series of ecological, economic and social assessments of climate change impacts on marine resources and the fisheries sector were undertaken between March 2018 and January 2019. This synthesis provides key conclusions arising from the assessment of (1) climate risks and ecological impacts for Caribbean marine fish stocks, (2) the economic consequences of ecosystem shifts and of increased tropical cyclone activity and (3) fisheries viability and resilience through the lens of value chains. Overall, multiple lines of evidence suggest large risk and impacts of climate variation on the Caribbean Sea's fish stocks and fisheries. Economic assessment results suggest a large pre-existing "adaptation deficit", as the estimated economic impacts of climate change appear small relative to documented losses and damages under current climate conditions.. Research at two local fishing sites reveals opportunities to improve climate resilience across the seafood value chain by empowering resource users to self-organize and build local adaptive capacity, promoting seafood product differentiation and identifying enablers for governance effectiveness. Several improvements and extensions to the ecological and economic modelling undertaken under this project are possible and recommended; however, sufficient information from this and previous research is available to inform adaptation planning and targeted measures. Assessment results will form the basis of a communications campaign and monitoring and management recommendations undertaken as part of the project.

1 INTRODUCTION

The impacts of climate change for fisheries production and the state of marine ecosystems are a mounting concern (Brander, 2010; Cheung *et al.*, 2010; Barang *et al.*, 2018). Small changes in environmental conditions, such as temperature, salinity, wind and ocean currents, can alter the abundance, distribution and availability of fish populations (McIlgorm *et al.*, 2010). The increasing frequency and/or intensity of extreme climatic events can affect fish habitat, productivity or distribution, as well as have direct impacts on fishing operations and the physical infrastructure of coastal communities (FAO, 2013). Many fisheries-dependent communities already live a precarious and vulnerable existence because of poverty, lack of social services and essential infrastructure (FAO, 2016).

Negative impacts on marine resources and fisheries from climate change are already evident in the Caribbean (Oxenford & Monnereau, 2018) and combine with existing threats from coastal development, pollution and overfishing to affect ecosystems, communities and economies. Visible and documented climate change impacts include coral bleaching, increasing frequency of major storms and hurricanes, rising sea levels and beaching of masses of Sargassum. In the Caribbean region, marine biodiversity and ecosystems are critical to human well-being as they provide security, food and livelihood opportunities for coastal inhabitants as well as a source of foreign exchange through ecosystem services such as fisheries and tourism. Fisheries employ nearly 200,000 people in the Caribbean Community, earning US

$5 billion to $6 billion per year in foreign exchange and providing about 10 per cent of the region's protein intake (Nurse, 2011). Fisheries overexploitation, including illegal unreported and unregulated (IUU) fishing, pollution of coastal waters, invasive species, habitat destruction and coastal erosion are threats to the sector. The FAO (2016) estimates that approximately 55 percent of the commercially-harvested fisheries stocks in the region are already overexploited or depleted and some 40 percent of the stocks are fully exploited (FAO, 2016). Reef fisheries (e.g., snapper, grouper, lobster, conch), which support the majority of livelihoods in Caribbean fisheries have been particularly badly affected due to both their accessibility from shore and the compounding effects of reef, mangrove, and seagrass habitat loss (Oxenford & Monnereau, 2018). In addition, IUU fishing is estimated at between 20 and 30 percent of total reported production levels (FAO, 2016). Climate change adds to the challenge of sustainably managing fisheries and aquaculture in the Caribbean.

Because of the sector's economic, social and ecological importance in the Caribbean there is an urgent need to improve understanding of climate risks and potential impacts, as well as the sector's vulnerability and options to enhance climate resilience. The Inter-American Development Bank has invested in supporting the region's climate resilience, through grant funding for the Caribbean Regional Track of the Pilot Programme for Climate Resilience (PPCR). The "*Fishery-Related Ecological and Socio-Economic Assessments of the Impacts of Climate Change and Variability and Development of an Associated Monitoring System"* project ("the project") delivers on the PPCR regional track. Executed by the Mona Office for Research and Innovation (MORI) at the University of West Indies at Mona, Jamaica, and with the Caribbean Regional Fisheries Mechanism (CRFM) as the co-implementer, the project aims to improve availability and use of information for "climate-smart" planning and management in the fisheries and aquaculture sector in the Caribbean. Research activities and stakeholder engagement are centered on the following six climate-sensitive countries (referred to a "case study countries"): The Commonwealth of Dominica, Grenada, Haiti, Jamaica, Saint Lucia, and Saint Vincent and the Grenadines (SVG). The project began in January 2018 and is scheduled to conclude in January 2020.

This Research Paper Collection is a main output of the project's Work Package 1, focused on assessment of climate change impacts on the fisheries resources and sector in the six case study countries. It contains the combined results of original ecological and economic modelling as well as quantitative and qualitative analytical approaches to increase the region's understanding of current and future risks and opportunities of climate change. Regional and national-level analyses and results predominate, with primary research at two local fishing sites (Montego Bay, Jamaica; Kingstown, Saint Vincent and the Grenadines) providing important insights from people on the front lines of climate change. This synthesis draws insights across scientific disciplines, as a springboard for project activities related to communications and monitoring and management recommendations. The rest of the synthesis is structured around high-level conclusions, supported by examples and insights from individual research papers in the Collection (labelled A, B, C and D, respectively).

2 KEY MESSAGES

With this project, access to quantitative information on the ecological impacts to fisheries species and socio-economic impacts in the region under broad future climate has increased (A, B, C).

Studies on the impacts of climate change on fishery species in the Caribbean and on the social and economic implications for the fisheries sector are scant (Oxenford & Monnereau, 2018). Research Papers (A) and (B) in this Collection use state-of-the art ensemble modelling approaches and higher resolution climate datasets than ever previously available for the Caribbean Sea to show that the region is projected to become warmer, less oxygenated, with higher acidity and salinity levels, as well as lower primary production throughout the 21st century. Specifically, the research team assessed climate change impacts on 110 of the region's key marine species and associated fisheries by: (1) projecting future ocean conditions throughout the region; (2) assessing the impacts of environmental changes to key marine species; (3) determining selected species future vulnerability as a result of projected environmental changes, as well as the species' sensitivity and adaptive capacity to these changes; and (4) estimating climate change impacts on the region's future fisheries production. Despite the limitations of modelling approaches, these results currently represent the best estimate of ecological impacts to fisheries species in the region under broad future climate and fisheries management scenarios.

Research paper (C) applies innovative approaches to estimate economic impacts on fishery production from changing ocean conditions and from changes to the intensity of tropical cyclones. The economic impacts of climate-induced changes in fishery production (landings) are assessed using a market supply-demand model developed specifically for each of the six PPCR countries. This market supply-demand model is an application of an analytical framework used for economic impact assessment of fisheries under climate change in the South Pacific. An important accomplishment in this research project is the linkage across disciplines. Economic impact assessment built on the results of changes in potential catch generated through ecological modelling. Economic impacts to fishery production from shifts in the intensity of tropical cyclones use historical data to estimate the quantitative link between fishery output and tropical cyclone intensity, adjusting the intensity metric to account for the impact of climate change. Both economic analyses generate estimates of direct as well as economy-wide impacts, using creative approaches to confront data constraints.

Virtually no species, including commercially-important fishery species, are expected to be spared negative impacts under a future climate. Climate change places most exploited species at high conservation risk, as habitats become increasingly unsuitable (A, B).
Exposure, vulnerability and overall risk to climate hazards (warming, deoxygenation, acidification and decline in net primary production) are expected to be high to very high across all species in the region under both "strong mitigation" (RCP2.6) and "business-as-usual" (RCP8.5) carbon emission scenarios. In response to changing ocean conditions, marine species are projected to shift their distributions by tens to hundreds of kilometers resulting in local species gains and extinctions that significantly reduce species richness and change community composition. Most exploited marine species in the region will be at very high conservation risk because of climate change, with much of their current habitat becoming unsuitable. A large part of risk of marine species assemblages to climate change in the Caribbean Sea is attributable to the high biological sensitivity of tropical and sub-tropical species, with little tolerance to temperature increases and a strong dependence on particular habitats to successfully complete their life histories. Table 1 below includes values for indicators of climate vulnerability (1) and risk (2) as well as net change in habitat suitability (3) by country.

Table 1: Indicators of climate change impact on marine species and associated fisheries in the Caribbean Sea, broken down by country

Indicator		Jamaica	Haiti	Dominica	St. Lucia	St. Vincent and the Grenadines	Grenada
1	Median Climate Vulnerability Index for Fished Species / 100	57.5 (across 78 species)	56.5 (across 82 species)	56.4 (across 42 species)	57 (across 72 species)	55.5 (across 60 species)	55.0 (across 66 species)
2	Median Risk Index for Fished Species / 100	**RCP SF SQ OF** 2.6 72 84 87 8.5 73 87 87	**RCP SF SQ OF** 2.6 61 77 84 8.5 63 78 86	**RCP SF SQ OF** 2.6 61 78 83 8.5 71 83 97	**RCP SF SQ OF** 2.6 56 70 81 8.5 63 78 87	**RCP SF SQ OF** 2.6 50 67 79 8.5 58 75 85	**RCP SF SQ OF** 2.6 50 66 78 8.5 59 76 84
3	Δ In The Sum Of Species' Habitat Suitability Index (HSI) (relative to current HSI)	**RCP 2030-39 2050-59** 8.5 - 18% - 29%	**RCP 2030-39 2050-59** 8.5 - 25% - 29%	**RCP 2030-39 2050-59** 8.5 - 21% - 49%	**RCP 2030-39 2050-59** 8.5 - 26% - 39%	**RCP 2030-39 2050-59** 8.5 - 32% - 47%	**RCP 2030-39 2050-59** 8.5 - 32% - 47%
4	Δ In Maximum Catch Potential (relative to 1970-2000)	**RCP 2030-39 2050-59** 2.6 - 5-15% - 10-30% 8.5 - 10-30% - 20-60%	**RCP 2030-39 2050-59** 2.6 - 5-15% - 10-30% 8.5 - 10-30% - 20-60%	**RCP 2030-39 2050-59** 2.6 - 5-15% - 15-30% 8.5 - 10-30% - 30-60%	**RCP 2030-39 2050-59** 2.6 - 5-15% - 10-30% 8.5 - 10-30% - 20-60%	**RCP 2030-39 2050-59** 2.6 - 5-15% - 10-30% 8.5 - 10-30% - 20-60%	**RCP 2030-39 2050-59** 2.6 - 5-15% - 15-30% 8.5 - 10-30% - 30-60%
5	Key Geographic Areas of Change within National EEZs	Offshore areas to the northwest were projected to have both particularly high species gains (>50%) and extinctions (40-50%), while Pedro Bank may see relatively lower impacts in terms of shifting species composition and local extinctions. Catches are projected to decline in all areas around the island, particularly along the north coast and Pedro Bank.	Offshore areas in the Gulf de la Gonâveare expected to see the greatest species gains (40-60%) and, to a lesser extent, extinctions (30-50%), while the north coast of Haiti will also see a high proportion of species extinctions with few gains. Catches are projected to decline in all areas around the island.	Offshore areas closer to the west side of the island are expected to see modest species losses (10-20%), while offshore areas to the southwest are expected to see the greatest species gains (30-40%). Maximum catch potential will remain concentrated in eastern offshore waters, but overall catches are projected to decline to some degree in all areas around the island.	Offshore areas to the south and west are projected to have large species losses (up to 50-60%), while limited species gains (30-40%) will be concentrated in limited offshore areas east of the island. Catches are projected to decline in all areas around the island, but especially to the southwest.	Offshore areas to the east are expected to see modest species gains (20-30%) while species losses (up to 50-60%) will be seen in all offshore areas surrounding the islands, but will be less pronounced throughout the Grenadine Bank. Catches are projected to decline in all areas around the islands.	Offshore areas to the east and south are expected to see modest species gains (20-40%) while species losses (up to 50-60%) will be seen in all offshore areas surrounding the islands, but will be less pronounced throughout the Grenadine Bank and in southernmost areas of the EEZ. Catches are projected to decline in all areas around the islands.

RCP=Representative Concentration Pathway. RCP2.6 and RCP8.5 represent the "low-range"/ "strong mitigation" and "high-range"/"low mitigation" scenarios for carbon emissions, respectively. Observed global emissions and resulting concentration pathways follow the RCP8.5 scenario making it the "business as usual" scenario. SF = Sustainable Fishing; SQ = Status Quo Fishing; OF = Overfishing. EEZ=Economic Exclusion Zone.

Indicators (1) and (2) are indices of vulnerability to climate change and risk of impacts from climate change and fisheries for exploited marine fishes that scale from 1 to 100, with 100 being the most vulnerable or at risk. In this context, vulnerability is the intrinsic sensitivity and biological adaptive capacity of the species to stressors. Median values for the index of climate vulnerability ranges from 55 (Grenada) to 57.5 (Jamaica).

Risk combines the species' vulnerability with the estimated degree of exposure to hazards from both climate (temperature, oxygen concentrations and acidification) and non-climate stressors (hazards from fishing to fishes' population viability). Factoring in exposure to climate and non-climate hazards shows an elevated risk level, with median values for climate risk indices significantly higher than values for climate vulnerability, especially for scenarios combining business as usual emissions (RCP 8.5) and unsustainable fishing levels (OF). Previous work (Cheung *et al.*, 2018) using applications of the climate risk index demonstrated a significant link between it and the risk of extinction, as defined by the IUCN Red List of Endangered Species.

Indicator (3) describes the impacts of climate change on the availability of suitable habitats for selected marine assemblages, reported as a percentage change relative to current conditions. Indicator (5) reports the projected number of species newly occurring or disappearing locally, expressed as a percentage of total species. A net decline in habitat suitability for fished species (indicator (3) and (5) in Table) is expected in a scenario of business as usual emissions (RCP8.5), ranging from 18% (Jamaica) to 32% (Saint Vincent and the Grenadines, Grenada) in 2030s, and ranging from 29% (Jamaica, Haiti) to 49% (Dominica) in 2050s.

As a consequence of changes in species distributions and abundances, potential fisheries catches are projected to decline (A, B). Smaller catches will have significant repercussions for those involved in harvesting and post-harvesting activities and for the economy overall (C, D), in the absence of adaptation.

Changing species distributions and abundances are in turn projected to result in a substantial decrease in maximum fisheries catch potential (indicators (4) and (5) in Table 1). Even in scenarios of strong global mitigation (RCP2.6) maximum catch potential could drop between 5 and 15% by 2030s and between 10 and 30% by 2050s relative to baseline values (1970-2000). Under business as usual emissions (RCP8.5) the projected drop in maximum catch potential relative to baseline values ranges from 10 to 30% in 2030s to 20 to 60% in 2050s. As the modelling approach used to estimate these indicator values employs coarse resolution models, projected percentage decreases in maximum catch potential show virtually no difference across PPCR countries. Regionally, decreases in maximum catch potential are projected to occur across both pelagic and demersal reef species, especially in the southern part of the Caribbean Sea, with many commercially valuable species such as groupers, snappers and parrotfish among the most vulnerable.

The impacts of ecological shifts on fisheries catches have cascading effects on national economies (Table 2). The modelled decline in catch potential (or fishery production) is projected to increase domestic fish prices and decrease fish quantities demanded by consumers. Under business as usual emissions (RCP8.5), domestic fish prices are projected to increase by 4.8% (Haiti) to 9.5% (Grenada) by 2050s, relative to projected prices under the reference case (see indicator (2) in Table 2). Changes in fish prices influence demand, with domestic fish consumption projected to decrease between 5.2% (Dominica) and 5.8% (Grenada) by 2050s, relative to the reference case (see indicator (1) in Table 2). In turn, these market shifts result in decreased economic well-being. Under business as usual emissions, projected climate-induced changes in prices and consumption will result in net annual welfare losses by 2050s that range from US$600,000 (Dominica) to US$8,985,000 (Jamaica) (see indicator (3) in Table 2). Welfare is an economic metric closely linked to the concepts of well-being and income. In this context, Caribbean nations experience a loss in economic well-being due to too little production and consumption of seafood.

Table 2: Indicators of economic impact of climate change impact on marine species and associated fisheries in the Caribbean Sea, broken down by country. All monetary values are in US$2010, meaning that 2010 is the base year and all estimates are converted from current (nominal) dollar values to constant (real) dollar values.

	Indicator	Jamaica		Haiti		Dominica		St. Lucia		St. Vincent and the Grenadines		Grenada	
Due to Climate-Change Induced Impacts on Fishery Production													
1	Δ in Fish Consumption	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
	(relative to projected future demand))	2.6	-4.6%	2.6	-4.6%	2.6	-4.1%	2.6	-4.3%	2.6	-4.6%	2.6	-4.7%
		8.5	-5.7%	8.5	-5.8%	8.5	-5.2%	8.5	-5.5%	8.5	-5.6%	8.5	-5.8%
2	Δ in Fish Prices	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
	(relative to projected future demand)	2.6	5.6%	2.6	3.8%	2.6	5.6%	2.6	7.1%	2.6	6.8%	2.6	7.7%
		8.5	6.9%	8.5	4.8%	8.5	7.2%	8.5	9.1%	8.5	8.2%	8.5	9.5%
3	Net Welfare Loss	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
	(thousand US $ per year in 2010 prices)	2.6	-8000	2.6	-3200	2.6	-500	2.6	-1600	2.6	-580	2.6	-600
		8.5	-8900	8.5	-3800	8.5	-600	8.5	-2000	8.5	-640	8.5	-760
Due to More Intense Tropical Cyclones under Climate Change													
4	Direct Losses in Fishery Production	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
		2.6	-920 to -3060	2.6	-400 to -1350	2.6	-40 to -120	2.6	-28 to -94	2.6	-24 to -81	2.6	-30 to -100
	(tonnes per event)	8.5	-1600 to -5340	8.5	-710 to -2350	8.5	-60 to -200	8.5	-50 to -160	8.5	-43 to -142	8.5	-50 to -180
5	Direct Losses in Landed Value	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
		2.6	-1660 to -5530	2.6	-420 to -1400	2.6	-50 to -170	2.6	-40 to -150	2.6	-58 to -195	2.6	-40 to -150
	(US$2010 thousand per event)	8..5	-2900 to -9670	8..5	-730 to -2450	8..5	-90 to -300	8..5	-77 to -255	8..5	-102 to -340	8..5	-80 to -260
6	Total Losses in Economic Output (US$2010 thousand per event)	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
		2.6	-2017 to -6720	2.6	-510 to -1701	2.6	-61 to -207	2.6	-49 to -183	2.6	-70 to -237	2.6	-55 to -181
		8..5	-3524 to -11750	8..5	-887 to -2977	8..5	-109 to -365	8..5	-97 to -317	8..5	-124 to -413	8..5	-95 to -316
7	Total Reductions in Household Income	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
		2.6	-473 to -1574	2.6	-120 to -399	2.6	-14 to -49	2.6	-11 to -43	2.6	-16 to -55	2.6	-13 to -42
	(US$2010 thousand per event)	8..5	-826 to -2752	8..5	-208 to -698	8..5	-26 to -86	8..5	-23 to -74	8..5	-29 to -97	8..5	-22 to -74
Fish as Food													
8	Reduction in Household Fish Food Consumption due to Climate-Induced Δ in Price and Consumption (per capita per day)	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
		2.6	-4.6%	2.6	-4.4%	2.6	-4%	2.6	-4.2%	2.6	-4.6%	2.6	-4.5%
		8.5	-5.8%	8.5	-5.8%	8.5	-5%	8.5	-5.6%	8.5	-5.6%	8.5	-6%
9	Reduction in Daily Food Supply as Fish due to More Intense Tropical Cyclones (relative to 2009-2013 average, grams of edible fraction per capita per day)	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**	**RCP**	**2050s**
		2.6	-0.1% to -0.7%	2.6	0% to -0.7%	2.6	0% to -0.8%	2.6	0% to -0.5%	2.6	0% to -0.7%	2.6	0% to -0.75%
		8.5	-0.1% to -1.3%	8.5	-0.1% to -1.1%	8..5	-0.1% to -1.5%	8..5	0% to -0.8%	8..5	-0.1% to -1.3%	8..5	-0.1% to -1.4%

Interviews with fish value chain actors in both Jamaica and Saint Vincent and the Grenadines shed light on potential social implications of reduced access to commercially-important fish species and related shifts in market dynamics. Fishers are already contending with declines in raw material supply and other stressors that affect fishing operations and their ability to make a living. According to fishers in Jamaica, the fisheries are currently viable although there is dwindling of raw material supply through poor catch, frequency of killer whales that limits fishing trips, loss and damage from extreme events such as hurricanes, piracy, and the incidence of Sargassum that affects their fishing operations. To be viable, fishers are taking extended trips out at sea for days, often incurring higher operational costs due to fuel costs and safety at sea. Nevertheless, fishers interviewed in both locations are, for the most part, full-time occupants in the industry, content with their monthly and annual returns and reluctant to change occupation or retrain to work in other professions. This reveals the potential for high vulnerability, in the event of stock migration and lower total catches, if fishers are not integrated into other economic sectors. Harvesters can bear a disproportionate amount of risk, financial and otherwise, relative to other actors across the fish value chain. For fishers, the operational expense of fuel and safety risks for longer trips is seldom reflected in an increase in landed value.

The rate of ecological change projected, especially if global carbon emissions continue largely unabated following the “business-as-usual” scenario; will demand swift transformations across the fish value chain. Yet, field research revealed potential capacity gaps related to this. At present, two major types of fish chains operate in Saint Vincent and the Grenadines and Jamaica: small-scale artisanal and small-scale industrial fisheries. These two chains have three features in common: (1) low fishing capacity, (2) limited value addition and (3) low skills and infrastructure support toward product differentiation and up-scaling opportunities.

Economic loss and damage to the fisheries sector from severe storms in the region is sizable at present. Climate change will exacerbate the region’s existing adaptation deficit (C).

The average annual economic cost of tropical cyclones across the Caribbean between 1950 and 2014 has been estimated at equivalent to 2% of gross domestic product (GDP) (Acevedo, 2016). These losses do not include important non-market impacts, such as damages to marine environments and resources like coral reefs and ecosystem services. Analysis focused on loss and damage to the fisheries sector is uncommon but countries’ documentation of the economic consequences from tropical cyclones via damage and loss assessments shed light on the severity of the impact. For example, in 2017 Hurricane Maria the total estimated value of fishing boats, engines and gear damaged, destroyed or lost in Dominica amounted to XCD $11,271,520 (about US$ 4 million). Hurricane Sandy caused extensive damage to the fisheries and aquaculture sectors in Jamaica, totaling more than J $90 million (about US$70,000).

This study simulated the economic consequences of climate change-induced increases in the intensity of historical tropical cyclones occurring between 1950 and 2013 (indicators (4) to (7) in Table 2). Under business as usual emissions (RCP8.5) regional losses to fishery production by 2050s amount to 5.2 kilo tonnes (central estimate). The corresponding losses in landed value for the six case study countries by the 2050s is $8.3 million (2010 US dollars). At a national level projected losses in landed value due to more intense cyclone activity from climate change by the 2050s range from just under 0.4% of historic totals (for Saint Lucia and Saint Vincent and the Grenadines) to just over 0.5% of historic totals (for Jamaica). National losses in landed value appear in Table 2 (indicator 5).

Further, under business as usual emissions (RCP8.5) climate change is projected to reduce economic output of the six countries by $10.1 million (2010 US dollars) by 2050s (central estimate). The corresponding reduction in regional household incomes by the 2050s is $2.4 million.

Under climate change, smaller catches and supply disruptions will alter patterns of household fish consumption (C).

Seafood is an important source of animal protein globally. Its consumption in 2013 was estimated at 9kg per capita in the Caribbean, with seafood amounting to 10% of animal protein consumed (Vannucinni *et al.* 2018). Projected changes in fish supply and demand induced by ecological shifts under a changing climate result in reduced fish consumption on a per-capita basis (indicator 8 in Table 2) in the six PPCR countries. Under business as usual emissions (RCP8.5) individuals' daily fish consumption could decrease between 5.2% (Dominica) and 5.8% (Grenada and Haiti) by 2050s (indicator (8) in Table 2).

Supply disruptions from more intense tropical cyclones under climate change will also limit the amount of seafood available to eat. Under business as usual emissions (RCP8.5) the incremental impact on fish supply across the six case study countries equates to, on average, a reduction of about 0.2% to 1% in daily food supply as fish (indicator 9 in Table 2). Hurricanes are bigger threats to food security than tropical storms.

Although uncertainties in estimating climate change impacts remain sufficient information exists to guide fisheries policy, planning and community-based action.

Estimates of climate change impacts on marine resources and corresponding fisheries in the region are sophisticated, but not capable of capturing the full breath of processes that may influence ecological, economic and social outcomes under a future climate. In ecological modelling, uncertainties remain on the potential roles of evolutionary capacity to adapt to changing environmental conditions; indirect effects of climate-related shifts in trophic interactions; tipping points in ecosystem function (e.g., rapid changes in ocean circulation) and the cumulative effects of other stressors (e.g., coastal development, pollution, sedimentation, and others). In economic modelling, improvements in the accuracy of input data (e.g., price and income elasticities, GDP multipliers), an expanded scope of climate hazards and induced economic impacts considered, as well as the potential role of autonomous adaptation are among the suggested extensions to the work initiated under this project. Further, assessing the potential for planned climate change adaptation in either mitigating or exacerbating projected climate change impacts is a logical extension to the ecological and economic impact assessment undertaken by the project.

At the same time, assessment results, combined with qualitative research through value chain analysis highlight directions for adaptation initiatives in the sector. Broadly speaking, reduced global carbon emissions, more sustainable fisheries management, greater resilience of supporting habitats and improved coastal zone management are all expected to contribute to reduce climate impacts of future climate change on fisheries resources. Ideally, all of these approaches could be used in concert with one another to reduce cumulative pressures and improve the overall resilience of the fisheries system to future climate change. Institutional reforms and cross-sectoral planning to improve self-organization and resilience of local value-chain actors are also important. Examples of efforts with the potential to yield benefits regardless of the magnitude of climate change impacts are as follows: (a) engaging in citizen science and co-management with fishers for protected areas; (b) achieving product differentiation and supporting processing infrastructure, as in Kingstown (Saint Vincent and the Grenadines); (c) fostering collaborative ties among fishers and processors through cooperatives for marine stewardship, value addition and market access (d) developing and enforcing zoning by-laws for vulnerable coastal regions (e.g., at the Parish level in Jamaica); (e) protecting and insuring coastal infrastructure, (f) improving hazard early warning systems through mobile applications and providing training on safety for small-scale fishers and (g) promoting cross-sectoral working groups at multiple levels as in Jamaica, which seek to mainstream adaptation in fisheries management and related sectors. National and local-level measures to reduce climate-related and disaster risks to the sector and to increase the resilience of fisherfolk are already underway (Oxenford & Monnereau, 2018), with many more identified in national adaptation plans and strategies (Government of Saint Lucia, 2018).

Empirical studies of climate change impacts to fished species in the Caribbean are still uncommon; these types of studies will become increasingly important for validating or refining the kinds of regional climate model projections projected in this study and informing smaller-scale management responses by countries in the region. To this end, the later phases of this broader project aim to develop standardized monitoring frameworks and protocols to facilitate tracking and responding to climate change effects on fish and fisheries in the future.

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A. CLIMATE CHANGE EFFECTS ON CARIBBEAN MARINE ECOSYSTEMS AND FISHERIES - REGIONAL PROJECTIONS

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Abstract

In the Caribbean region, marine biodiversity and ecosystems are critical to human well-being as they provide security, food and livelihood opportunities for coastal inhabitants as well as a source of foreign exchange through ecosystem services such as fisheries and tourism. However, an increasing number of threats including climate change, coastal development, pollution, and overfishing are threatening the capacity for these living marine resources to deliver services such as fisheries catches. A portfolio of modelling approaches, simulation outputs and quantitative indices are used in this study to assess climate risk, vulnerability and impacts of Caribbean Sea marine fish stocks and fisheries under contrasting CO_2 emission scenarios. Increasing CO_2 emissions are projected to result in changes in ocean conditions that will impact marine biodiversity throughout the region. The Caribbean Sea is projected to become warmer, less oxygenated, with higher acidity and salinity levels, as well as lower primary production throughout the 21st century relative to the 20th century. As a result, exposure to climate hazards of all assessed species is estimated to be high to very high under both 'strong mitigation' (RCP2.6) and 'business-as-usual' (RCP8.5) CO_2 emission scenarios by mid-century.

The vulnerability of selected species assemblages is estimated to be moderate to high, with commercially-valuable fishes such as groupers, snappers and parrotfish among the most vulnerable. With the high level of exposure to climate hazards, no species will have low or moderate risk of climate impacts under the RCP8.5 scenario. The high risk of impacts can be translated into greater risk of extinction. Suitable habitat conditions in the Caribbean Sea for marine fishes and invertebrates were projected to decrease under a higher CO_2 emission scenario. Marine species are projected to shift their distribution by tens to hundreds of kilometers under marine environmental conditions associated with increasing atmospheric CO_2 concentration over the next few decades. As a result, the Caribbean region was projected to have large changes in species assemblages, with substantial local loss of species across the region. Climate change is also projected to result in a substantial decrease in maximum fisheries catch potential. Regionally, this decline was projected to be higher in the southern part of the Caribbean Sea. The projected changes in species composition, lower catches, and the high risk to associated species, particularly those that are commercially valuable, are expected to have important impacts on dependent

fishing communities. Overall, multiple lines of evidence suggest large risk and impacts of climate change on the Caribbean Sea's fish stocks and fisheries. The short time frame over which these impacts are projected to occur poses substantial challenges for both the ecological and human systems to adapt to these impacts.

1 INTRODUCTION

This report is part of the deliverables under Work Package 1 for the project Fishery-Related Ecological and Socio-economic Impact Assessments and Monitoring System. Specifically, this report addresses the following components of the overarching objectives of Work Package 1:

- Assess the ecological impacts of climate change and variability on the Caribbean region's fisheries resources;
- Develop tools and methods for fisheries and marine ecosystem analyses and assessments to quantify the current and future impacts of climate change and variability on fisheries production.

This report focuses on the regional-scale assessment of these impacts. Paper B in this Collection (national assessment, the next paper) also includes assessments for each of the six selected highly climate-vulnerable nations of the Commonwealth of Dominica, Grenada, Haiti, Jamaica, Saint Lucia, and Saint Vincent and the Grenadines (SVG).

1.1 Fisheries and Marine Resources

In the Caribbean region, fisheries activities, largely small-scale and artisanal in nature, provide a number of goods and services that are critical to human well-being, and also represent an important source of foreign exchange. Fisheries employ over 200,000 people in the Caribbean Community, earning USD $5 billion to $6 billion per year in foreign exchange and providing about 10 percent of the region's protein intake (Nurse 2011). Key target species include pelagics (coastal and oceanic), shelf and slope demersals, reef fish, and high-value benthic invertebrates, such as spiny lobster (*Panulirus argus*) and queen conch (*Lobatus gigas*). Caribbean coral reefs specifically, have been estimated to generate between USD$3.1 and 4.6 billion annually from fisheries, tourism and shoreline protection (Burke and Maidens 2004; Burke and Kushner 2011). However, the health of corals reefs and associated ecosystems, such as seagrass beds and mangroves, from which these essential goods and services are flowing from, is declining rapidly under the mounting pressure of many human activities.

Coastal development, growing coastal and tourism populations, poor land management practices, overfishing - including illegal unreported and unregulated (IUU) activities-, disease, and ineffective management include some of the threats that have contributed to changing the ecological balance of Caribbean coastal environments (Burke *et al*. 2004, Gill *et al*. 2017, CRFM *et al*. 2017). Recent studies estimate that the region has lost more than 50% of its coral reef cover since the 1970s (Mumby *et al*., 2014; Jackson *et al*., 2014). Rates of loss for mangroves and seagrass beds are comparable (Waycott *et al*., 2009). The FAO (2016) estimates that approximately 55 percent of the commercially-harvested fisheries stocks in the region are already overexploited or depleted; and some 40 percent of stocks are fully exploited (FAO 2016). Reef fisheries (e.g., snapper, grouper, lobster, conch), which support the majority of livelihoods in Caribbean fisheries, have been particularly badly affected (Hawkins and Roberts, 2004; Mumby *et al.;* 2012; Linardich *et al.*, 2017). Decline in the health of key coastal habitats will lead to further losses in fishery productivity (Cinner *et al*., 2012), in turn negatively affecting artisanal reef fisheries and dependent communities (Munday *et al*., 2008; Cinner *et al*., 2013; Sale *et al*., 2014). These declines also significantly undermine the ability of coastal ecosystems to cope with climate change hazards.

1.2 Climate Change Challenges

Concerns over the consequences of climate change for fisheries production and the state of marine ecosystems is mounting, particularly when added to the increasing pressures on coral reefs from marine and terrestrial-based activities (Brander, 2010; Cheung *et al*., 2010; Mora *et al*., 2013). Climate change, manifested through increases in water temperature, declines in oxygen concentration and increase in acidity as well as other changes in ocean physical and chemical conditions, is affecting and will continue to affect fishes and invertebrates (Perry *et al*., 2005; Pörtner *et al*., 2007; McIlgorm *et al*., 201 Cheung *et al*., 2012) in the Caribbean region. Impacts on either the larval, juvenile or adult phases - or all three - include, but are not limited to, changes in animal size and timing of spawning season; migration patterns (Rijnsdorp *et al*., 2009); larval swimming, distribution and settlement (Munday *et al*., 2008); declines in growth; abundance; and a poleward redistribution of many species important to fisheries (Cheung *et al*., 2010).

In addition to direct effects on important fish and invertebrate fishery species themselves, climate change, through ocean warming, sea-level rise, increased hurricane intensity (Uhrin, 2016), and more variable rainfall will have important negative impacts on the habitats, which these species depend on (i.e., coral reefs, mangroves and seagrass beds). While shifts in climate variability mostly associated with El-Niño conditions are also a concern and projected to continue (McConney, 2015), the impacts and/or interactions with climate change are currently poorly understood.

A number of studies have investigated global climate change and its projected effects on fisheries, with most assuming that the Caribbean is a data-poor region (e.g., Allison *et al*., 2009; Poloczanska *et al*., 2013; Barange *et al*., 2014). A recent regional study suggests that the Caribbean will warm by more than 2˚C of air temperature by the end of the century (Nurse and Charlery, 2014), while four other studies (Pérez-Ramírez, 2017; Oxenford and Monnereau, 2017; Oxenford and Monnereau, 2018; Monnereau and Oxenford, 2017) provide assessments, based on (limited) current observations, data and climate projections of likely impacts on fish, shellfish and fisheries in the Caribbean. These studies and others before them (e.g., Nurse *et al*., 2014) conclude that most species, the associated fishery sector and dependent coastal communities are all highly vulnerable to climate change. Oxenford and Monnereau (2017, 2018) in particular highlight that reef-associated species are likely to be the most vulnerable of the fishery groups considered as a result, in part, of their overexploited nature, observed negative climate change impacts on associated habitats, and pressures on coastal ecosystems more generally.

A better understanding of the projected impacts on and the likely vulnerability of key species of interest to climate change throughout the region is a significant step in contributing to better adaptive capacity for what the future may hold. The economic costs of adapting the fisheries sector to sea level rise alone have been estimated to range between US$26 and 61 billion in capital costs and US$4 and 6 billion in annual costs by 2050, increasing rapidly thereafter (Simpson *et al*., 2010). However, interventions that improve upon the management of coastal ecosystems and associated fisheries and slow down or reverse the loss of coral reefs can dramatically alter the magnitude of these costs. Doing so would significantly contribute to maintaining the flow of ecosystem services to dependent communities (Knowlton and Jackson, 2008) and support livelihoods and well-being in the face of impending changes.

This study sought to undertake a comprehensive assessment of climate change impacts on 110 of the region's key marine species and associated fisheries. Specifically, by integrating multiple modelling approaches – and making use of a previously unavailable high resolution global coupled climate model –, we (1) project future ocean conditions throughout the region; (2) assess the impacts of environmental changes to key marine species; (3) determine selected species future vulnerability as a result of projected environmental changes, as well as the species' sensitivity and adaptive capacity to these changes; and (4) estimate climate change impacts on the region's future fisheries production. We conclude by discussing the implications of these impacts for conservation and fisheries in the region.

2 METHODS

Assessments of climate risks and impacts for Caribbean marine fish stocks (including invertebrates) and fisheries broadly included three components: (1) data collection, (2) modelling, and (3) calculation of key indicators (Figure 1).

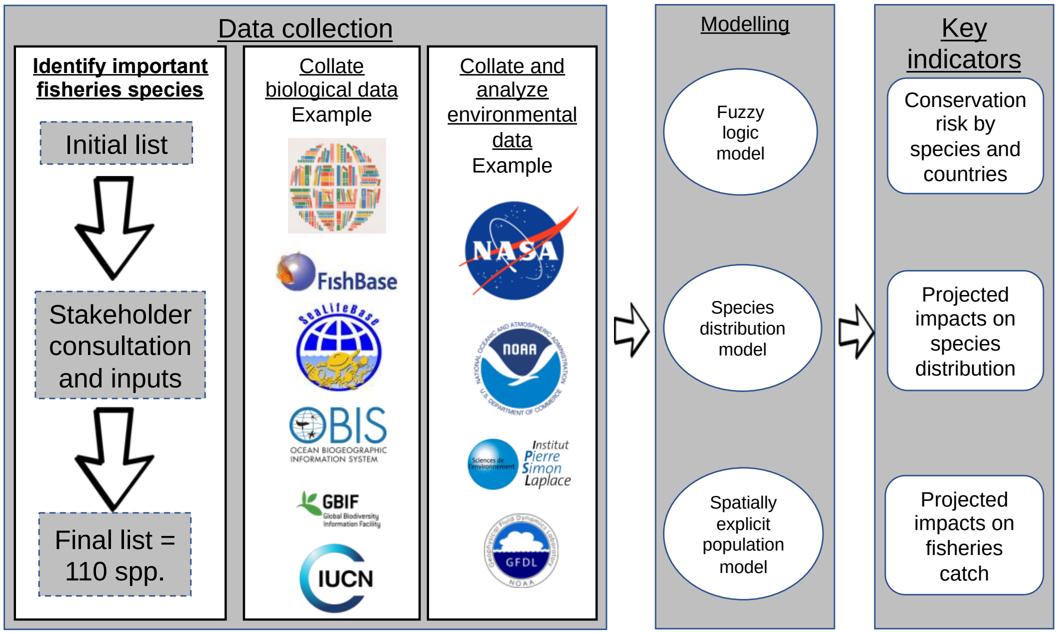


Figure 1. Methodological framework used in this assessment including three broad categories (i.e., data collection, modelling and key indicators) to assess climate risks and impacts for Caribbean marine fish stocks and fisheries.

2.1 **Data collection**

To assess climate risks for Caribbean marine fish stocks and fisheries, three separate, linked datasets were required and assembled: (1) variables that globally define the marine environment obtained from a number of separate model outputs; (2) the list of key species, agreed to together with stakeholders, this assessment should focus on; (3) occurrence data for species identified in (2), as well as life history (e.g., age at maturity) and ecological data (e.g., depth) associated with these species.

2.1.1 Environmental data

Environmental data for the region were derived from outputs of a subset of three Earth system models (ESM) made available as part of the fifth phase of the Ocean-Atmospheric Coupled Model Intercomparison Project (CMIP5): the Geophysical Fluid Dynamic Laboratory Earth System Model 2G (GFDL ESM 2G), the Institut Pierre-Simon Laplace Climate Model (IPSL-CM5A-MR), and the Max Planck Institute Earth System Model (MPI-ESM-MR) (see Laufkötter *et al*., 2015; Kwiatkowski *et al*., 2017 and references therein for an understanding of the differences across the models). We used one single realization of each model (i.e., used outputs from one set of input parameters for each Earth system model). The Earth system models were nominally run for the period 1850 to 2005 under historical forcing (i.e., radiative forcing estimated to have occurred during that time period), and over the period 2006 to 2100 under two Representative Concentration Pathways (RCP2.6 and RCP8.5), which represent two contrasting scenarios of alternative trajectories for carbon dioxide emissions and the resulting atmospheric concentration from 2000 to 2100 (van Vuuren *et al.*, 2011). RCP2.6 represents what might be described as the best case for limiting anthropogenic climate change, with climate policies emphasising ‘strong mitigation’ and as a result global CO_2 emissions peaking by 2020 and declining to around zero by 2080. RCP8.5 on the other hand represents a scenario in which emissions continue to increase, rapidly reaching CO_2 concentrations of 950 ppm by 2100 and continuing to increase for another 100 years. The models were selected based on the availability of variables from the CMIP5 database (Cheung *et al*., 2016). The feasible performance (e.g., time and spatial validation against observed trend) of these model systems has been assured in the context of the CMIP5 initiative (Laufkötter *et al*., 2015; Kwiatkowski *et al*., 2017 and references therein), while the variety of process representation and parameterisation among these systems reflects the structural uncertainty involved in these projections.

The model outputs used to drive future projections of fish distributions and catches using the Dynamic Bioclimate Envelope Model (DBEM - see section 2.2.3 below) include: seawater temperature (surface and bottom, °C), oxygen concentration (surface and bottom, $ml.L^{-1}$), hydrogen ion concentration ($mol\ L^{-1}$, a proxy for acidity levels - surface and bottom), net primary production (depth integrated, $mg.m^{-3}$), salinity (surface and bottom) and surface advection (a proxy for surface currents, which are important for species movement and larval dispersal, $m.sec^{-1}$). All model data were re-gridded onto a 0.5° latitude x 0.5° longitude grid using a bi-linear interpolation method.

A high-resolution global coupled climate earth system model from the Geophysical Fluid Dynamic Laboratory (0.1° latitude x 0.1° longitude) (GFDL CM2.6; Saba *et al*., 2016) was also used to define and project the spatial distribution of marine species identified as important to the region (see section 2.1.2 below). The GFDL CM2.6 model was initialized with pre-industrial conditions (global atmospheric CO_2 fixed at concentrations in the year 1860) and the model was allowed to run for 100 simulation years. To calculate the model's climate change response, the simulation was driven by a 1% per year increase in global atmospheric CO_2 for 80 years (CO_2 doubles at year 70) and subtracted by each model's 1860 control simulation for the corresponding years or months. An environmental dataset based on the outputs of the GFDL CM2.6 was then assembled. This environmental dataset was comprised of information on ocean temperature, as well as bottom and surface (0-100 m) salinity. Since the high-resolution global coupled climate model from the Geophysical Fluid Dynamic Laboratory does not model biogeochemical components such as nutrients or net primary production, we computed and used the climatology of net primary production in the region for the period 2008-2018 using the remotely observed MODIS aqua satellite database (http://orca.science.oregonstate.edu/2160.by.4320.monthly.hdf.chl.modis.php). Bathymetry was also added to the environmental database by using the high resolution General Bathymetric Chart of the Oceans product (GEBCO, https://www.gebco.net/).

2.1.2 Fisheries data and species selection

Initial species lists were compiled for key commercial fisheries species, for each of the 6 climate-vulnerable nations that are part of the project (the Commonwealth of Dominica, Grenada, Haiti, Jamaica, Saint Lucia, and Saint Vincent and the Grenadines), as measured by total 'reconstructed' catch (see section 2.1.4 below) and made available through the *Sea Around Us* project (http://www.seaaroundus.org/). As food security and livelihood opportunities are often met by fisheries that are non-commercial in scope, we also sought to include species that were of significance to the region from a subsistence and/or recreational perspective.

These initial lists, including the 50 top species, or species groups, with the highest catches in the 2000s period based on the *Sea Around Us* catch database, were provided to key stakeholders for feedback at a regional workshop held in Kingstown, Saint Vincent and the Grenadines, 25-26 April 2018. Specifically, representatives from each country were asked to identify the top 10 most important species/species groups listed for their country. Participants were also asked to identify whether a species or species group was important commercially, for subsistence purposes, or both; and whether any species listed was also targeted for recreational purposes. Stakeholders were invited to provide the name of species they thought should be included, but were not listed. Based on responses, 29 species/genera/families were identified (with some overlap - e.g., Caranx and Carangidae) as the most important across the region (Table 1).

These included fish as well as invertebrates associated with pelagic and seagrass-mangrove-coral reef ecosystems.

Table 1. Twenty nine species/species groups emerging as most important across the region based on top 10 key species identified by each of the 6 country representatives. S-M-CR = seagrass-mangrove-coral reef

Scientific name	Common name	Ecosystem	Category
Acanthocybium solandri	Wahoo	Pelagic	Fishes
Acanthuridae	Surgeons, tangs, unicornfishes	S-M-CR	Fishes
Carangidae	Jacks, pompanos	Pelagic/S-M-CR	Fishes
Caranx	Jacks	Pelagic	Fishes
Coryphaena hippurus	Common dolphinfish	Pelagic	Fishes
Decapterus macarellus	Mackerel scad	Pelagic	Fishes
Decapterus punctatus	Round scad	Pelagic	Fishes
Dendrobranchiata	Shrimps and prawns	S-M-CR	Invertebrates
Epinephelus guttatus	Red hind	S-M-CR	Fishes
Haemulon	Grunts	S-M-CR	Fishes
Hemiramphus brasiliensis	Ballyhoo halfbeak	Pelagic	Fishes
Istiophorus albicans	Atlantic sailfish	Pelagic	Fishes
Katsuwonus pelamis	Skipjack tuna	Pelagic	Fishes
Labridae	Wrasses, tuskfishes	S-M-CR	Fishes
Lobatus gigas	Queen conch	S-M-CR	Invertebrates
Lutjanidae	Snappers	S-M-CR	Fishes
Makaira nigricans	Blue marlin	Pelagic	Fishes
Mulloidichthys martinicus	Yellow goatfish	S-M-CR	Fishes
Ocyurus chrysurus	Yellowtail snapper	S-M-CR	Fishes
Opisthonema oglinum	Atlantic thread herring	S-M-CR	Fishes
Panulirus argus	Caribbean spiny lobster	S-M-CR	Invertebrates
Scomberomorus cavalla	King mackerel	Pelagic	Fishes
Scombridae	Mackerels, tunas, bonitos	Pelagic	Fishes
Serranidae	Basses, groupers, hinds	S-M-CR	Fishes
Sparisoma viride	Stoplight parrotfish	S-M-CR	Fishes
Thunnus	Tunas	Pelagic	Fishes
Thunnus alalunga	Albacore	Pelagic	Fishes
Thunnus albacares	Yellowfin tuna	Pelagic	Fishes
Thunnus obesus	Bigeye tuna	Pelagic	Fishes

A final list of key marine species in focal countries to support an assessment of risks and impacts from climate change was assembled based on respondents' answers to an online survey. The list consisted of 110 selected priority species, including 2 species of marine mammals (humpback whale and common bottlenose dolphin), 2 species of algae (belonging to the genus Sargassum), 7 species of invertebrates (queen conch, Caribbean spiny lobster and 5 species of sea cucumber), and 99 species of fish (see Appendix A.1 for a detailed list of species). The fourwing flyingfish (*Hirundichthys affinis*) while not commonly caught in any of the focal countries was added to the list at the request of one of the stakeholders as they thought it may become a key target species in the future. The two species of *Sargassum* were added due to mounting concerns and hardships faced by countries throughout the region associated with the mass-stranding events that have occurred with greater frequency and severity in recent years (Resiere *et al.*, 2018; Maréchal *et al*., 2017; van Tussenbroek *et al*., 2017). Increasing temperatures and nutrients associated with climate change are some of the drivers put forward as potentially creating an environment favourable for the growth and proliferation of the algae (Johnson *et al*., 2013; Louime *et al*., 2017).

2.1.3 Occurrence and ecological data

To identify the environmental niche and climate risk index of selected marine species (see Appendix A.1), records of species occurrence were collated from the following publicly accessible databases: the Ocean Biogeographic Information System (OBIS – www.iobis.org), the Intergovernmental Oceanographic Commission of UNESCO (IOC – ioc-unesco.org), the Global Biodiversity Information Facility (GBIF – www.gbif.org), FishBase (www.fishbase.org), and the International Union for the Conservation of Nature (IUCN – http://www.iucnredlist.org/technical-documents/spatial-data). In the final assembled dataset the following were removed: records that were equal to zero; records associated with a spatial location as "not assigned"; and records that were duplicated among databases (i.e., only one of those records was included in the final dataset). The final dataset comprised 1,877,550 records with at least 52 records per species covering the period from 1953 to 2012.

Life history information and ecological data for all species were collated from published databases including FishBase, SeaLifeBase and the *Sea Around Us* database. Examples of life history data included growth parameters, age at maturity, and fecundity. Assembled ecological data included habitat association, as well as latitudinal and depth ranges. These data were used as inputs into the fuzzy logic risk assessment modelling component of this work, as well as the dynamic bioclimate envelope model (DBEM) (see sections 2.2.1 and 2.2.3 below).

2.1.4 Fisheries catch time-series

Catch data used in all analyses consisted of total "reconstructed" fisheries catches, as available from the *Sea Around Us* database for the region as a whole, and for each of the 6 focal countries. Catch reconstructions are part of a global, country-by-country effort to add comprehensive, but conservative catch estimates for all unreported fisheries components to the official landings statistics reported by the FAO on behalf of countries (Zeller *et al*., 2016).

Country-level catch reconstructions are as independent from each other as possible (to avoid systematic biasing), but follow the general and well-established reconstruction principles by starting in 1950, covering all fisheries sectors that exist in a country, and including at least minimal estimates of discards for major fisheries (Zeller *et al*., 2016). Reconstructions provide both the reported catches as well as best estimates of unreported catches, all separated by industrial (large-scale, commercial), artisanal (small-scale, commercial), recreational and subsistence (both small-scale, non-commercial) sectors. Reconstructions also estimate the volume of discards from major fisheries in each country (fish caught, but discarded at sea) as part of a global discard analysis (Zeller *et al*., 2018). Individual country reconstruction details and data sources are described in detail in dedicated technical reports (Ramdeen *et al*., 2014; Mohammed and Lindop, 2015a; Lingard *et al*., 2012; Ramdeen *et al*., 2012; Mohammed and Lindop, 2015b; Mohammed and Lindop, 2015c), freely available from the seaaroundus.org website.

For the Caribbean Sea Large Marine Ecosystem as a whole, catches by fishing entities targeting stocks throughout the region increased sharply from the 1950s to the 1990s (peaking at just above 92 thousand tonnes), before a sharp decline in the late 1990s. This was followed by a brief increase in catches in the early 2000s (reaching a value of just above 90 thousand tonnes) and a subsequent dramatic decline until the present, levelling off just above 40 thousand tonnes. Overall, artisanal fisheries represent the most important sector for fishing in the region (56%), followed by the industrial and subsistence sectors (24% and 18% respectively). Close to half of all catches were estimated to be unreported. Discards accounted for 10% of total catches. Medium-sized demersal fish (30-89cm) followed by medium-sized reef-associated species (30-89cm) dominated overall production (30% and 14% respectively).

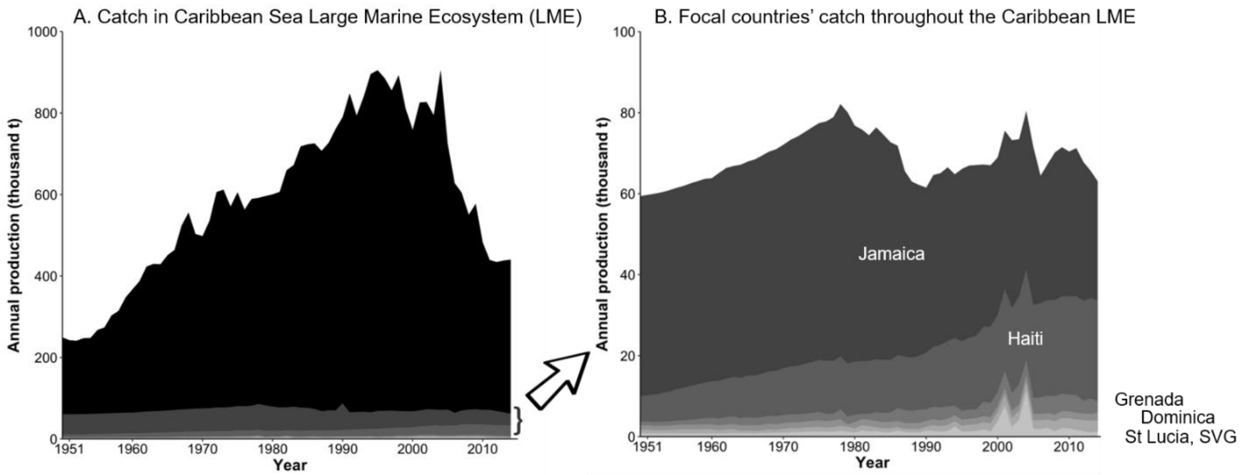


Figure 2. Reconstructed catches for the Caribbean Sea region from 1950 to 2015: (A) total regional catches, where the region is defined as the Caribbean Sea Large Marine Ecosystem; and (B) catches by the six selected focal countries (Grenada, Dominica, Jamaica, St. Lucia, St. Vincent and the Grenadines) in the Caribbean Large Marine Ecosystem region. Catch from countries other than these six countries in the region is represented by the black area on the left panel. Data source: Sea Around Us project database (www.seaaroundus.org).

Focusing on fishing activities by the six countries covered in this study throughout the Caribbean Sea, total catches by these focal countries show important fluctuations over the last six decades (Figure 2). Jamaica, followed by Haiti contributed most to total production (69% and 21% respectively). The four remaining countries had similarly low levels of catches. Unreported catches were found to account for as low as 0.2% of total catches by Saint Lucia, making up to 52% for catches by Jamaica and 13% for catches by Haiti in waters throughout the region (Table 2). Discards represented 1.7% of catches by Jamaica in Caribbean Sea waters.

Table 2. Percentage of unreported and discarded catch for fishing by each of the 6 countries of interest in waters throughout the Caribbean Sea region.

Country	Discards	Unreported
Jamaica	1.70	52.05
Haiti	0.00	12.55
Grenada	0.18	1.24
Saint Vincent & the Grenadines	0.10	0.76
Dominica	0.00	0.95
Saint Lucia	0.01	0.22

Reconstruction efforts estimated that artisanal fisheries made up 27% (Jamaica) and 59% (Haiti) of total catches by the six countries of interest in waters of the Caribbean Sea, while industrial fisheries contributed 28% and 22% to total catches by Grenada and Saint Vincent and the Grenadines respectively. Subsistence fisheries were highest for catches made by Jamaica (73%), followed by catches by Dominica (62%) and lowest for catches by Grenada (16%) in waters of the Caribbean Sea. Large pelagics (>90cm in size and including species such as yellowfin tuna, blackfin tuna, Atlantic sailfish and common dolphinfish) dominated catches by Dominica and Grenada. Medium pelagics (30-89cm in length and including species such as mackerels and bonitos, jacks and pompanos, mackerel scad and bigeye scad) made up most of the catch by Saint Lucia and Saint Vincent and the Grenadines. Reef-associated fish were the main target group by Haiti. A large proportion of the catch by Jamaica's fleet in waters of the Caribbean Sea consisted of unspecified 'finfishes' and 'marine fishes'.

2.2 Modelling climate risk and impacts

2.2.1 Fuzzy logic modelling of climate risk of select marine species

We assessed the climate risk of 106 marine fish and invertebrate species of interest to key stakeholders in the Caribbean using a fuzzy logic climate risk index (Jones and Cheung, 2017; Cheung *et al*. 2018) (see Appendix A.2 for detailed description of this method). In this risk assessment framework, climate risk consists of three components: exposure to climate hazards, sensitivity to climate hazards, and species capacity to adapt to climate changes (Figure 3). Exposure is the nature and degree to which a species might be subjected to climate hazards (i.e., predicted changes in the physical environment) (see Jones and Cheung 2017). Sensitivity refers to the degree to which species are sensitive to any changes in the environment they experience as a result of climate change. Adaptive capacity is the ability of species to respond and adjust to changes from climate stresses, and to cope with, and recover from these. Components are described by a specific set of variables accounting for changes in ocean conditions, biological characteristics of the selected priority species in relation to their sensitivity to environmental changes, and the likelihood a species may reduce its sensitivity to climate change through rapid adaptation (via evolutionary or phenotypic changes) (Table 3). For details of the algorithm used, we refer the reader to Jones and Cheung (2017) and Cheung *et al*. (2018). Below, we briefly describe the key principles behind the method to calculate the index.

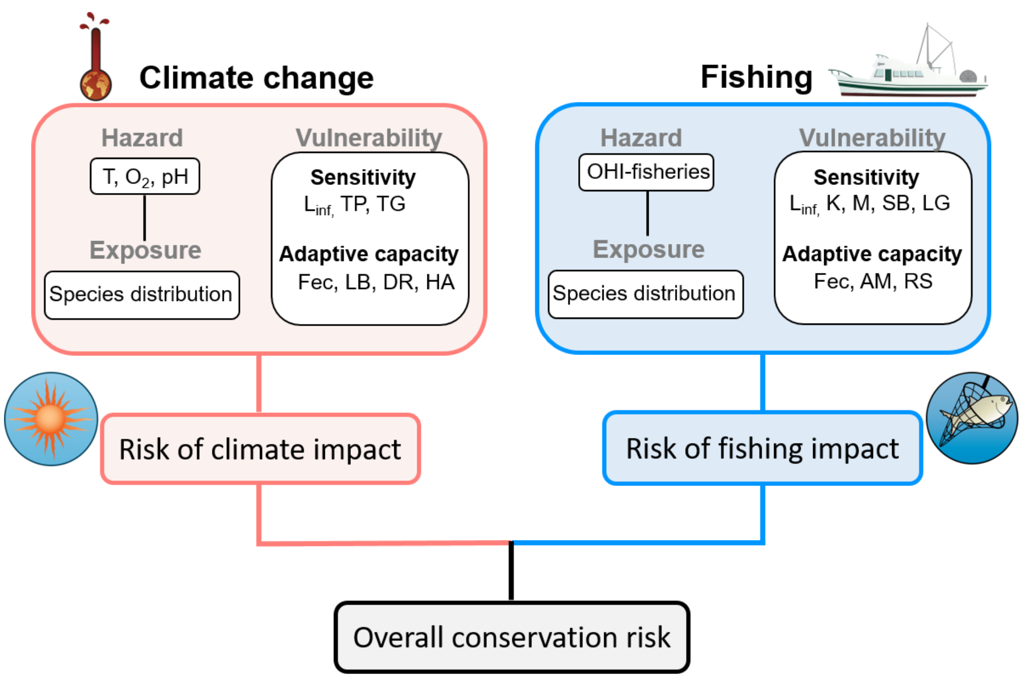


Figure 3. Framework applied in this study to calculate the risk of climate impacts for marine species in the Caribbean Sea region (redrawn from Cheung et al. 2018). Framework for assessing the vulnerability and risk of impacts from climate change and fishing on marine fishes (see Appendix A.2). T – sea water temperature, O_2 – sea water oxygen concentration, pH – sea water pH, Linf – maximum body size, TP – range of temperature preferences, TG – taxonomic group, Fec – fecundity, LB – latitudinal breadth, DR – depth range, HA – specific habitat association, OHI-fisheries – the fisheries component of the Ocean Health Index, K – von Bertalanffy growth parameter, M – natural mortality rate, SB – spatial aggregation behaviour, LG – longevity, AM – age-at-maturity, RS – range size. The fishing risk assessment was only conducted for the national assessment (see research paper B in this Collection).

Table 3. Variables that were used to define a species' exposure to climate hazards, its sensitivity to these hazards and its adaptive capacity.

Risk components	**Variables**	**Data sources**
Exposure	Temperature (surface and bottom), oxygen concentration (surface and bottom), pH (surface and bottom) and net primary production (surface and bottom)	Earth system models projections (see section 2.1.1)
Sensitivity	Temperature preference, asymptotic/maximum body length, habitat (particularly with association to coral reef), taxonomic group	Estimated from occurrence records and environmental data (see section 2.1.3) FishBase (www.fishbase.org) and Sealifebase (www.sealifebase.org)
Adaptive capacity	Latitudinal range, bathymetry range, fecundity and habitat specificity	FishBase (www.fishbase.org), Sealifebase (www.sealifebase.org) and *Sea Around Us* database (www.seaaroundus.org)

The index of exposure to climate change hazard (ExV) is based on the mean changes in each variable relative to an individual variable's historical variability (defined by the standard deviation in the historical time period). An exposure to hazard metric (ExV) for each variable (V)/ ExV was calculated for each 0.5^{o} latitude x 0.5^{o} longitude cell of the global ocean for 2050 (average of 2041 to 2060) under RCP2.6 and RCP8.5. The level of exposure to climate hazards are classified as low, medium, high and very high using a fuzzy logic algorithm (see Jones and Cheung, 2017). Fuzzy logic allows for the classification of multiple categories of exposure concurrently, with different levels of degree of membership (Figure 4; and see Jones and Cheung 2017, for details). Specifically, for each ExV estimate in a 0.5^{o} latitude x 0.5^{o} longitude grid cell of the four ocean variables considered here, we calculated the degree of membership to the four categories of exposure to climate hazard using pre-specified fuzzy membership functions. For the low and very high categories, trapezoid functions were used, while triangular functions were used for medium and high categories (Figure 4). For example, if the ExV for temperature is 2.5 times the historical variability, the species is exposed to both high and very high climate hazard with a degree of membership of 0.5 for both categories (Figure 4).

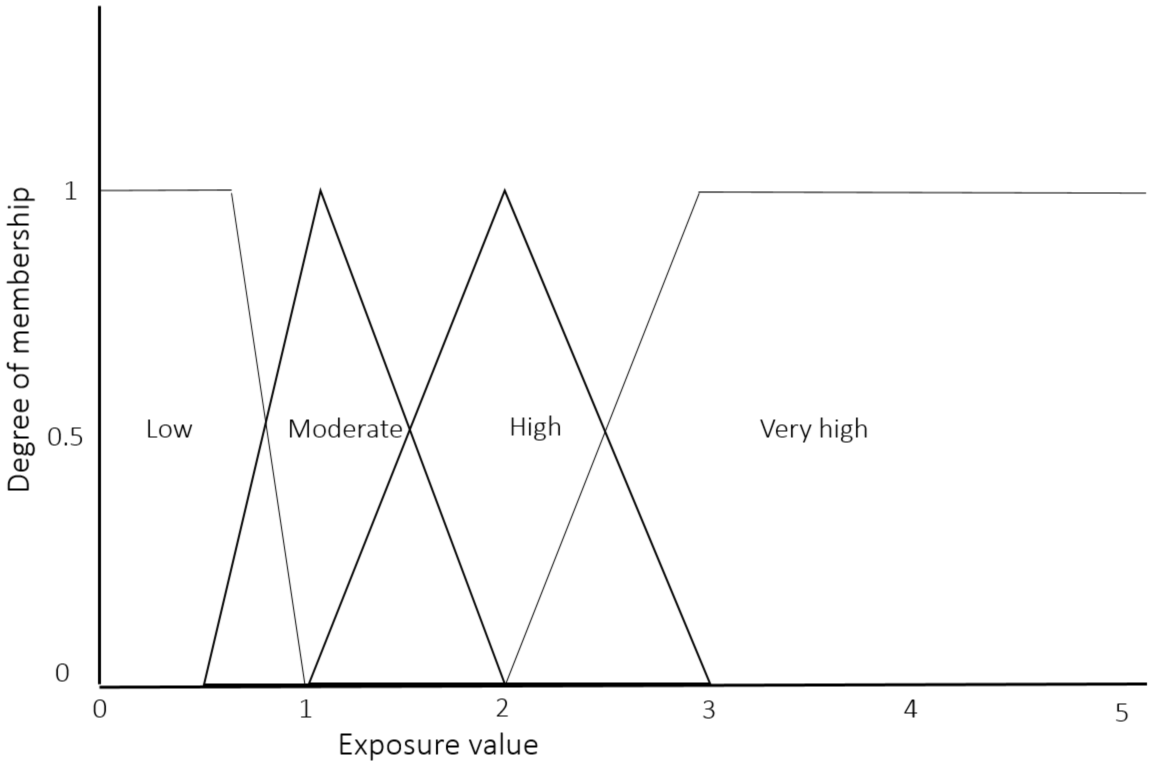


Figure 4. Fuzzy membership function for the exposure value to climate change hazard

The degree of climate change as well as categories of species' biological and ecological traits were classified into levels of exposure to hazards, sensitivity, adaptive capacity and consequently, their vulnerability and risk of impacts, according to predefined heuristic rules. These rules describe the empirical and/or theoretical relationship between the traits (e.g., temperature preferences, habitat specificity, latitudinal range, depth range, fecundity and maximum body length) and the expected levels of sensitivity, adaptive capacity and vulnerability of marine fishes and invertebrates. Trait values for each selected species were obtained from FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.org) and are listed in Appendix A.3. We used published heuristic rules described in Jones and Cheung (2017). Actions defined by each rule are operated when a threshold value of membership is exceeded, thereby defining the minimum required membership for a particular rule to be activated. The algorithm accumulates the degree of membership associated with each level of conclusions from the rules using an algorithm called MYCIN (see Cheung *et al*., 2005), where:

$$AccMem_{(i+1)} = AccMem_{(i)} + Membership_{(i+1)} \times (1 - AccMem_{(i)})$$

where *AccMem* is the accumulated membership of a particular conclusion (e.g., high vulnerability) and *i* denotes one of the rules that has led to this conclusion.

Vulnerability and risk of impacts were expressed on a scale from 1 to 100, 100 being the most vulnerable. Index values (*Indval*) correspond to each linguistic vulnerability category (*x*) where Low = 1, Medium = 25, High = 75 and Very high = 100. The final index (*FlnInd*) of risk of impacts or vulnerability was calculated as the average of the index values weighted by their accumulated membership (Cheung *et al*., 2005). For the risk of impact index (for both the mid-century and end-of-century periods), *FlnInd* was calculated for each spatial grid cell where occurrence of the species was reported. The risk of impact for each species was then calculated as the average *FlnInd* across grid cells weighted by a cell's marine surface area (as some cells would include more land than others).

2.2.2 Species distribution modelling and biodiversity indicator

The current and future distributions of the selected 110 marine species were modelled using an environmental niche approach (*sensu* Hutchinson 1957). This method quantifies the environmental preferences (e.g., temperature, salinity, dissolved oxygen) of marine species and projects their potential distribution according to present and future conditions. Sea surface and sea bottom environmental conditions were used for pelagic and demersal species, respectively. We used these species-specific environmental envelopes to project the probability of occurrence of a given species in each spatial cell of the ocean according to environmental conditions associated with that cell. A multi-model approach was adopted to best approximate the environmental niche of each species. Presenting the results from just one model would require scientists endorsing that specific model as possibly more valid than the others (i.e., it has fewer biases, lower variability, and therefore greater reliability). As the climate system is complex, current evidence indicates that it remains fundamentally impossible to describe all of the climate's processes in a single model, no matter how complex the model is, with developers making choices with regards to what processes to include (and which to exclude) and how to parameterize them. As a consequence, an ensemble of several models is recommended to better account for structural and other uncertainties over time (Krishnamurti *et al*., 2000; Tebaldi *et al*., 2007).

Using presence only data, four environmental niche models (ENM) were applied to our dataset: the (1) Bioclim and (2) Boosted Regression Trees models from the Biomod2 R package (Thuillier *et al*., 2008), (3) Maxent (Phillips *et al*., 2004), and (4) NPPEN (Beaugrand *et al*., 2011). These models were selected as they are currently the most widely used in the published literature given the type of data we had access to for the region (Philips *et al*., 2004; Thuiller *et al*., 2009). Each ENM was applied to the climatological average over the last 30 years of the historical run of the GFDL CM2.6. For each of the 110 selected marine species, the models quantified individual species' environmental envelope by estimating the best combination of environmental conditions that describe a given species current distribution in the Caribbean Sea. The spatial distribution of each species from the four ENMs was then projected for the current period (average of the last 30 years of the historical run), as well as for mid-century and end-of-the-century conditions for the Caribbean region. Each model was evaluated using an AUC (Area Under the Curve) analysis and only model outputs with AUC values over 0.80 were considered for inclusion in multi-model averaging. Spatial uncertainty in model efforts was evaluated for each species by computing the standard deviation of each ENM output.

Species richness (i.e., alpha diversity) was determined as the number of species present in each cell with a predicted Habitat Suitability Index (HSI) above a specific threshold for current environmental conditions. The threshold for the occurrence of an individual species was computed by numerically identifying a probability threshold of confirmed occurrence of a species based on a Receiver Operating Characteristic (ROC) Curve (see Park, 2004) using species occurrence data and a modelled species distribution for the historical period. If HSI was greater than or equal to the threshold, the species was considered present. Species richness was then computed by summing the number of species present in each grid cell over each time period.

To assess potential changes in marine biodiversity driven by climate change, two indices were computed: local species gain and local species extinction (Jones and Cheung, 2015). Local species gain represents the number of species newly occurring in a geographical area relative to the number in that area during the reference period. Local species extinction (losses) represent(s) the number of species no longer found in a geographical cell relative to the reference period. Maps of local species gain and local extinction were produced for time periods with atmospheric CO_2 concentration of ~400 ppm and ~535 ppm (average of year 31-40 and 71-80, respectively, of the simulation time frame of GFDL CM2.6 under the scenario of 1% $year^{-1}$ increase in atmospheric CO_2 concentration).

2.2.3 Spatially-explicit population dynamic model

We employed the Dynamic Bioclimate Envelope Model (DBEM) to project future changes in maximum catch potential for exploited marine fishes and invertebrates in the Caribbean Sea region. DBEM is a spatially-explicit population dynamic model that simulates changes in distribution, abundance and potential catches of species on a 0.5^o latitude x 0.5^o longitude grid of the global ocean. The key components and workings of DBEM are summarized below, while details of the model can be found in Cheung *et al*. (2001) and Cheung *et al.* (2011):

1. The current distributions of commercially exploited species, representing the average pattern of relative abundance in recent decades (i.e., 1970-2000), were produced using an algorithm developed by the *Sea Around Us* Project (see www.seaaroundus.org). The algorithm predicts the relative abundance of a species on a 0.5^o latitude x 0.5^o longitude grid based on the species' depth range, latitudinal range, known Food and Agriculture Organization statistical areas, and polygons encompassing their known occurrence regions. The distributions were further refined by assigning habitat preferences to each species along their life history (if information available), such as affinity to shelf (inner, outer), estuaries, and coral reef habitats (see www.seaaroundus.org).

2. An index of habitat suitability for each species in each spatial cell based on temperature (bottom and surface temperature for demersal and pelagic species, respectively), bathymetry, specific habitats (this is based on habitat maps of various habitat types as described in Cheung *et al*., (2008), salinity and sea ice with 30-year averages of outputs from 1971-2000 from Earth system models (the coarser global models at the resolution of 1° latitude x 1° longitude, see 2.1.1). DBEM estimates the temperature preference profile (TPP) of each species by overlaying estimated species distributions with annual seawater temperature and calculates the area-corrected distribution of relative abundance across temperature for each year from 1971 to 2000, subsequently averaging annual temperature preference profiles (TPP). The estimated TPP was used to predict the thermal physiological performance of a species (aerobic scope) in each area.

3. Population carrying capacity in each spatial cell is a function of the unfished biomass of the population, habitat suitability (as defined by HSI), and net primary production. We assumed that the average of the top-10 annual catches was roughly equal to the maximum sustainable yield (MSY) of the species. As the simulation was carried out at the global scale, MSY was first estimated at the same scale and then pro-rated to each spatial cell according to the predicted species distribution. Our analysis focuses on the projected change relative to baseline level (i.e., relative to 1996-2005) thus any biases associated with using this MSY for assessing climate change impacts on potential fisheries catches would not substantially affect the conclusion of our findings.

4. DBEM calculates a characteristic weight representing the average mass of the population in a cell. The model then simulates how changes in temperature and oxygen would affect growth and body size of individuals using a sub-model derived from a generalized von Bertalanffy growth function for all species (Cheung and Pauly, 2016).

5. The model simulates changes in relative abundance and biomass of a species based on changes in population carrying capacity, intrinsic population growth, and the advection-diffusion of adults and larvae in the population driven by ocean conditions projected from the Earth system models. Movement and dispersal of adults and larvae were modelled through advection-diffusion-reaction equations for larvae and adult stages. Larval movement is partly determined by species' predicted pelagic larval duration, which is partly dependent on sea surface temperature and is also accounted for in the model. Population growth is represented by a logistic function.

6. Maximum catch potential from each population was predicted by applying a fishing mortality rate at the level required to achieve MSY. The projected relative changes in maximum catch potential over time are robust to the estimation of MSY, although the cumulative total MSY across species can be affected by the uncertainties in the magnitude of the estimation.

For each simulation, changes in total annual maximum catch potential by mid-century (2050: 2041-2060) and relative to 2000 (1996-2005) under RCP2.6 and RCP8.5 were calculated for the Caribbean region. The ensemble average across maximum catch potential projections from the three earth system models (GFDL ESM 2G, IPSL-CM5A-MR, and MPI-ESM-MR) are presented here.

2.3 **Key indicators**

We calculated a set of key indicators of climate risks and impacts for marine fish stocks and fisheries in the Caribbean region. These indicators are summarized in Table 4.

Table 4. Description of indicators calculated using different modelling approaches and their interpretation. Climate projections used refer to: 1 = RCP2.6 & RCP8.5; mid-21st century (GFDL, IPSL, MPI); 2 = Idealized doubling of CO_2 emission (GFDL CM2.6). GFDL CM2.6 is much more highly resolved and was applied when using species distribution models as it allows for much finer scale estimates according to available parameters. The first set of climate projections were used when calculating exposure and climate risk indices as well as changes in maximum catch potential as, while coarser than GFDL CM2.6, it includes a larger suite of parameters that are needed for the estimation of these indicators.

Indicators	**Model(s) used**	**Climate projections used**	**Interpretation**
Fuzzy exposure index	Fuzzy logic model	1	A composite multi-stressor index indicating the degree of exposure of marine species to climate hazards; 1 - 100, with 100 indicating the highest level of exposure to hazards.
Fuzzy climate risk index	Fuzzy logic model	1	Risk of impacts of marine species to climate change; 1 - 100, with 100 indicating the highest risk of impacts.
Changes in species' habitat suitability index (HSI)	Species distribution models	2	Impacts of climate change on the environmental niche of each species.
Changes in the sum of species' habitat suitability index (HSI)	Species distribution models	2	Impacts of climate change on the availability of suitable habitats for marine assemblages
Species invasion	Species distribution models	2	Projection of the number of species newly occurring locally
Species local extinction	Species distribution models	2	Projection of the number of species disappearing locally
Change in maximum catch potential	Dynamic bioclimate envelope model (DBEM)	1	Projection of changes in potential fisheries catches.

3 RESULTS

3.1 Projected changes in ocean conditions

Increasing CO_2 emissions in the 21st century are projected to change mean conditions of key ocean variables that are important to marine species in the Caribbean Sea (Figures 5 and 6, e.g. bounding box defined by the GFDL ESM 2.6). Specifically, the Caribbean Sea is projected to become warmer, less oxygenated, with higher acidity, lower primary production and higher salinity across scenarios and models. The changes are consistent across the lower resolution and higher resolution Earth system models (Figures 5 and 6).

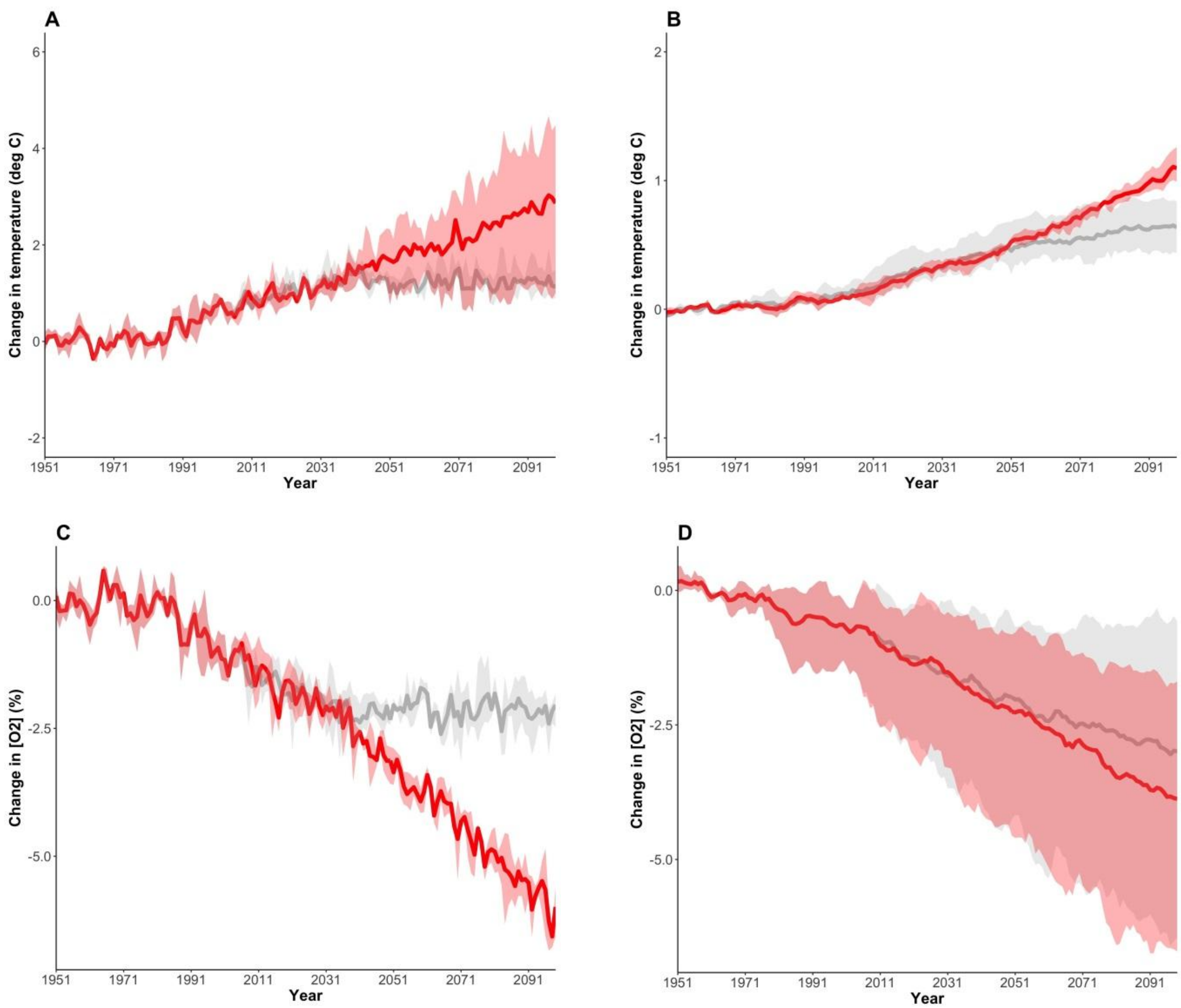


Figure 5. Projected changes in oceanic and atmospheric variables in the Caribbean Sea region until the end of the century under RCP2.6 (grey) and RCP8.5 (red) from the three Earth system models (GFDL, IPSL, MPI). (A) Change in sea surface temperature (^oC), (B) change in sea bottom temperature (^oC), (C) change in sea surface oxygen concentration (%), (D) change in sea bottom oxygen concentration (%).

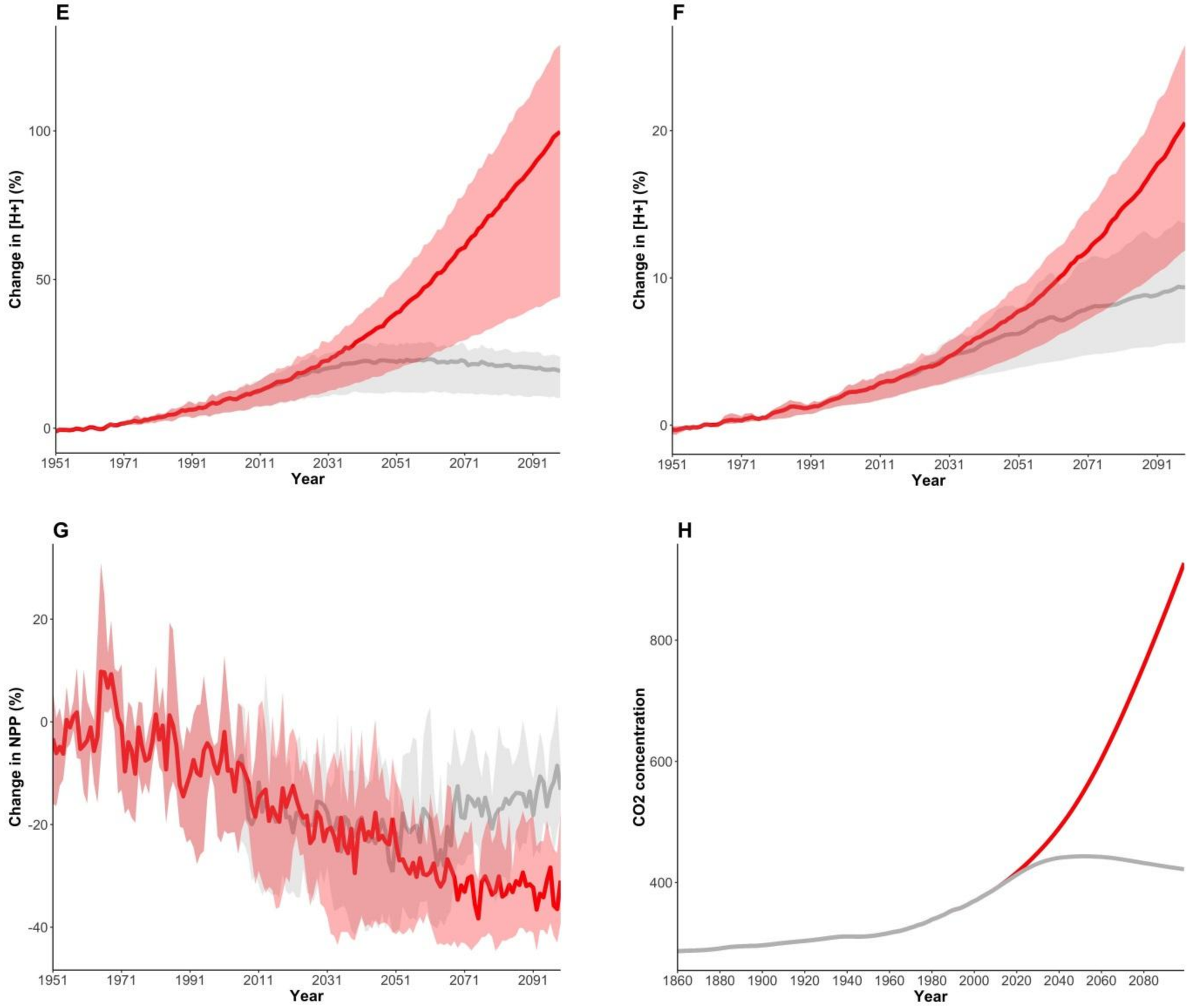


Figure 5 – cont'd. Projected changes in oceanic and atmospheric variables in the Caribbean Sea region until the end of the century under RCP2.6 (grey) and RCP8.5 (red) from the three Earth system models (GFDL, IPSL, MPI). (E) Change in sea surface acidity (hydrogen ion concentration) (%), (F) change in sea bottom acidity (%), (G), change in net primary production (%), and (H) change in atmospheric CO_2 concentration (ppm). The shaded area represents the range projected across the three Earth system models.

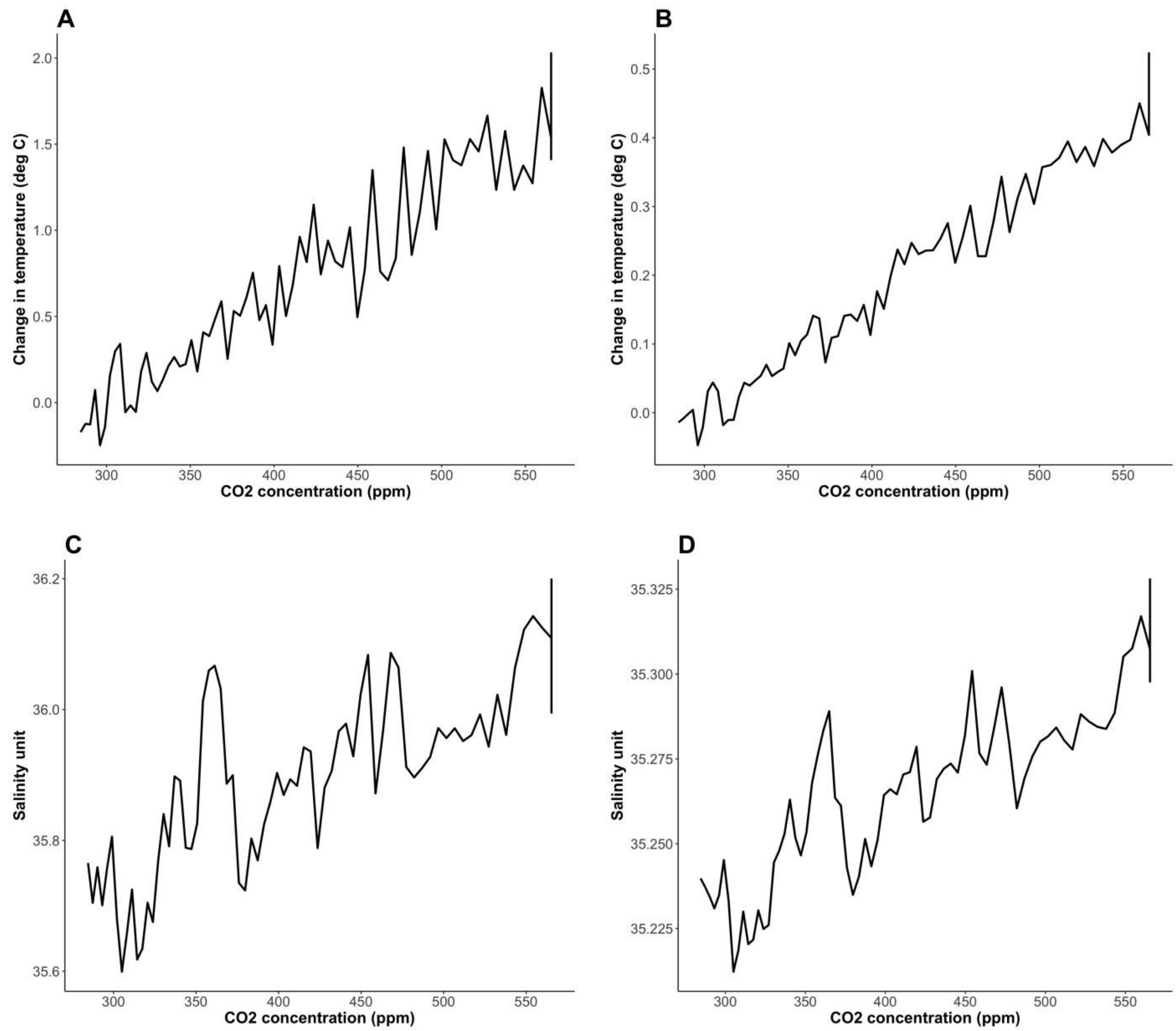


Figure 6. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (^oC), (B) sea bottom temperature (^oC), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels. The projected changes in atmospheric CO_2 concentration over time is shown in Figure 5H.

Spatially, the surface and bottom waters in the Caribbean Sea would become substantially warmer with atmospheric CO_2 concentrations at levels projected by the 2030s and 2050s under RCP8.5 relative to the average of 1970 to 2000 (Figure 7 - 9). Temperature is the primary driver of biological impacts of climate change on exploited fish stocks (Cheung and Pauly, 2016; Cheung, 2018). Warming of surface waters was projected be more homogenous across the Caribbean Sea compared to warming of bottom water, although surface water temperature was projected to increase more in the southern and western parts of the Caribbean Sea. In contrast, warming of bottom water was generally projected to follow bathymetry, with a greater increase in temperature projected to occur along shallow shelf and coastal areas. Across the water column, warming was projected to be positively related to atmospheric CO_2 concentration. This warming trend is less pronounced in the bottom environment owing to the diffusion of the heat from the surface to the benthic compartment. These general spatial patterns of projected ocean warming in the Caribbean Sea are consistent across the high and low resolution Earth system models' outputs (Figures 7 to 9).

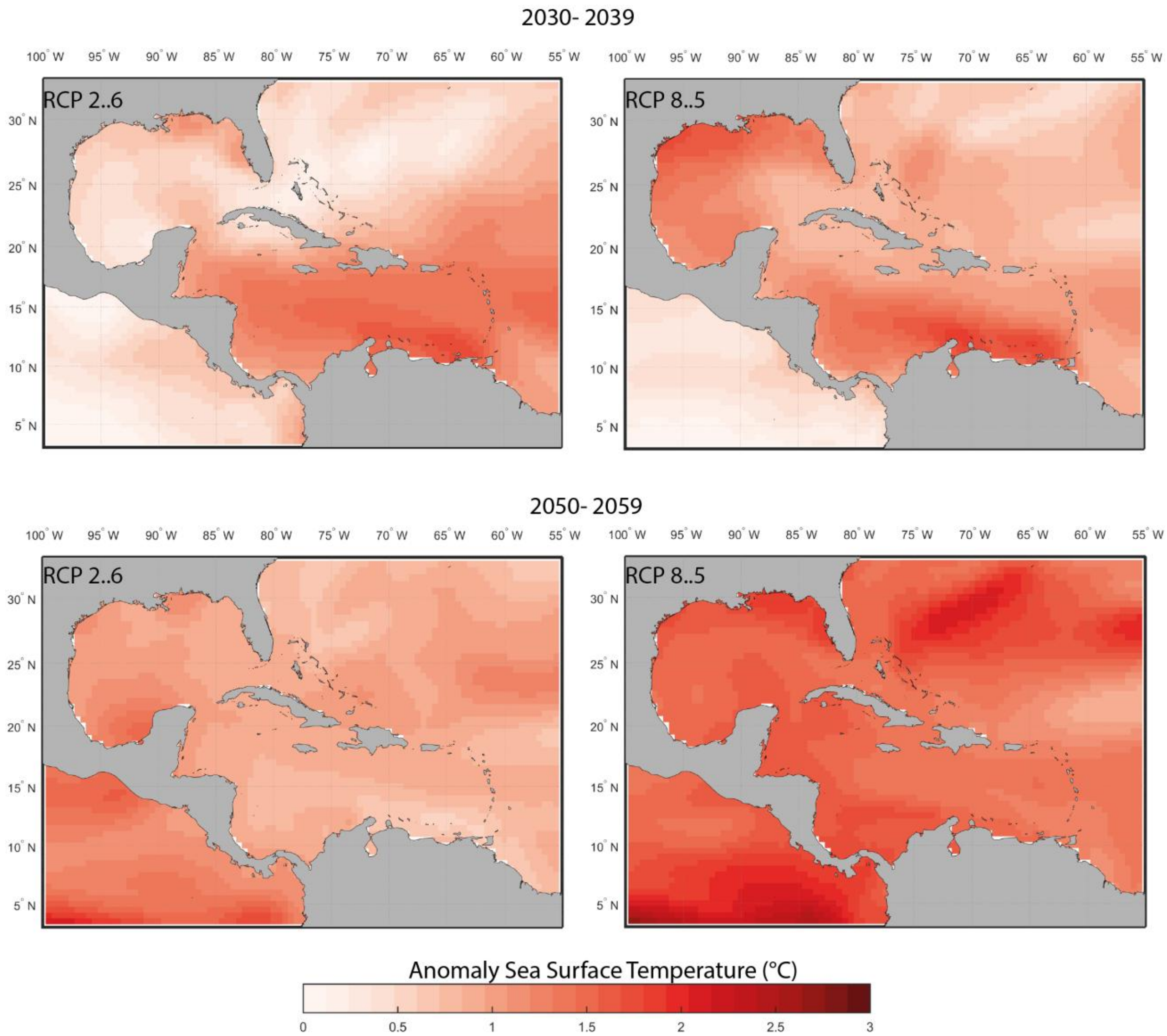


Figure 7. Projected changes in sea surface temperature by the early (upper panel) and the mid (lower panel) 21st century relative to the 1970-2000 time period under RCP2.6 (left panel) and RCP8.5 (right panel) from the coarser resolution Earth system models (GFDL, IPSL, MPI). The panels show the projected sea surface temperature as averaged across the outputs from the three Earth system models.

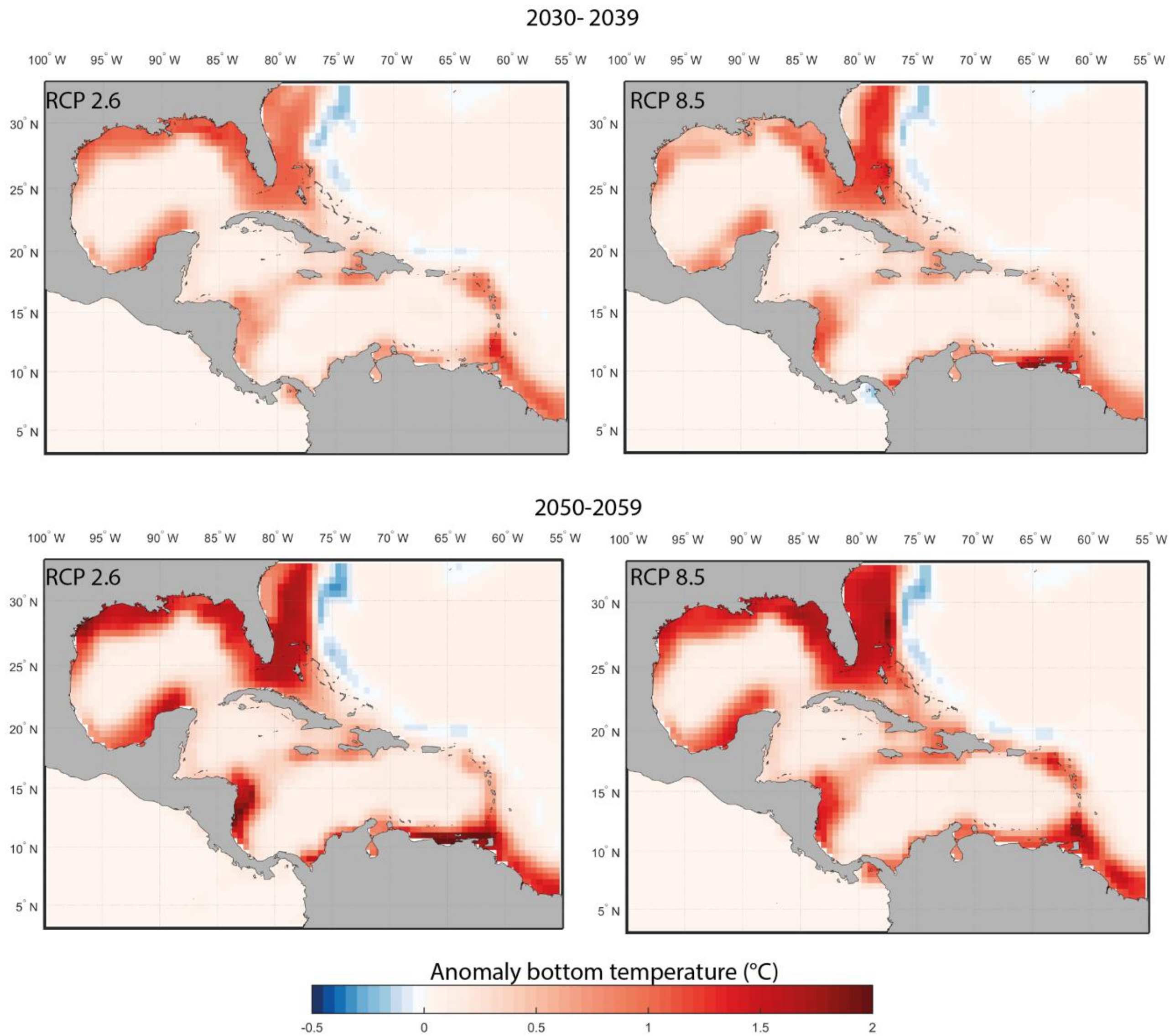


Figure 8. Projected changes in sea bottom temperature by the early (upper panel) and mid (lower panel) 21st century relative to the 1970-2000 time period under RCP2.6 (left panel) and RCP8.5 (right panel) from the coarser resolution Earth system models (GFDL, IPSL, MPI). The panels show the projected sea bottom temperature as averaged across the outputs from the three Earth system models.

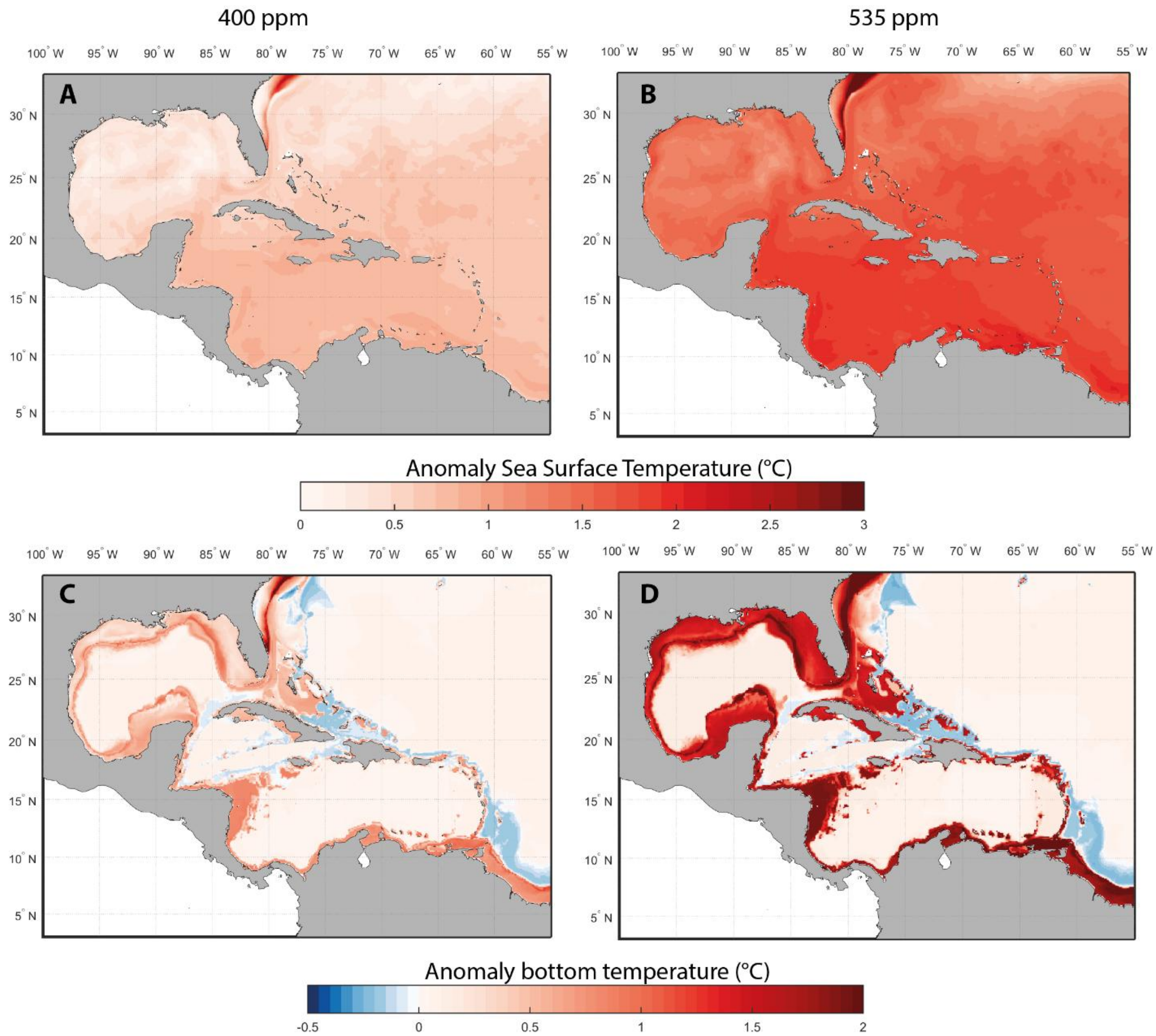


Figure 9. Projected changes in sea surface temperature (A, B) and sea bottom temperature (C, D) from the high resolution Earth system model (GFDL CM2.6) under an average atmospheric CO_2 concentration of 400 ppm (A, C) and 535 ppm (B, D).

3.2 **Vulnerability of exploited species to climate hazards in the Caribbean Sea**

Overall, the selected 106 marine fishes and invertebrates were found to prefer temperatures ranging from 12^{o}C to 27^{o}C (Figure 10). We predicted considerable differences in temperature preferences between pelagic and demersal species. Pelagic species, inhabiting surface water layers, generally have similar temperature preferences of between 23^{o}C and 27^{o}C, with a narrow breadth (95% confidence intervals ± 5^{o}C). In contrast, demersal species, inhabiting sub-surface or bottom layers of water, prefer lower temperatures and have a much wider range of temperature preferences.

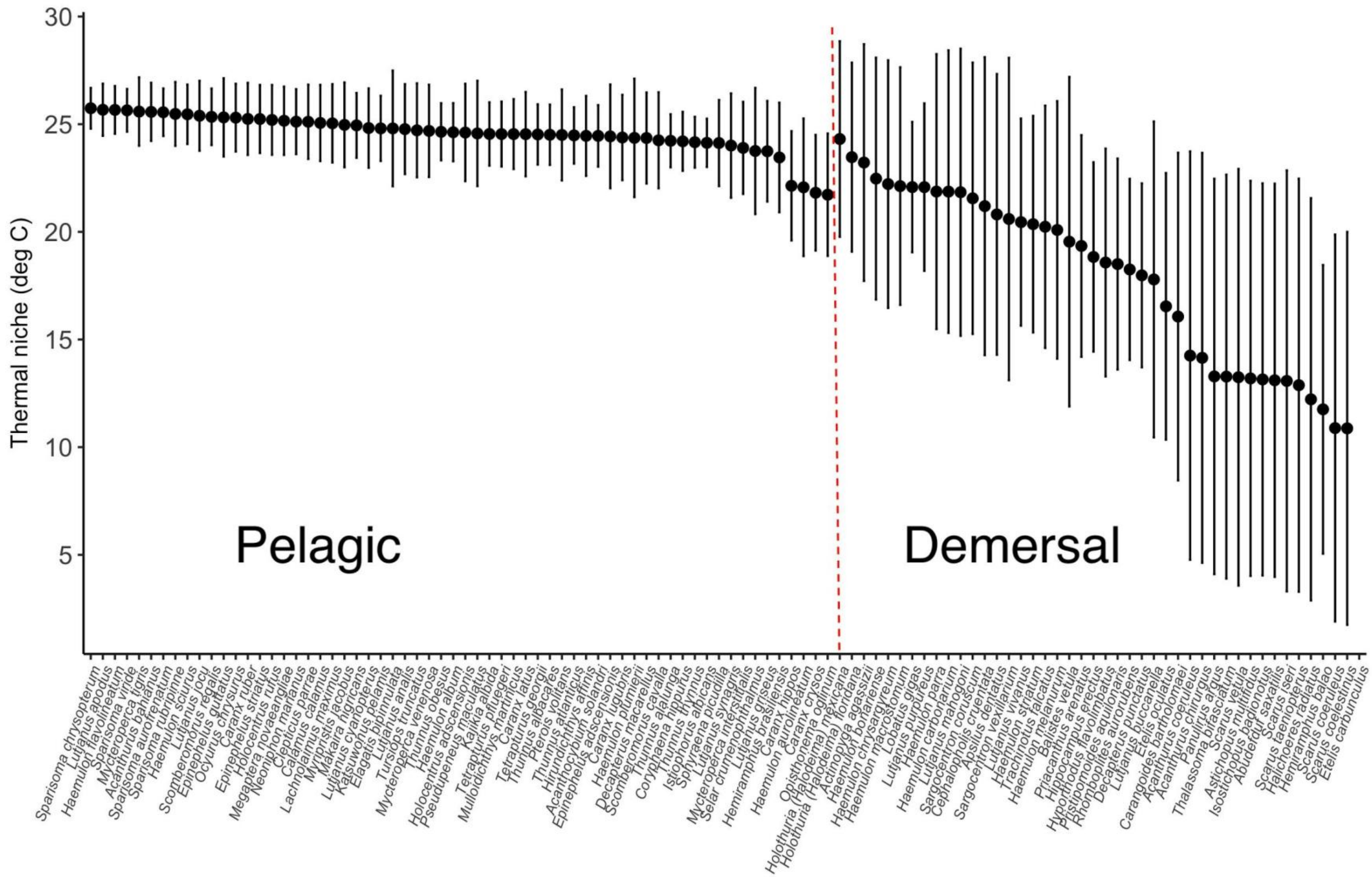


Figure 10. Estimated thermal preferences and tolerances of the 106 selected marine fishes and invertebrates. These variables were used to determine species' sensitivity to climate hazards. The black dots represent the preferred temperature while the vertical line represents the 95% confidence intervals of species' temperature preference profiles (see Appendix A.4).

Exposure of the 106 selected marine species to climate hazards were estimated to be high to very high under both RCP2.6 and RCP8.5 by the mid-21st century (Figure 11). Overall, the median exposure index for all species combined was estimated to be 94 and 100 under RCP2.6 and RCP8.5, respectively, indicating a very high level of exposure to climate hazards (warming, deoxygenation, acidification and decline in net primary production as projected by the three coarser resolution global Earth system models).

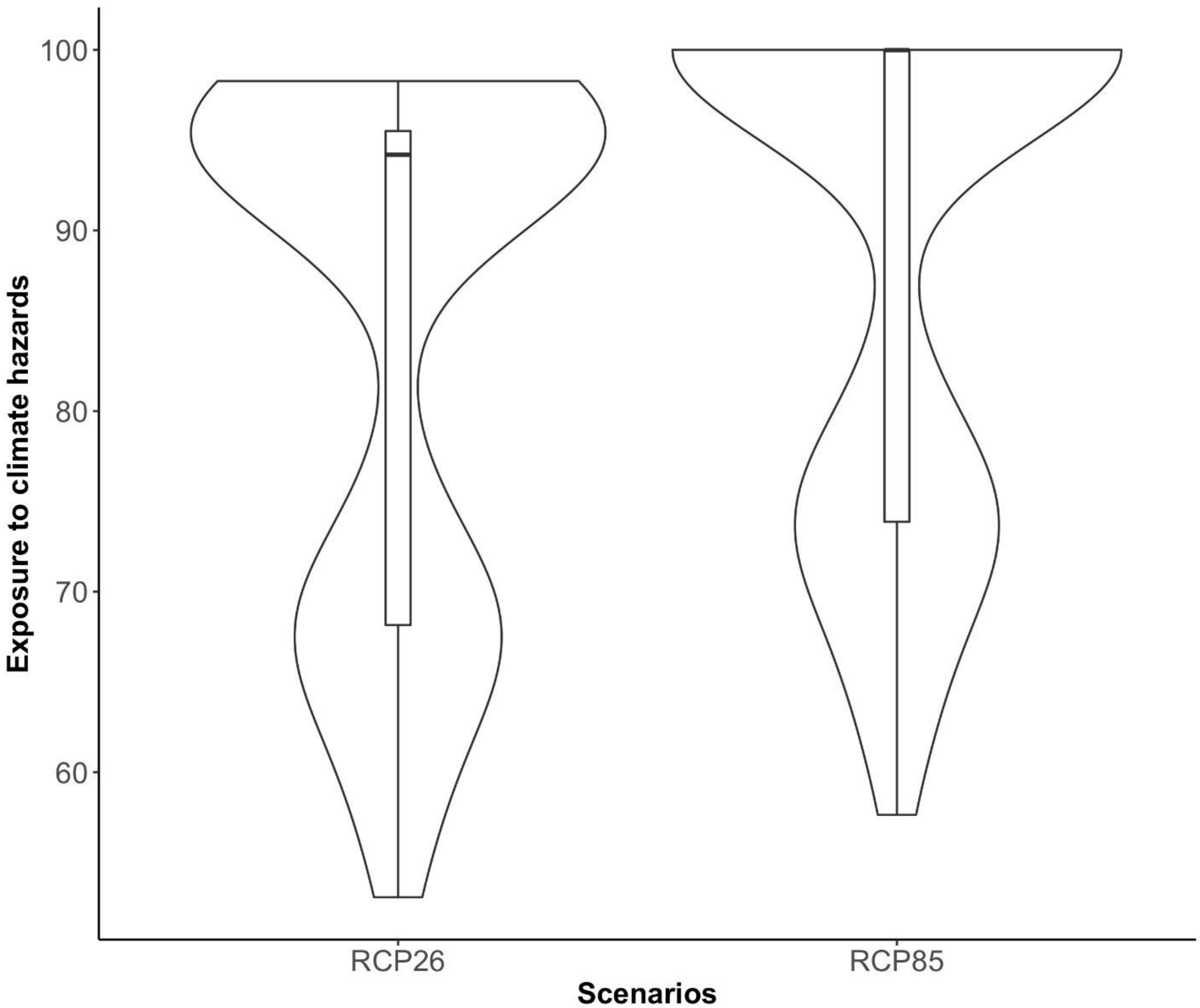


Figure 11. Calculated exposure to the climate hazard index for the 106 selected marine fishes and invertebrates in the Caribbean Sea. These violin plots show the distribution of the data, including the data's density distribution; with the width of the plot representing the frequency distribution of the exposure index across the 106 species (i.e., the wider the plot the greater the number of species that fall into a given exposure index value, the narrower the plot the lower the frequency). An index value of 100 indicates the highest possible exposure to climate hazards. The box plots included within the violin plots show the median (dark horizontal bar, 94 for RCP2.6 and 100 for RCP8.5), interquartile range (box), as well as the minimum and maximum values (whiskers).

The vulnerability (a combination of sensitivity and adaptive capacity - see Figure 3) of the selected marine assemblages was evaluated at moderate to high. The average calculated vulnerability was 60 across the 106 selected fishes and invertebrates, with 25th and 75th quartiles of 45 and 74, respectively (Appendix A.5). Fisheries species that were amongst the most vulnerable were snappers (e.g., *Lutjanus* *cyanopterus*, vulnerability index = 93), parrotfish (e.g., *Scarus coeruleus*, vulnerability index = 90) and groupers (e.g., *Mycteroperca tigris*, vulnerability index = 89). Species with the lowest calculated vulnerabilities were small(er) reef and pelagic fishes such as *Pseudupeneus maculatus* (spotted goatfish) (vulnerability index = 19), *Decapterus macarellus* (mackerel scad) (vulnerability index = 24) and *Abudefduf saxatilis* (sergeant major) (vulnerability index = 27).

Combining species' exposure to climate hazards with their vulnerability, we estimated a very high risk to climate change impacts for the majority of the 106 selected marine fish and invertebrates species (Figure 12, see Appendix A.5 for detailed methods). Projections show that most of the Caribbean Sea would register a climate risk index >75 under both RCP2.6 and RCP8.5. Under RCP8.5, more than 70% of pixels (geographical cells of 0.5^o latitude x 0.5^o longitude grid) were estimated to have a climate risk index >80 (Figure 12C). More than 70% of selected Caribbean marine species were projected to have a very high risk to climate impacts. Under RCP8.5, no species were categorized as at low or moderate risk (Figure 12D). The climate risk index is significantly correlated with the risk of extinction as defined by the IUCN Red List of Endangered Species (Cheung *et al*., 2018).

When we projected the climate risk index spatially using the predicted species habitat suitability of each species, we found that climate risk of the species assemblages were highest along the coastal and shelf seas region (Figure 13). Offshore, climate risk is greater in the southern part of the Caribbean Sea (high and very high risk under RCP2.6 and RCP8.5 by 2050), while the northern region was projected to have a slightly lower (moderate level) climate risk. Across both scenarios, the area between Cuba, Mexico, Guatemala and Honduras registered consistently lower climate risk indices, as did two small pockets along Costa Rica and Panama.

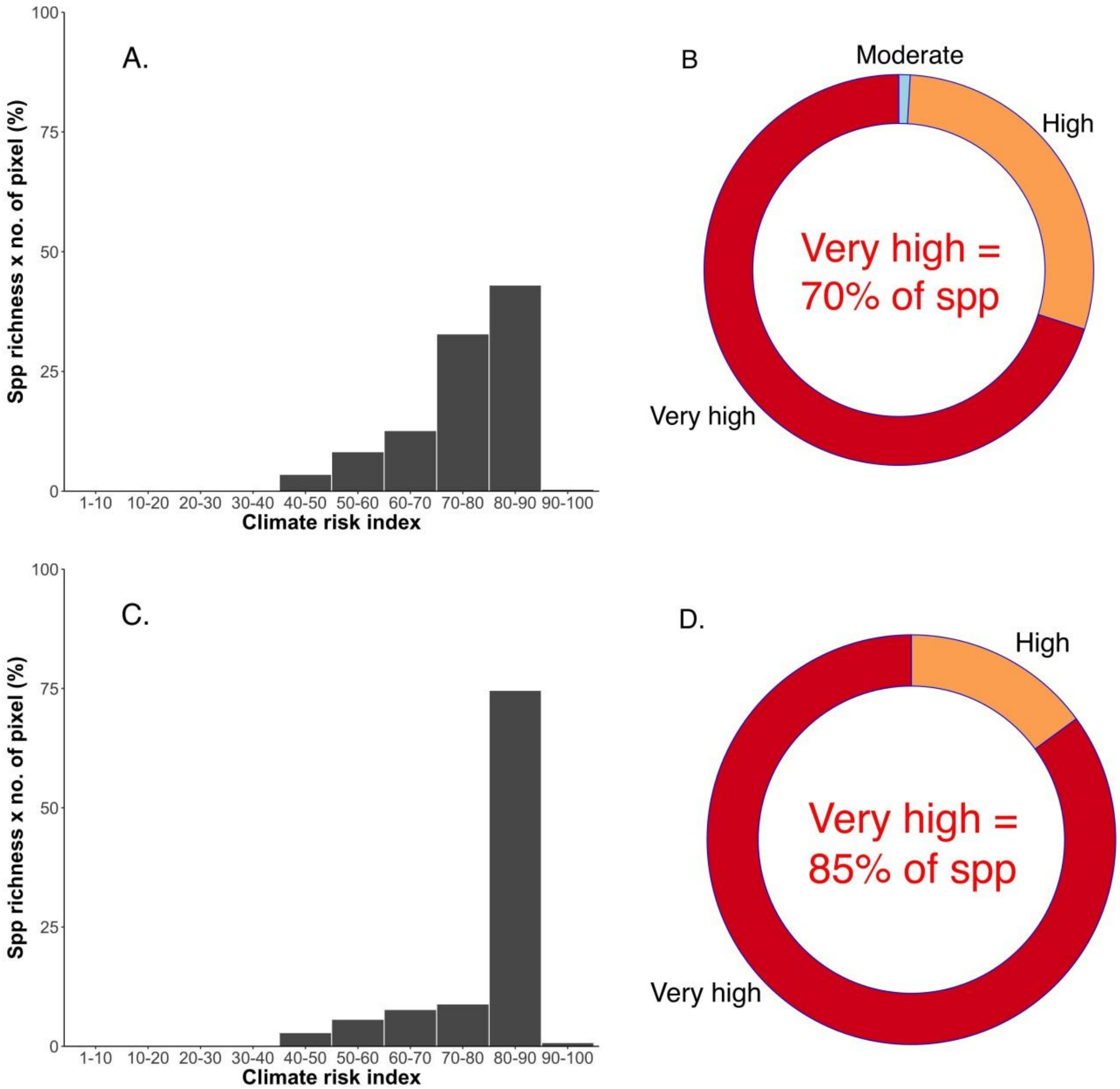


Figure 12. Projected climate risk index for the 106 selected marine fish and invertebrate species in the Caribbean Sea using the fuzzy logic risk assessment model. (A, C) frequency distribution of the percentage of pixels (0.5^o latitude x 0.5^o longitude grid) by climate risk index for all 106 species under RCP2.6 and RCP8.5, respectively. (B, D) The proportion of species categorized according to different levels of climate risk in the region under RCP2.6 and RCP8.5, respectively.

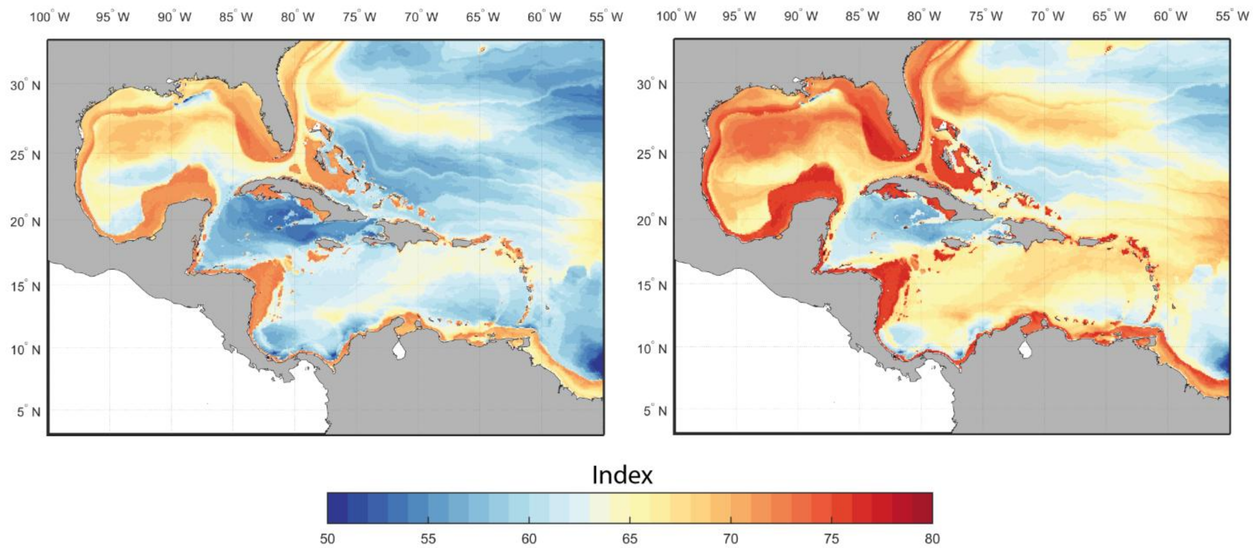


Figure 13. Calculated average climate risk index for the 106 selected marine fish and invertebrate species projected spatially using the predicted species habitat suitability of each species under RCP2.6 (left panel) and RCP8.5 (right panel) by the mid-21st century.

3.3 **Projected changes in habitat suitability of marine species**

Marine species in the Caribbean Sea are projected to shift their distribution in response to increasing atmospheric CO_2 concentration and associated ocean warming and other changes in ocean conditions compared to current conditions. Based on outputs from the species distribution models, we projected that under atmospheric CO_2 concentration of ~400 ppm, selected species assemblages would shift the centre of their distribution range (distribution centroid) by 135 km ± 77 km (standard deviation) north – relative to average conditions between 1970 and 2000 based on outputs from the high resolution Earth system model and across the three species distribution models. Under atmospheric CO_2 concentration of ~535 ppm, selected species assemblages would shift by 308 km ± 121 km north. Species' distribution centroids were also projected to shift to deeper waters with an average shift of 2.5 m and 19.6 m under the lower and higher CO_2 concentration conditions, respectively, relative to average conditions between 1970 and 2000.

Habitat conditions in the Caribbean Sea for marine fishes and invertebrates were projected to decrease under the higher CO_2 emission scenario. Across the region, the sum of individual selected marine species' habitat suitability index, an indicator of the environmental quality for the species, was projected to decline substantially under both ~400 ppm and ~535 ppm atmospheric CO_2 concentration conditions (Figure 14). This pattern was particularly pronounced for the southern and eastern Caribbean Sea.

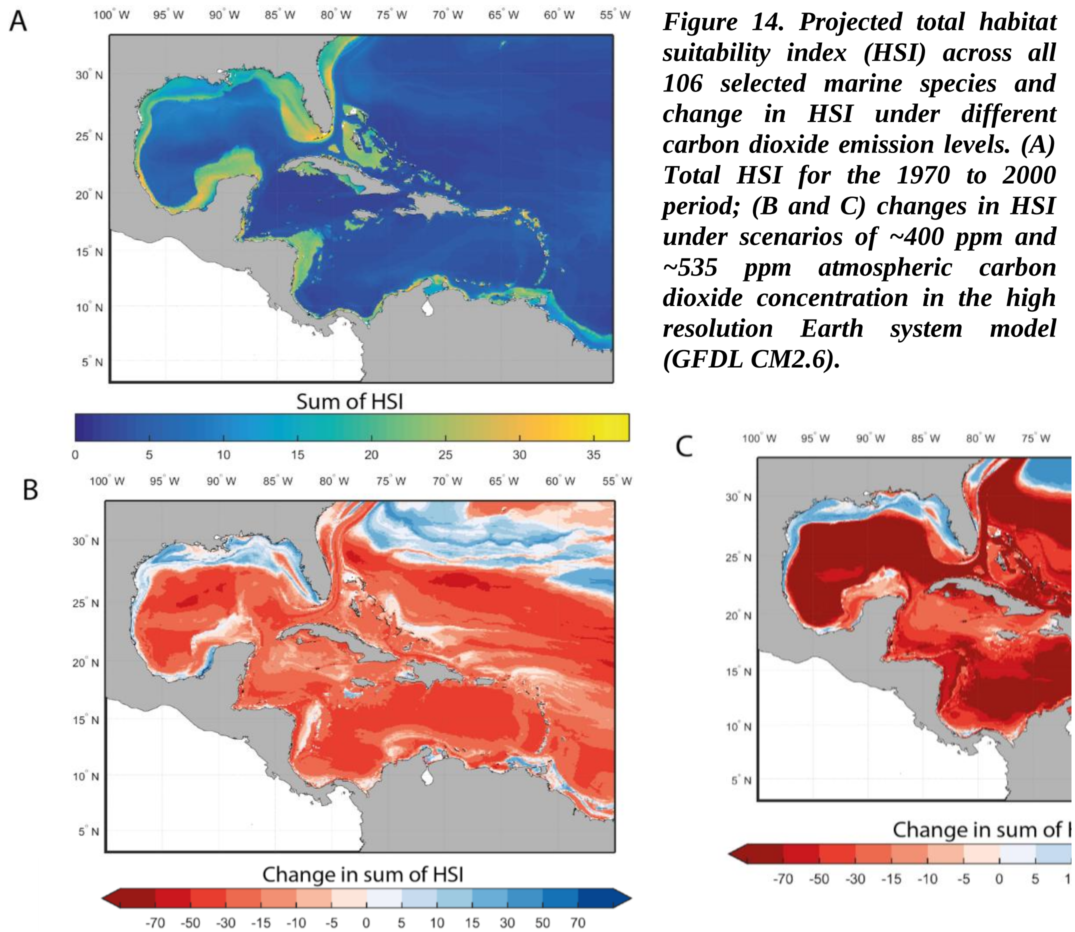


Figure 14. Projected total habitat suitability index (HSI) across all 106 selected marine species and change in HSI under different carbon dioxide emission levels. (A) Total HSI for the 1970 to 2000 period; (B and C) changes in HSI under scenarios of ~400 ppm and ~535 ppm atmospheric carbon dioxide concentration in the high resolution Earth system model (GFDL CM2.6).

The projected species range shifts and large declines in habitat suitability resulted in large changes in species assemblages across the Caribbean Sea (Figure 15). The loss of suitable habitat for the majority of species under the higher CO_2 emission scenario was projected to result in high rates of local extinction, particularly in the northern and southwestern part of the Caribbean Sea - including the area around Cuba and throughout the Bahamas. In contrast, species gains were projected for the northern parts of the Gulf of Mexico along the Texas and Louisiana state coasts, in an area west of the Dominican Republic and south of Cuba, as well as along the coast of Venezuela and northern Brazil. The overall percentage local extinction and species gains were projected to increase with higher atmospheric CO_2 concentration. The fact that areas of greatest species gains are similar across both CO_2 concentrations is attributable to oceanographic conditions that remain similar under these future climates.

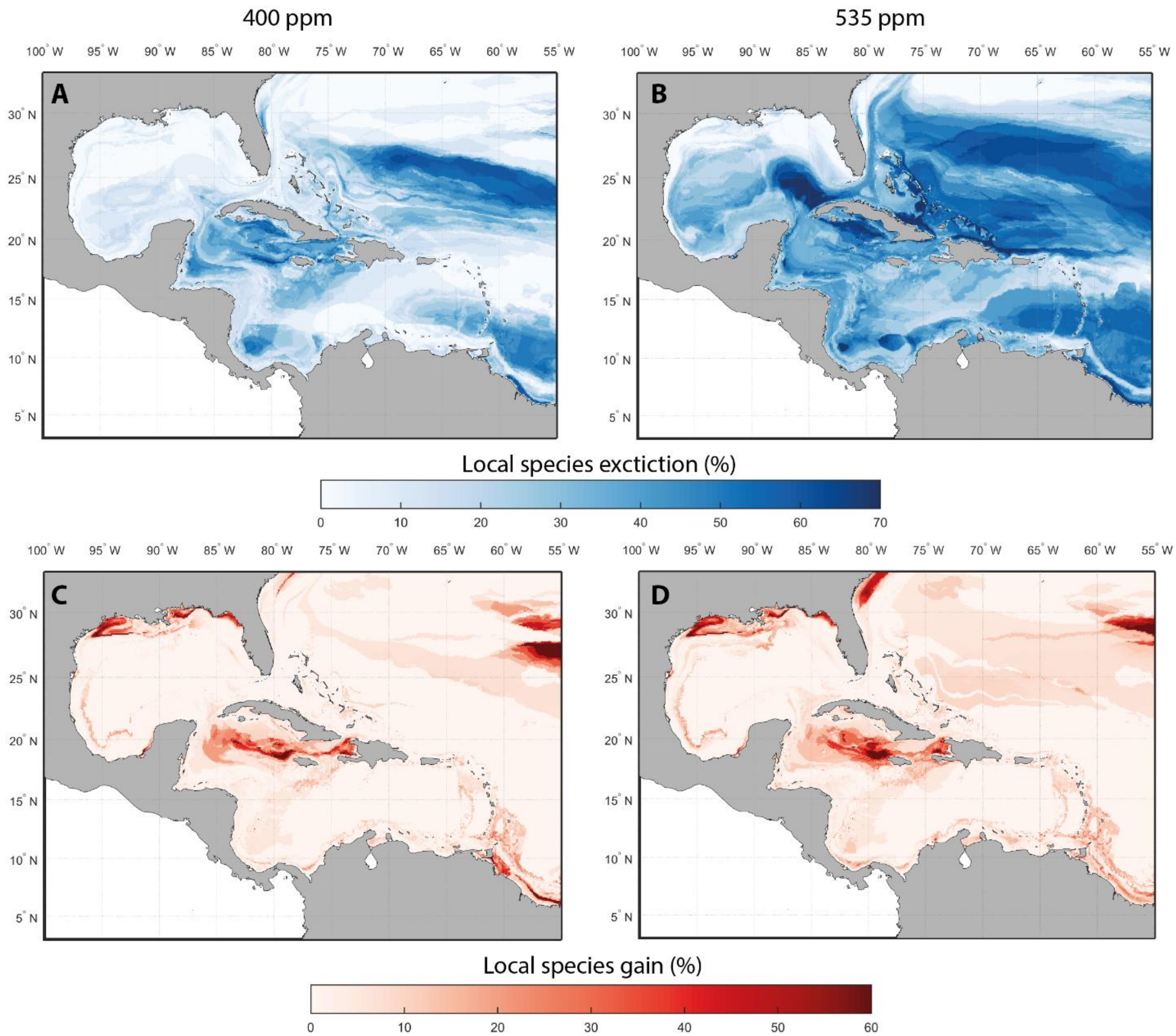


Figure 15. Projected rate of local species extinction (A, B) and gain (C, D) in the Caribbean Sea under lower (A, C) and higher (B, D) carbon emission scenarios. The rates of local species extinction and gain were calculated based on the selected fishes and invertebrates. The lower and higher emission scenarios corresponded to atmospheric carbon dioxide concentration of ~ 400 ppm (A, C) and ~ 535 ppm (B, D) used in the high resolution Earth system model (GFDL CM2.6).

These results focused on aggregate change of the entire species assemblage, but it is also possible to examine disaggregated results for additional insights on habitat suitability changes for individual species, particularly alongside supporting literature on empirical studies that can lend support to the mechanisms assumed to be driving these patterns. Results for all individual species would be too numerous to examine here, instead we present model outputs and supporting empirical studies for four case study species that are important to fisheries in the region and representative of a broad range of taxa and habitats. Empirical studies of climate change impacts to fished species in the Caribbean are still uncommon, but these types of studies will become increasingly important for validating or refining regional climate model projections and informing smaller-scale management responses by countries in the region. To this end, the later phases of this broader project aim to develop standardized monitoring frameworks and protocols to facilitate tracking and responding to climate change effects on fish and fisheries in the future.

3.3.1 Species Case Study:
Common Dolphinfish (*Coryphaena hippurus*)

3.3.1.1 Biology

Common dolphinfish's preferred range spans the Caribbean, Gulf of Mexico and from the Straits of Florida to North Carolina (Oxenford, 1999). Dolphinfish typically live between 2 - 4 years, grow fast, mature quickly (<1 year, Beardsley 1967), produce many eggs, and spend the majority of their time in waters above 25°C (Palko, 1982; Hammond, 2008; Zuñinga Flores, *et al*. 2008). They can grow to sizes >2 m, though typically range about 100 cm in length and weigh around 7.5 kg (Froese and Pauly, 2018). Females are usually smaller than males. Dolphinfish support commercial, artisanal and recreational fisheries and are considered the most important large surface-dwelling fish landed by commercial fishers in the eastern Caribbean (Oxenford and Hunte, 1986; Mahon, 1999). They are caught using handlines, trolling lines and longlines. Total catches by all fishing entities operating in the Caribbean Sea region have remained fairly stable and were estimated at around 4,000 tonnes per year between 2000 and 2014 (*Sea Around Us* data).

3.3.1.2 Modelling Projections

Habitat suitability for common dolphinfish is projected to experience modest declines throughout much of the wider Caribbean Sea and very strong declines in areas of currently high habitat suitability in the northern Gulf of Mexico (Figure 16). In both of these regions, declines in more southerly areas are expected to be associated with increases in habitat suitability in more northerly areas. In the Caribbean Sea, habitat suitability is expected to decline most strongly along the northern coastlines of South America, while habitat suitability in the central Caribbean between Cuba, Mexico, and Haiti is expected to slightly increase as southerly populations move north. In the Gulf of Mexico, a similar pattern is observed where habitat suitability declines offshore, but increases closer to the northern shore of the Gulf. These projections suggest that ongoing development of pelagic fisheries may be a more successful adaptation strategy for Jamaica and Haiti than for nations in the Lesser Antilles.

3.3.1.3 Empirical Evidence for Climate Impacts to Date

A. Direct Impacts of Temperature and Acidification

Catch per unit of longline effort (CPUE) data over time and space of dolphinfish along the U.S. east coast showed sea surface temperature and chlorophyll-a concentration to be the most important variables to understand the distribution and abundance of common dolphinfish. Studies have documented that dolphinfish generally stay within 8°C of the maximum temperature observed at the surface, equivalent typically to temperatures >18°C (Furukawa *et al.,* 2011; Merten *et al*., 2014). As they are highly migratory, peak catch is seasonal (Oxenford, 1999; Luckhurst and, Trott 2000; Farrell *et al*., 2014) and influenced by inter-annual and seasonal temperature changes (Kleisner, 2009). Dolphinfish catches were particularly low in the region in 2005[1], a year of unusually warm temperatures. This finding is in line with research showing declines in catch rates for high temperatures off the U.S. east coast (Farrell *et al*. ,2014), likely a result of northward migration following increases in sea surfaces temperature (SST). Zuñinga-Flores *et al*. (2008) also reported lower catch rates off Cabo St Lucas, Mexico, in 1998, due to lower abundances because of higher temperatures associated with a particularly strong El Niño event that year. During this event, fish displaced their distribution northwards, with record catches for fishermen in southern California (Norton, 1999; Lea, 2000).

[1] Note numbers caught were the highest ever recorded in Barbados in 2006-2007, but individual were undersized, which was unusual (Brathwaite 2007). That year was associated with cooler temperatures and ocean fronts.

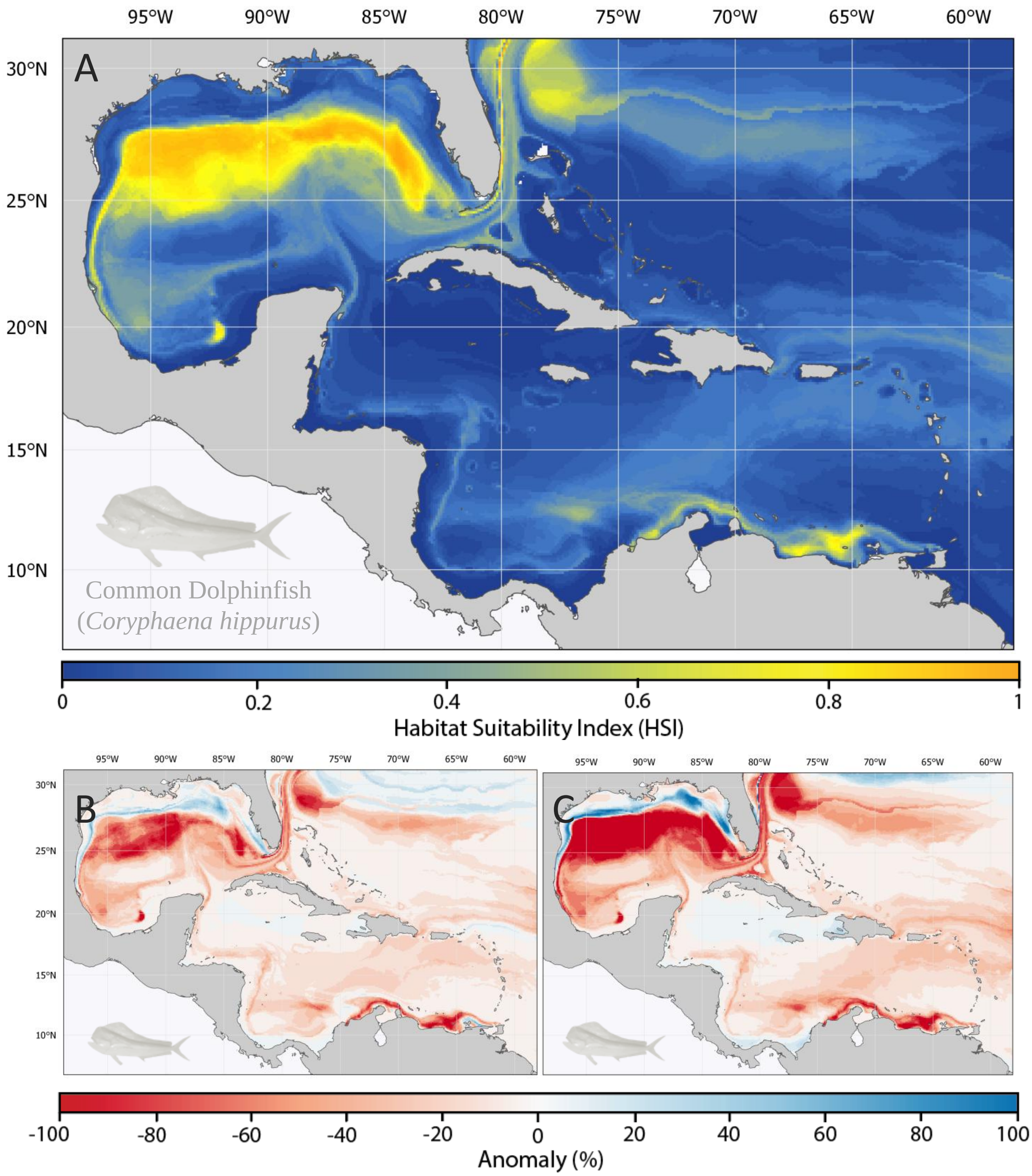


Figure 16. Species-specific projected total habitat suitability index (HSI) and HSI's change or 'anomaly' under different carbon dioxide emission levels for common dolphinfish (Coryphaena hippurus). (A) Total HSI for the 1970 to 2000 period; (B and C) changes in HSI under scenarios of ~400 ppm and ~535 ppm atmospheric carbon dioxide concentration in the high resolution Earth system model (GFDL CM2.6).

Consequently, increases in temperature because of climate change are likely to see dolphinfish increasingly extend their range poleward, with reduced abundance and catches in the Caribbean. In addition, climate-related reductions in mixing of the water column – leading to greater stratification - and reduced oxygenation of the upper ocean layers is already leading to a compression of the available suitable habitat for highly migratory pelagic species (Prince *et al*., 2010; Stramma *et al*., 2012). These authors report that the rise of the oxygen minimum layer (the zone in which oxygen concentrations are below those suitable for a large number of pelagic species) in the tropical northeast Atlantic between 1960-2010 has resulted in an annual loss of 15% of suitable habitat, with projected habitat losses under climate change threatening the sustainability of the pelagic fisheries that these species support – with species-specific declines depending on the oxygen range tolerated by individual species. Over the short term, fishers may be able to rely on catches around Fish Aggregating Devices or from travelling further from shore to track the northward moving fish (Oxenford and Monnereau, 2017; 2018).

While previous studies have shown that adult common dolphinfish have evolved the ability to adapt to different acidity levels in the water, their young larvae have not. Under an ocean-acidification scenario representative of future ocean conditions, the metabolism and movement abilities of recently hatched dolphinfish larvae were significantly different from normal conditions, with expected impacts on recruitment, dispersal success, and the population dynamics of the species (Pimentel *et al*., 2014). Although Bignami *et al*. (2014) found acidification treatment to have small effects on growth, swimming activity, and otolith formation of larval dolphinfish, a lack of effect on most variables measured in their study lead the authors to conclude that dolphinfish may not be very sensitive to ocean acidification.

B. Indirect Impacts from Effects on Food, Habitat, and Pathogens

Common dolphinfish are carnivorous predators that mostly consume surface-dwelling prey (e.g., Exocoetidae, Clupeidae, Carangidae, Scombridae) (Oxenford and Hunte, 1999) and sometimes mesopelagic species such as musky octopus (*Eledone moschata*), half-naked hatchetfish (*Argyropelecus hemigymnus*), Sloane's viperfish (*Chauliodus sloani*), and Spotted barracudina (*Arctozenus* risso) (Massutí *et al*., 1998). Long-term changes in plankton caused by climate change could have a significant impact on commercial fish stocks (Hays *et al*., 2005, Osman *et al*., 2019), including dolphinfish, especially because a wide range of this species' prey consume plankton. However, such changes could also have limited impacts on dolphinfish as they typically are found and caught in areas of low chlorophyll-*a* concentrations (Farrell *et al*., 2014). Their highly migratory nature makes them well suited for life in low nutrient waters as they can cover great distances in search of widely dispersed prey items. Moreover, dolphinfish eat a wide variety of organisms and are mainly opportunistic predators that adapt to preying on species that are abundant in their environment. While under climate change they would likely be able to adapt their feeding habits to mostly eat species that are plentiful (Torres Rojas *et al*., 2014), modelling studies have confirmed their strong trophic dependence on flyingfish as prey and demonstrated the vulnerability of their stock status to the abundance of flyingfish (Mohammed *et al*., 2007; Fanning and Oxenford, 2011). Thus, declines in flyingfish in the future could negatively affect dolphinfish abundances, irrespective of direct climate change impacts on dolphinfish.

Juvenile and smaller-sized dolphinfish are known to school and associate with drifting objects such as *Sargassum* spp. (*Sargassum natans* and *Sargassum fluitans)* and flotsam (Hemphill, 2005; Rooker *et al*., 2006; Merten *et al*., 2014b; Farrell *et al*., 2014). The fish use the floating mats to shelter from predators (tuna, sharks, marlin, sailfish, and swordfish) and because large numbers of their prey can be found underneath the seaweed or driftwood (Palko *et al*., 1982; Luckhurts, 2014). The Caribbean region has been experiencing a surge of *Sargassum* influx in recent years – probably in part because of increasing temperatures and nutrient loads (Gow*et al*., 2013; Maurer *et al*., 2015; Mengqiu and Hu, 2017) – which in the case of common dolphinfish has been associated with increases in landings (Monnereau and Oxenford, 2017; 2018).

3.3.2 Species Case Study: Yellowtail Snapper (*Ocyurus chrysurus*)

3.3.2.1 Biology

This species has been estimated to live up to between six and 17 years (Piedra, 1969; Claro, 1983; Manooch and Drennon, 1987), with age at maturity around 2 years (Claro *et al*., 2001; Muller *et al*., 2003). Maximum length is 81 cm (Anderson, 2002). Yellowtail snapper is commonly associated with coral reefs as adults, seagrass beds as juveniles, and widely distributed throughout its range – from Florida to Southeastern Brazil. Larvae take approximately 30 days to develop (Lindeman *et al*., 2001) and display strong swimming ability (Hogan *et al*., 2007). A recent study found four distinct stocks of *O. chrysurus* in the region (Saillant *et al*., 2012), with one single stock along the entire coast of Brazil (da Silva *et al*., 2015). Yellowtail snapper is an important part of commercial, artisanal and recreational fisheries throughout the tropical, western Atlantic. It is caught using a number of gears, including hook and line, spears, traps and nets. Average annual landings from the entire Caribbean region for 1997-2000 were estimated at 3,458 tonnes (Muller *et al*., 2003). Total reconstructed catches for all fishing entities within the entire Caribbean Sea region were estimated at around 3,000 tonnes per year between 2000 and 2014 (*Sea Around Us*).

3.3.2.2 Modelling Projections

In the near-term (roughly the 2030s), habitat suitability for yellowtail snapper is projected to experience modest increases in some coastal waters of Mexico, on Jamaica's Pedro Bank, off the south coast of Haiti, and in the coastal waters of the southerly Lesser Antilles (Figure 17). Many of these gains are expected to disappear by mid-century as populations continue to move north, with reductions in habitat suitability in the southern parts of the Caribbean Sea along with modest increases in habitat suitability north of the Yucatan Peninsula, around the northern Gulf of Mexico and the Florida panhandle, on the Bahamian Bank, and in the coastal waters of the more northerly Lesser Antilles.

3.3.2.3 Empirical Evidence for Climate Impacts to Date

A. Direct Impacts of Temperature and Acidification

Yellowtail snappers normally are found in waters between 24^{o}C and 30^{o}C. Wallace (1977) found that juvenile yellowtail snappers died at temperatures between 33.5 and 34°C. As climate change will increase water temperatures within the Caribbean region, to remain within their preferred temperature range, yellowtail snapper may shift their distribution range northwards. This already appears to be happening as, for example, 2006-2007 surveys found a large number of juveniles of tropical species, including yellowtail snapper, in seagrass meadows along the northern Gulf of Mexico that were completely absent during surveys undertaken in the 1970s (Fodrie *et al*., 2010). These shifts were found to agree with observed regional increases in air and sea surface temperatures (> 3°C) between the two surveys (Fodrie *et al*., 2010). Such shifts northwards (and southward along the coast of Brazil) are likely to be accompanied by declines in the abundance of relevant species in the Caribbean itself, and reflected in lower catches.

B. Indirect Impacts from Effects on Food, Habitat, and Pathogens

Juveniles of yellowtail snapper typically settle into seagrass beds (so called nursery areas) (Nagelkerken *et al*. 2000; 2001; 2002; 2017; Dorenbosch *et al*., 2004) where they spend about 2 years of their life (Verweij *et al*., 2008). As they grow into adults, the fish move on to reef habitats (Nagekerken *et al*., 2009). Therefore, in addition to climate change impacts on the species itself, yellowtail snapper stocks also will be influenced by the effects of climate change (and other stressors) on reefs and seagrass beds. Juveniles' dependence on seagrass beds may mean that yellowtail snapper are more resistant to declines in coral reefs and that degradation of reef habitats would have less of an effect on yellowtail snapper, than fish that exclusively depend on corals as juveniles and adults. However, should seagrass beds be particularly affected by other human stressors in addition to climate change, yellowtail snapper populations may decline just as quickly or more rapidly.

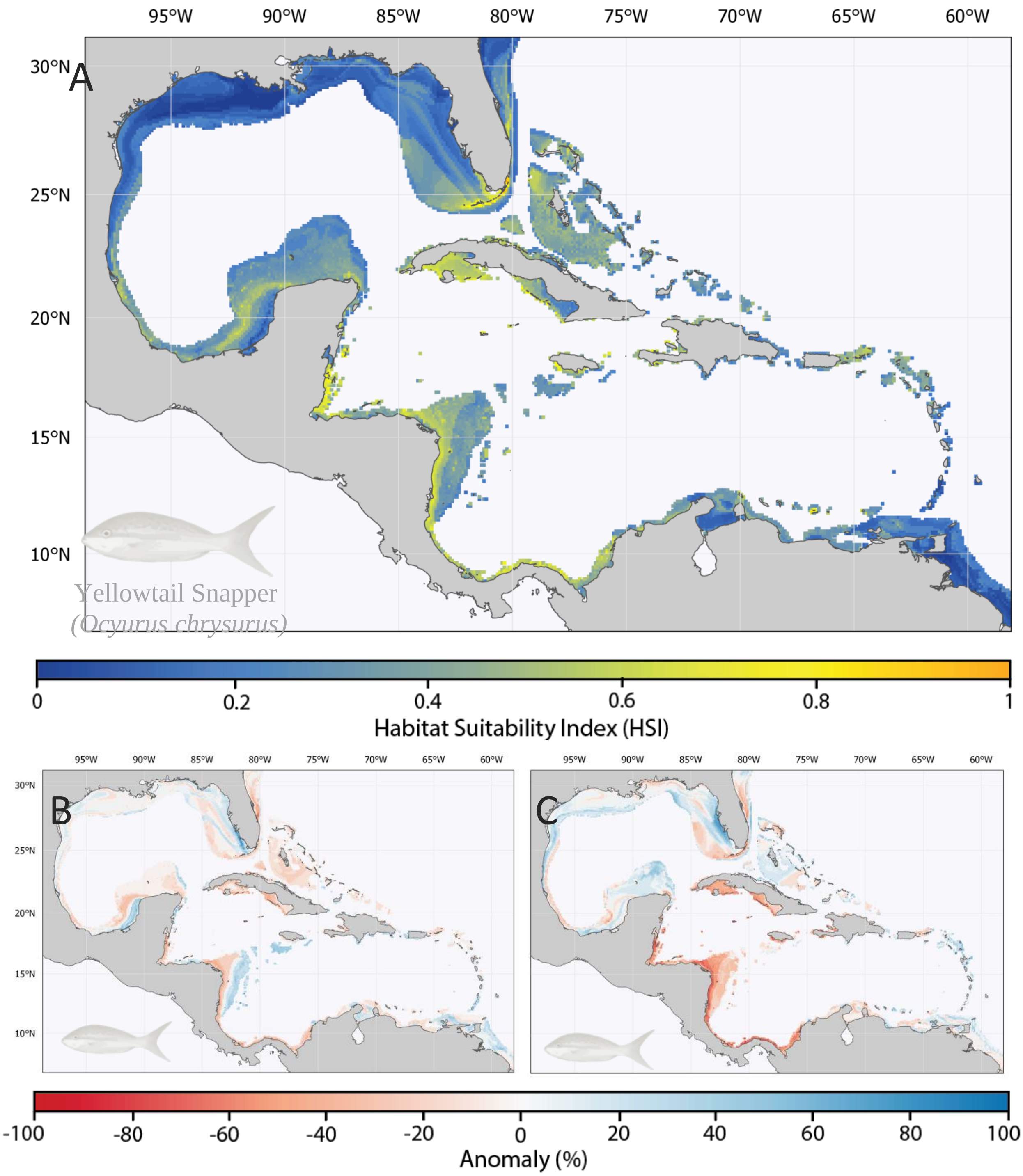
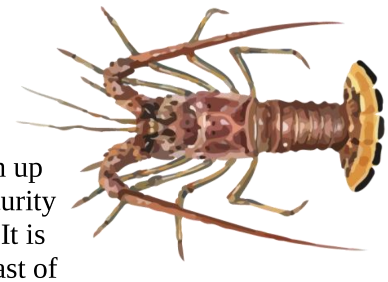


Figure 17. Species-specific projected total habitat suitability index (HSI) and HSI's change or 'anomaly' under different carbon dioxide emission levels for yellowtail snapper (Ocyurus chrysurus), including (A) total HSI for the 1970 to 2000 period; (B and C) changes in HSI under scenarios of ~400 ppm and ~535 ppm atmospheric carbon dioxide concentration in the high resolution Earth system model (GFDL CM2.6).

3.3.3 Species Case Study: Caribbean Spiny Lobster (*Panulirus argus*)



3.3.3.1 Biology

Spiny lobster is a crustacean that can grow to 45 cm in length and weigh up to seven kilos. Spiny lobster mature late (~2 years) – with age at maturity being site dependent - and typically live up to 12 years (Chávez, 2001). It is a species with a broad geographic range: from Bermuda and the east coast of the United States, to Rio de Janeiro in Brazil in the south, including the Wider Caribbean region and the Gulf of Mexico (Holthuis, 1991). This species can be found to a depth of 90 m and across a range of different habitats, including rocky reefs, coral reefs and seagrass beds. Spiny lobsters are omnivores eating other crustaceans, shellfish (including conch), sea urchins, worms and algae (Holthuis, 1991). Spiny lobsters support some of the region's most important fisheries, estimated to contribute USD456 million to fishers and support 200,000 livelihoods throughout the Wider Caribbean region (van Gerwen, 2013). Spiny lobsters are harvested using a range of gear types including traps, gill nets, by hand (divers), and aggregating devices (FAO, 2006). Stock assessments consider the species as fully or over-exploited over much of its range (Cochrane and Chakalall, 2001). Total reconstructed catches for all fishing entities operating throughout the Caribbean Sea region were estimated on average at just above 4,000 tonnes per year between 2000 and 2014 (*Sea Around Us*).

3.3.3.2 Modelling Projections

Caribbean spiny lobster is notable for a generally higher current baseline of habitat suitability index across most parts of the Caribbean and Gulf of Mexico (Figure 18). As a result, many of the future changes to habitat suitability for this species in either direction are relatively minor and generally limited to changes of less than 20%. In the shorter-term (roughly the 2030s), lobster are expected to experience increased habitat suitability along the north coast of South America, in the more southerly Lesser Antilles, in offshore continental shelf areas of Jamaica, and along the deeper edge of the continental shelf in the Gulf of Mexico. Toward the end of the century, many of these minor gains will be erased while habitat suitability continues to improve in the northern Gulf of Mexico. Notably, a few locations in the Caribbean Sea including some offshore areas south of Jamaica and some areas between Anguilla, St. Kitts and Nevis, and Antigua and Barbuda may continue to act as climate refuges for this species through the end of the century. Due to their greater resilience, effective fisheries management of spiny lobster now may help to preserve continued sustainable harvests under a future climate.

3.3.3.3 Empirical Evidence for Climate Impacts to Date

A. Direct Impacts of Temperature and Acidification

Studies in Western Australia have suggested that the low settlement levels of post-larvae of local spiny lobster (*Panulirus cygnus*) observed since 2006 are likely due to increasing temperatures, which are triggering animals to spawn earlier and may result in a mismatch between environmental conditions that are favourable to the post-larvae (de Lestang *et al*., 2015). Such patterns may well apply to Caribbean stocks as well. Increasing temperatures are also likely to reduce total size and size at maturity of animals (Caputi *et al*., 2013). Increasing storm activity and intensity, as well as changes in wind patterns could negatively affect the success of recruits in coastal habitats through direct impacts on the habitats themselves as well as a reduction in lobster's prey (Puga *et al*., 2013). A recent study using an ecological niche modelling approach found large projected losses in suitable habitat for coastal lobster species throughout the tropics and especially the Wider Caribbean region (Boavida-Portugal *et al*., 2018). Greater variability in stock dynamics as a result of climate-induced changes in the North Atlantic Oscillation are expected, particularly as spiny lobsters are characterized by long larval duration, therefore requiring closer monitoring of stocks and effective implementation of fisheries management controls.

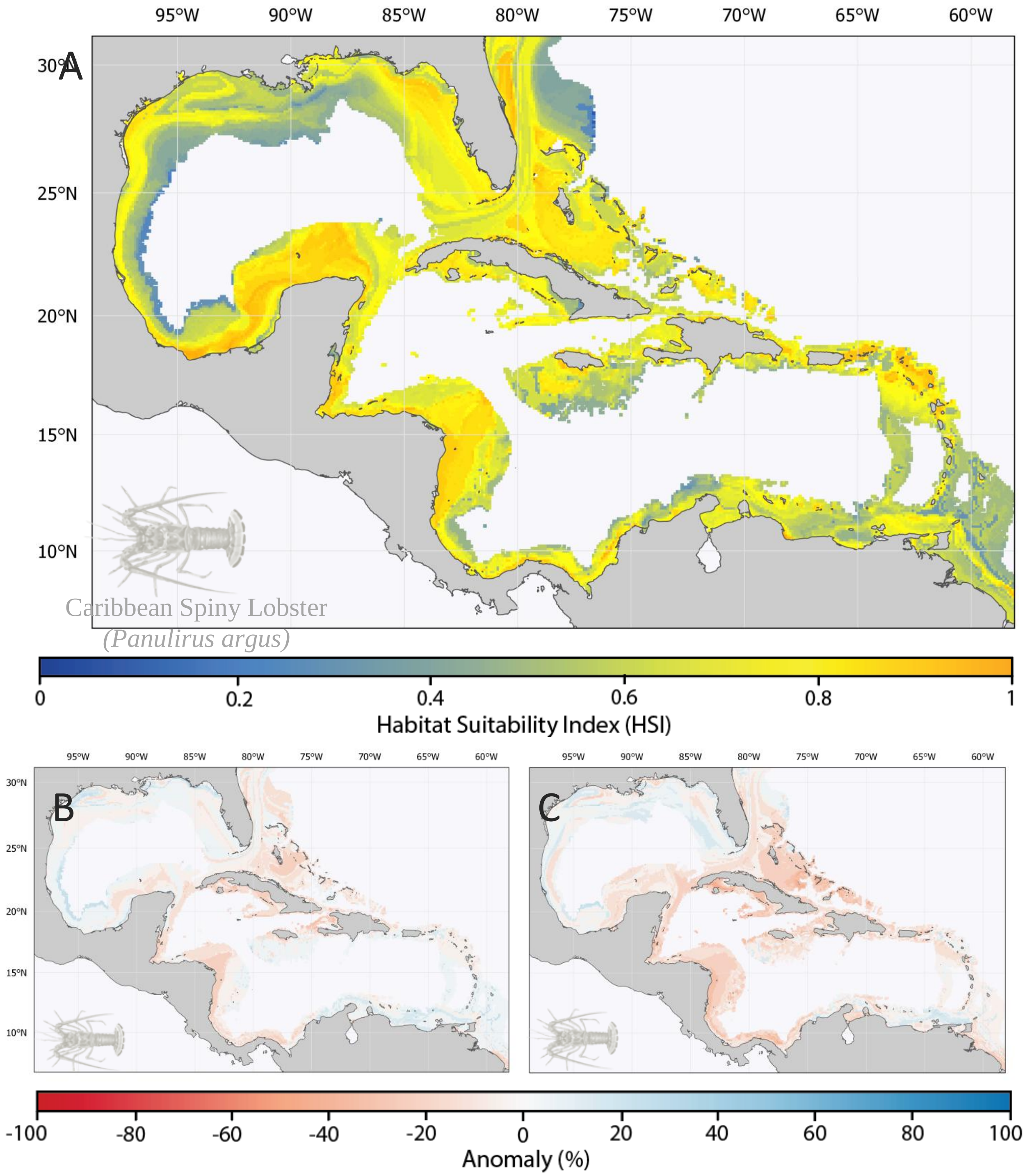


Figure 18. Species-specific projected total habitat suitability index (HSI) and HSI's change or 'anomaly' under different carbon dioxide emission levels for Caribbean Spiny Lobster (Panulirus argus), including (A) total HSI for the 1970 to 2000 period; (B and C) changes in HSI under scenarios of ~400 ppm and ~535 ppm atmospheric carbon dioxide concentration in the high resolution Earth system model (GFDL CM2.6).

B. Indirect Impacts from Effects on Food, Habitat, and Pathogens

Panulirus argus virus 1 (PaV1) – discovered in Florida in 1999 but since reported throughout much of the Caribbean – kills spiny lobsters by reducing the number of oxygen-carrying cells in the animals' blood, making them extremely lethargic and unable to eat or move. While prevalence throughout the region is unknown, the number of infection reports is increasing (Moss *et al*., 2013), with the virus found to have infected 60 percent or more of spiny lobsters in some areas of the Caribbean (Behringer *et al*., 2011). Laboratory studies suggest that increasing temperatures associated with climate change may increase the virulence (intensity) of the virus-caused infections, and associated mortality of juvenile animals (Behringer *et al*., 2009). In addition to increased disease pressure, existing human impacts such as coastal development, pollution, hydrological changes in coastal areas have led to the loss of, and continue to threaten the health of, mangroves, seagrass beds and coral reefs (Duarte *et al*., 2008). These habitats are important to spiny lobster particularly for recruitment (Butler *et al*., 2006). Projected increases in storm frequency and intensity, rising temperatures and sea level rise all threaten these habitats (Gardner *et al*., 2005; Ward and Smith, 2007; Fourquran and Rutten, 2004). Moreover, a general deterioration in ecosystem condition may lead to the increased susceptibility of spiny lobsters to diseases.

3.3.4 Species Case Study: Queen Conch (*Lobatus gigas*)

3.3.4.1 Biology

Queen conch (formerly known as *Strombus gigas)* is a shellfish distributed throughout the Wider Caribbean region that can grow to 30 cm in length and weigh up to three kilos. Queen conch is a herbivore feeding on seagrass, algae and particulate (very small) organic matter. Queen conch mature late (3.5-4 years) (Stoner and Sandt, 1992; de Jesus-Navarrete and Aldana-Aranda, 2000; Stoner *et al*., 2012) and can live up to 20 years or more (Prada *et al*., 2017). Conch move slowly, only breed in aggregations and may not reproduce if their densities fall below 50 adults per hectare (4,700 per km^2) (Stoner and Ray-Culp, 2000). Therefore, conch distribution and density is strongly influenced by fishing pressure (Glazer and Kidney, 2004), with populations showing low resilience to fishing mortality. Once depleted, they may not recover easily (Appeldoorn *et al*., 2011). Queen conch is one of the most important and highly valued fishery resources in the Caribbean with a long tradition throughout the region. The fishery is generally artisanal in nature operating primarily out of Jamaica (which also has an industrial fishery), Colombia, Cuba, Honduras, Nicaragua, Belize, Turks and Caicos, and The Bahamas (Appeldoorn *et al*., 2011; CRFM, 2012).Total reconstructed catches for all fishing entities operating throughout the Caribbean Sea region were estimated on average at 2,500 tonnes per year between 2000 and 2011, and close to 3,500 tonnes per year on average between 2011 and 2014 (*Sea Around Us*). A large proportion of catches is fished for export with only 5-15% of total landings being consumed locally in the region (CRFM, 2012).

Queen conch is listed under CITES Appendix II – meaning trade is allowed, but requires the delivery of permits and for exporting countries to demonstrate that the trade is not detrimental to the species' survival in the wild. In the context of the Review of Significant Trade in specimens of Appendix-II listed species, the CITES Standing Committee regularly recommends trade suspensions for countries that it has determined to have failed to implement Article IV of the Convention. Currently, Grenada and Haiti are subject to a recommendation to suspend trade of queen conch (CITES, 2019).

3.3.4.2 Modelling Projections

Despite modest baseline habitat suitability indices across the greater Caribbean, habitat suitability is expected to experience only small changes in either direction (less than 20%) across the region under a near-term atmospheric carbon scenario. Changes are expected to become more pronounced as atmospheric carbon concentration increases, with habitat suitability declining along the Caribbean coast of Central America, around the Florida Keys, and across the Bahamian Bank. Queen conch habitat suitability is also expected to decline across the Pedro Bank of Jamaica, but increase in areas around the bank, which may be associated with a shift of the resource into deeper demersal habitats that may make harvest more challenging.

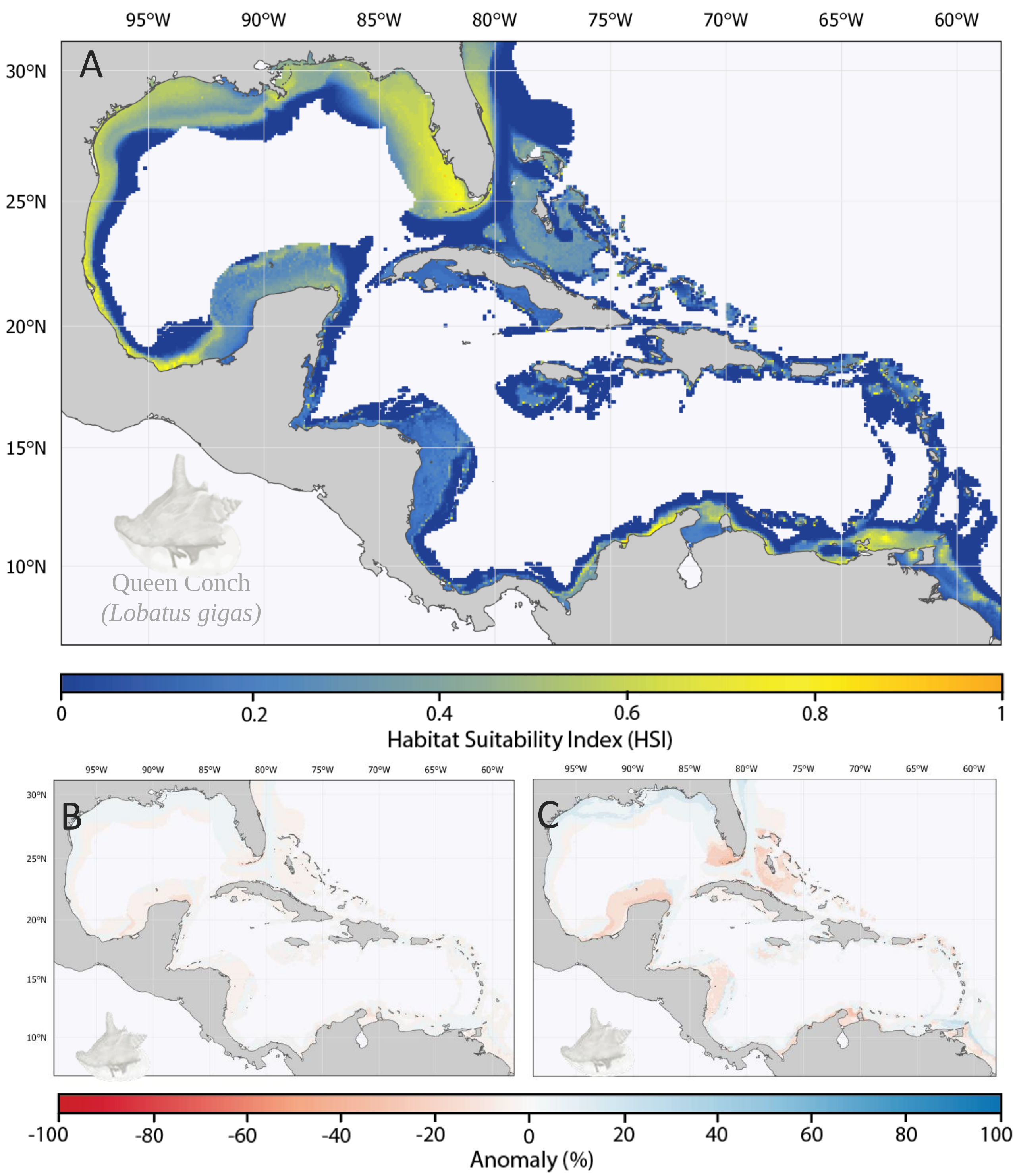


Figure 19. Species-specific projected total habitat suitability index (HSI) and HSI's change or 'anomaly' under different carbon dioxide emission levels for Queen Conch (Lobatus gigas), including (A) total HSI for the 1970 to 2000 period; (B and C) changes in HSI under scenarios of ~400 ppm and ~535 ppm atmospheric carbon dioxide concentration in the high resolution Earth system model (GFDL CM2.6).

3.3.4.3 Empirical Evidence for Climate Impacts to Date

A. Direct Impacts of Temperature and Acidification

Extended spawning seasons because of higher temperatures may buffer direct effects on conch populations through changes in habitat suitability. Indeed, as conch require a minimum temperature of 27.7°C to reproduce (with individuals being in resting stage below 27.5 °C), higher temperatures may lead to greater proportions of individuals spawning/being ripe all year round (rather than few individuals with a discrete spawning season). This however may depend on the degree to which reproductive strategy is genetically informed as well as food availability (Contreras Espinosa *et al*., 1994, cited in Aldana Aranda, 2014). Heat stress may also affect peak reproduction if conch are unable to acclimate to further temperature increases (Apeldoorn and Baker, 2013). Higher temperatures may also alter reproductive patterns across the region, with continuous annual low levels of reproduction dominating in the west and isolated, intense reproductive events in the east (Aldana Aranda, 2014). In combination with climate driven changes in ocean circulation this could affect ultimate settlement success, especially as more acid waters are also likely to reduce larval survival rates (Aldana Aranda, 2014; Aldana Aranda, 2016, cited by Oxenford and Monnereau, 2017). Finally, as conch are density-dependent with regards to mating and egg-laying, possible climate change reductions in number of individuals could have a profound effect on the reproductive strategies and reproductive success of conch populations (Stoner *et al*., 2012b). However, higher temperatures could also be expected to increase queen conch growth rates, reducing juvenile mortality, and leading to individuals reaching maturity faster, in turn increasing the reproductive output of any population (Appeldoorn and Baker, 2013).

Acidification has negative consequences on queen conch's shell formation because it consists of aragonite, which can dilute in acidic environments (Kamat *et al*., 2000; Aranda and Manzano, 2017). In more acidic waters, queen conch may expend more energy to produce their shells, at a cost to growth rate and reproduction or simply build less dense and thus weaker shells (Doney, 2006). In combination with high temperatures, acidification may lower survival rates of conch larvae (Aldana Aranda, 2016, cited in Oxenford and Monnereau, 2017). Overall however, to date, there is mixed evidence for clear acidification effects on animal fitness – with some studies, conducted on a range of species, indicating little to no impact, while others showed lowered ability to escape predators efficiently at high acidification levels (see summary provided in Oxenford and Monnereau, 2017).

B. Indirect Impacts from Effects on Food and Habitat

Projected changes in ocean currents under climate change (Liu *et al*., 2012) could also have more subtle impacts on conch populations through changes in the rate and condition of larval. Effects of these changes are not known; results could be either positive or negative to conch populations.

Increasing storm activity because of climate change can cause substantive disturbance to habitats important to the species (e.g., reefs, algal plains, seagrass beds), negatively affecting queen conch recruitment. As overfishing is currently one of the most major and immediate threats to the species (Appeldoorn *et al*., 2011), effectively regulating fishing activities and protecting critical habitat throughout the Caribbean are key tangible measures to support conservation of the species.

3.4 **Projected changes in fisheries catch potential**

Climate change is projected to result in a substantial decline in maximum fisheries catch potential throughout the Caribbean region (Figure 20). Overall, maximum fisheries catch potential across all exploited species was projected to decrease by 2030-2039 and 2050-2059 relative to 1970-2000 under RCP8.5. Although these projections were based on the coarse resolution Earth system models, the atmospheric CO_2 concentration in these two time frames under RCP8.5 closely correspond to the ~400 ppm and ~535 ppm projection outputs from the high resolution Earth system model. Regionally, the decline in maximum catch potential was projected to be highest throughout the southern part of the Caribbean Sea.

Even under RCP2.6 maximum catch potential is projected to decrease across the two time periods (Figure 20, B and D). Some observations require explanantion – for instance in D. Even with significant GHG mitigation efforts (RCP 2.6), climate change will continue to have substantial impacts on the oceans for the next 60 years, due to ongoing biogeochemical processes.

In all scenarios, the projected maximum catch potential is also a reflection of selected species, the combination of environmental preferences that make up their niche and how these will change in the future, as well as how the species throughout their life history respond to these changes.

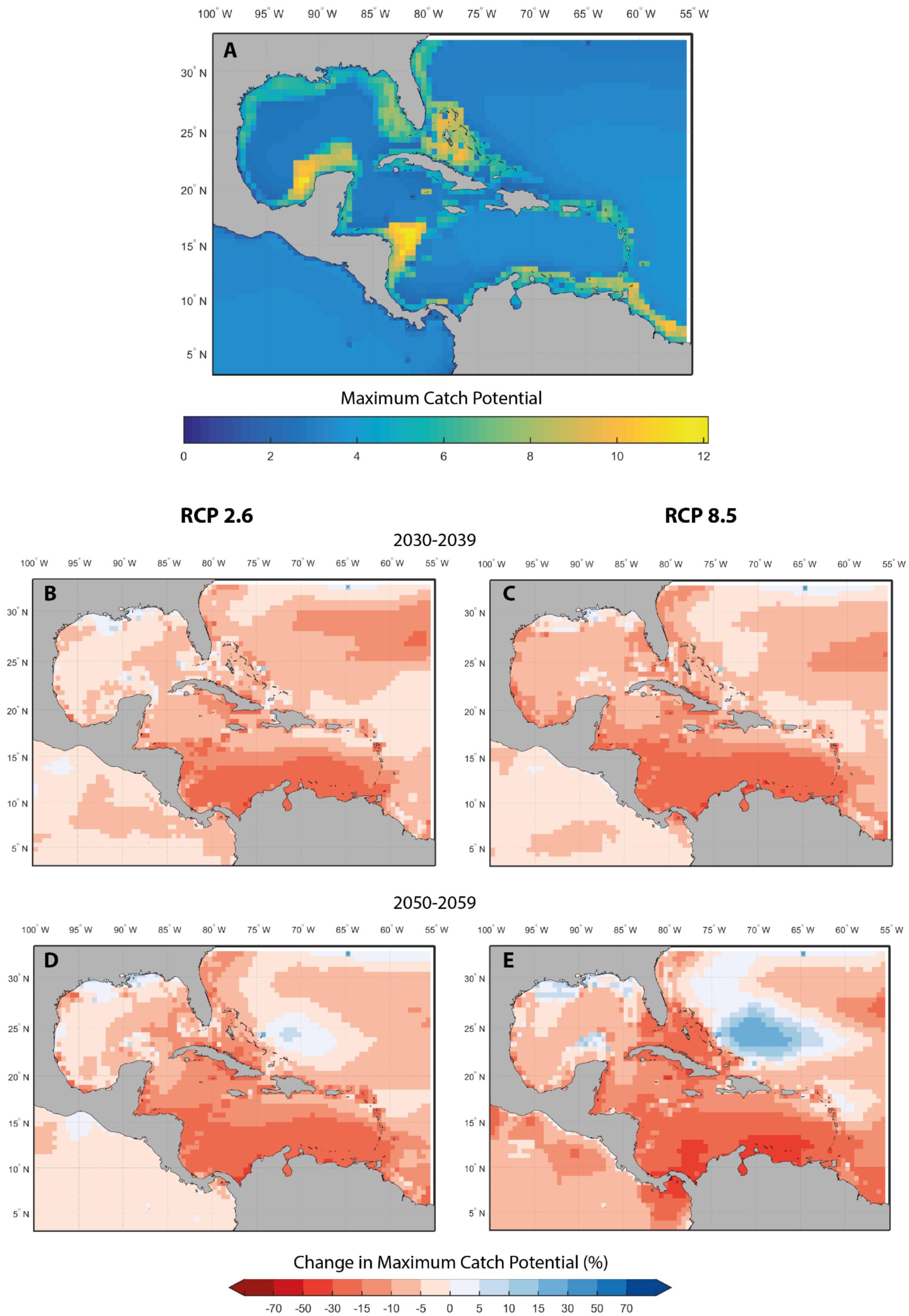


Figure 20. Projected maximum fisheries catch potential across all exploited species and the index' change into the 21st century based n outputs from three Earth system models (GFDL, IPSL, MPI). (A) Modelled average maximum catch potential in 1970-2000; (B and D) Projected changes in maximum catch potential by 2030-2039 and 2050-2059 under RCP2.6; (C and E) Projected changes in maximum catch potential by 2030-2039 and 2050-2059 under RCP8.5.

Based on the outputs from the coarser resolution Earth system models, projected changes in exploited species distribution and maximum catch potential declined across the exclusive economic zones of the six case study countries (Figure 21).

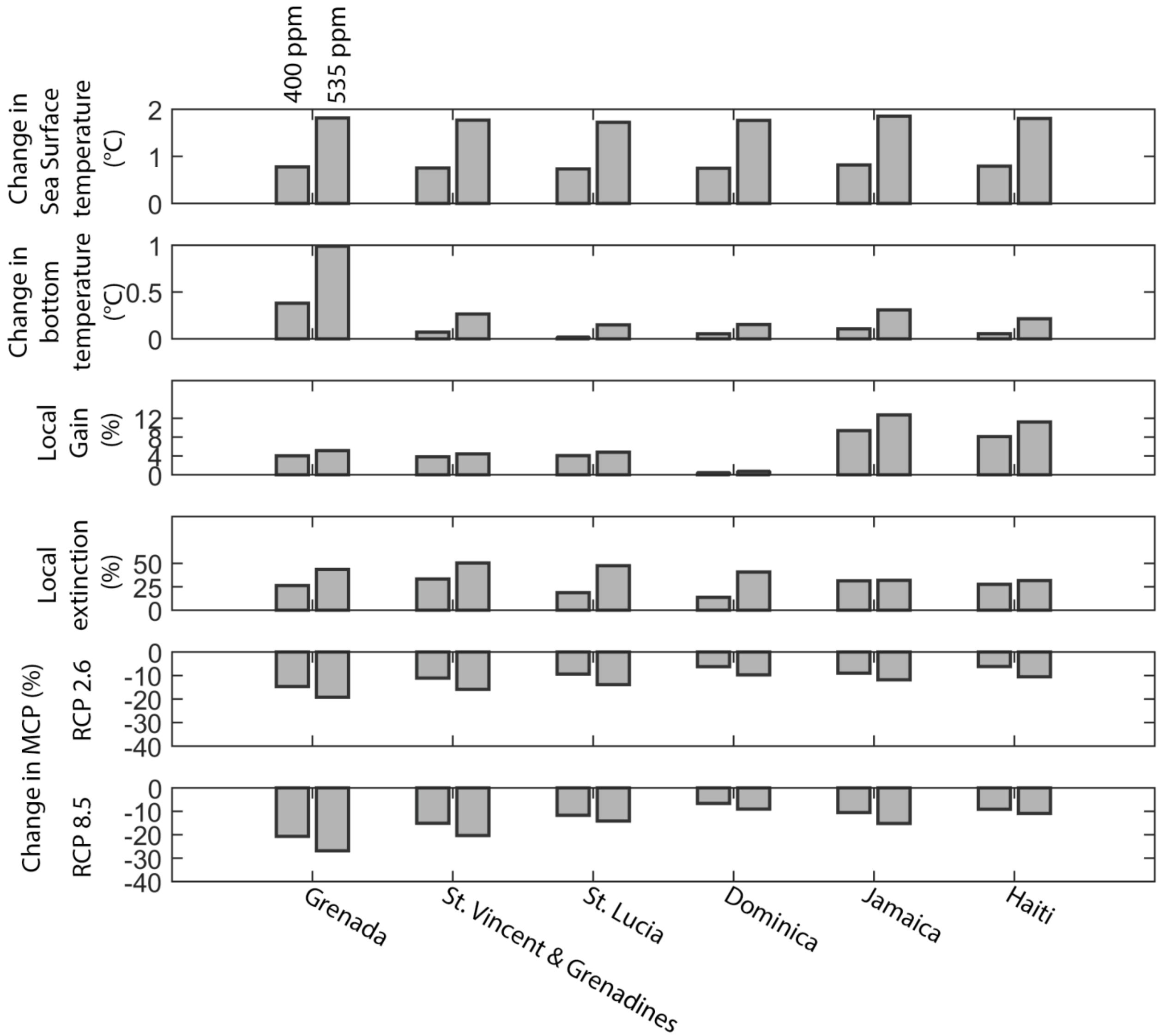


Figure 21. Projected changes sea surface temperature, bottom temperature according the higher resolution earth system model (CM2.6) and projected changes in species richness (as represented by local extinction and local gains) and marine catch potential (under RCP2.6 and RCP 8.5) in the exclusive economic zones of the six case study countries as projected by the coarser Eart system models (GFDL, IPSL, MPI). Projected changes in sea bottom temperature for Grenada differ markedly than for the other countries because of the island's close proximity to the shelf area off Venezuela.

4 DISCUSSION

4.1 Risk and impacts of climate change

This assessment highlights that the Caribbean Sea is amongst the most highly vulnerable and at risk region of the world's oceans under climate change (Cheung *et al*., 2018). Results presented in this study generally support the conclusions from previous global-scale assessments and studies such as the Fifth

Assessment of the Intergovernmental Panel on Climate Change (IPCC) (Gattuso *et al*., 2015; IPCC, 2014). Increasing greenhouse gas emissions are altering ocean conditions and are projected to increase the risk of impacts to marine species and ecosystem services as a result of warming, ocean deoxygenation, acidification and changes in ocean productivity. The herein provided multiple lines of evidence from different climate-ocean and living marine resource models suggest that the Caribbean Sea's marine biodiversity and fisheries are facing large challenges in the near future under climate change. Specifically, most exploited marine species will be at very high conservation risk because of climate change, with much of their current habitat becoming unsuitable to them. Thus, the Caribbean region will see a substantial decline in species richness. As a consequence, potential fisheries catches are also projected to suffer declines. All of these changes are projected to happen in the next few decades, particularly if carbon emissions continue unabated following the 'business-as-usual' scenario.

A large part of the high climate risk of marine species assemblages in the Caribbean Sea is a result of their biogeography. Species assemblages in the region are largely dominated by tropical and sub-tropical species with relatively narrow thermal tolerances compared to species adapted to live in temperate waters. Also, many of the species have strong associations to particular habitats during part or all of their life history stages. These characteristics render the species assemblages highly sensitive to climate change hazards. Such high biological sensitivity is reflected in the large changes in the habitat suitability index and projected species local extinction in the region. This finding is in line with previous global scale analyses that project large declines in species richness throughout the tropical seas (Jones and Cheung, 2015). However one novel aspect of the analysis presented in this study, is the use of a not previously available high resolution Earth system model that allowed us to reveal sub-regional patterns of risk and impacts. From this model's outputs, the southern part of the Caribbean Sea region emerges as amongst the most at risk and impacted under ocean conditions to be expected over the next few decades.

The projected decrease in maximum catch potential and changes in species assemblages will likely pose substantial challenges to the fishing communities in the region. Many of the highly vulnerable and at risk species to climate change are commonly targeted and highly valuable species such as groupers, snappers and parrotfishes. The loss of these species may have large impacts on coastal fisheries and dependent communities from both a food security as well as livelihood perspective. Some species that are tolerant to the warmer ocean will be less affected by climate change, with our analysis suggesting that these species are likely to be smaller reef and pelagic species that are currently afforded lower market values, but still provide reasonable nutrition. Planned linked social-economic analyses as a part of the overarching project that will use the outputs produced herein will further elucidate the impacts of our projected ecological changes on the complexity of fisheries dynamics in the Caribbean Sea.

Given the high sensitivity of marine species in the Caribbean Sea to CO_2 emissions, the lead time for marine biodiversity and dependent human communities to adapt to climate change impacts is expected to be short. The projected high level of risks and impacts in the Caribbean Sea are based on environmental conditions and atmospheric CO_2 concentrations that are expected in the next few decades, highlighting the urgency of impending climate challenges and acute need to develop and implement effective mitigating and adaptive measures. Other aspects of climate change-related impacts such as storms, sea level rise and other extreme events, in addition to other non-climatic stressors such as overfishing (see Final Report – Part B for analysis of the interactions between fishing and climate change), poor land management practices, and pollution are likely to further exacerbate the climate risks in the region, pose additional constraints to adaptation and further underline the need to urgently develop appropriate social-ecological response mechanisms (Pittman et al. 2015; Gattuso et al. 2018; Miller *et al.* 2018).

4.2 Key uncertainties and challenges

Assessing climate change impacts on biological systems in the future inevitably requires making a range of assumptions. The following are highlighted as key assumptions in our analysis. We also describe the potential implications of these assumptions for the findings and conclusions of this assessment.

<u>Biological adaptation</u>: our projection models did not account for the scope of evolutionary adaptation of marine species. If species can adapt genetically, they may be less sensitive to the projected changes in ocean conditions. However, the close relationship between biological responses of marine species such as range shifts and ocean temperature in paleo- and contemporary periods under a similar rate of warming suggest that evolutionary adaptation to climate change may be limited for marine species (Portner *et al*., 2014). Also, we have accounted for the potential scope for adaptation in the risk assessment, and we found that those species that were estimated to have highest risk may tend to be species that grow slowly, mature late and have long generation times. These biological traits do not favour rapid evolutionary responses to environmental changes.

<u>Trophic interactions</u>: our modelling approaches are species-based and do not consider trophic interactions explicitly. Shifts in species distribution and other biological responses such as changes in growth and food consumption will likely alter species interactions (Blanchard, 2015; Libralato *et al*., 2015). This may further exacerbate the risk of climate change on the ecological communities in addition to adding uncertainties to the future of marine ecosystems in the Caribbean Sea. Thus, our estimates of potential risk and impacts may be considered conservative.

<u>Others</u>: there are other potential sources of uncertainties in our assessment. Firstly, we may underestimate the ecological risk from the potential existence of ‘ecological tipping points’ that may result in rapid irreversible changes. Given the high level of projected climate hazards and the sensitivity of marine assemblages, the risk of such ecological tipping points cannot be ignored. Moreover, we did not consider the interactions between climatic and other non-climatic human stressors such as pollution, habitat destruction and overfishing (Graham *et al*. 2011; Zaneveld *et al*., 2016; Duran *et al*. 2018). Current knowledge suggests that these other human stressors are likely to add to or exacerbate climate impacts.

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7 APPENDICES

Appendix A.1 List of selected species for this assessment.

Species name	Common name	Category	Habitat
Abudefduf saxatilis	Sergeant major	Fish	Coastal
Acanthocybium solandri	Wahoo	Fish	Pelagic
Acanthurus bahianus	Ocean surgeon	Fish	Coastal
Acanthurus chirurgus	Doctorfish	Fish	Coastal
Acanthurus coeruleus	Blue tang	Fish	Coastal
Actinopyga agassizii	Five toothed sea cucumber	Invertebrate	Coastal
Apsilus dentatus	Black snapper	Fish	Coastal
Astichopus multifidus	Furry sea cucumber	Invertebrate	Coastal
Balistes vetula	Queen triggerfish	Fish	Coastal
Calamus calamus	Porgy	Fish	Coastal
Carangoides bartholomaei	Yellow jack	Fish	Coastal
Caranx crysos	Blue runner	Fish	Coastal
Caranx hippos	Crevalle jack	Fish	Coastal
Caranx latus	Horse eye jack	Fish	Coastal
Caranx lugubris	Black jack	Fish	Coastal
Caranx ruber	Bar jack	Fish	Coastal
Cephalopholis cruentata	Graysby	Fish	Coastal
Cephalopholis fulva	Coney	Fish	Coastal
Clepticus parrae	Creole wrasse	Fish	Coastal
Coryphaena hippurus	Common dolphinfish	Fish	Pelagic
Decapterus macarellus	Mackerel scad	Fish	Pelagic
Decapterus punctatus	Round scad	Fish	Coastal
Elagatis bipinnulata	Rainbow runner	Fish	Coastal
Epinephelus adscensionis	Rock hind	Fish	Coastal
Epinephelus guttatus	Red hind	Fish	Coastal
Epinephelus striatus	Nassau grouper	Fish	Coastal
Etelis oculatus	Queen snapper	Fish	Coastal
Hirundichthys affinis	Fourwing flyingfish	Fish	Pelagic
Haemulon album	White margate	Fish	Coastal
Haemulon aurolineatum	Tomtate	Fish	Coastal
Haemulon bonariense	Black grunt	Fish	Coastal
Haemulon carbonarium	Caesar grunt	Fish	Coastal
Haemulon chrysargyreum	Smallmouth grunt	Fish	Coastal
Haemulon flavolineatum	French grunt	Fish	Coastal
Haemulon macrostomum	Spanish grunt	Fish	Coastal
Haemulon melanurum	Cottonwick grunt	Fish	Coastal
Haemulon parra	Sailor's grunt	Fish	Coastal
Haemulon plumierii	White grunt	Fish	Coastal
Haemulon sciurus	Bluestriped grunt	Fish	Coastal
Haemulon striatum	Striped grunt	Fish	Coastal

Species name	Common name	Category	Habitat
Halichoeres radiatus	Puddingwife wrasse	Fish	Coastal
Hemiramphus balao	Balao halfbeak	Fish	Coastal
Hemiramphus brasiliensis	Ballyhoo halfbeak	Fish	Coastal
Hippocampus erectus	Lined seahorse	Fish	Coastal
Holocentrus adscensionis	Squirrelfish	Fish	Coastal
Holocentrus rufus	Longspine squirrelfish	Fish	Coastal
Holothuria (Halodeima) floridana	Florida sea cucumber	Invertebrate	Coastal
Holothuria (Halodeima) mexicana	Donkey dung sea cucumber	Invertebrate	Coastal
Hyporthodus flavolimbatus	Yellowedge grouper	Fish	Coastal
Isostichopus badionotus	Three rowed sea cucumber	Invertebrate	Coastal
Istiophorus albicans	Sailfish	Fish	Pelagic
Kajikia albida	White marlin	Fish	Pelagic
Katsuwonus pelamis	Skipjack tuna	Fish	Pelagic
Lachnolaimus maximus	Hogfish	Fish	Coastal
Lobatus gigas	Queen conch	Invertebrate	Coastal
Lutjanus analis	Mutton snapper	Fish	Coastal
Lutjanus apodus	Schoolmaster	Fish	Coastal
Lutjanus buccanella	Blackfin snapper	Fish	Coastal
Lutjanus cyanopterus	Cubera snapper	Fish	Coastal
Lutjanus griseus	Gray snapper	Fish	Coastal
Lutjanus jocu	Dog snapper	Fish	Coastal
Lutjanus mahogoni	Mahagony snapper	Fish	Coastal
Lutjanus purpureus	Southern red snapper	Fish	Coastal
Lutjanus synagris	Lane snapper	Fish	Coastal
Lutjanus vivanus	Silk snapper	Fish	Coastal
Makaira nigricans	Blue marlin	Fish	Pelagic
Megaptera novaeangliae	Humpback whale	Marine mammal	Pelagic
Mulloidichthys martinicus	Yellow goatfish	Fish	Coastal
Mycteroperca interstitialis	Yellowmouth grouper	Fish	Coastal
Mycteroperca tigris	Tiger grouper	Fish	Coastal
Mycteroperca venenosa	Yellowfin grouper	Fish	Coastal
Myripristis jacobus	Blackbar soldierfish	Fish	Coastal
Neoniphon marianus	Longjaw squirrelfish	Fish	Coastal
Ocyurus chrysurus	Yellowtail snapper	Fish	Coastal
Opisthonema oglinum	Atlantic thread herring	Fish	Coastal
Panulirus argus	Caribbean spiny lobster	Invertebrate	Coastal
Priacanthus arenatus	Atlantic bigeye	Fish	Coastal
Pristipomoides aquilonaris	Wenchman	Fish	Coastal
Pseudupeneus maculatus	Spotted goatfish	Fish	Coastal
Pterois volitans	Red lionfish	Fish	Coastal
Rhomboplites aurorubens	Vermillion snapper	Fish	Coastal
Sargassum fluitans	Sargassum	Algae	Pelagic
Sargassum natans	Sargassum	Algae	Pelagic

Species name	Common name	Category	Habitat
Sargocentron coruscum	Reef squirrelfish	Fish	Coastal
Sargocentron vexillarium	Dusky squirrelfish	Fish	Coastal
Scarus coelestinus	Midnight parrotfish	Fish	Coastal
Scarus coeruleus	Blue parrotfish	Fish	Coastal
Scarus iseri	Striped parrotfish	Fish	Coastal
Scarus taeniopterus	Princess parrotfish	Fish	Coastal
Scarus vetula	Queen parrotfish	Fish	Coastal
Scomberomorus cavalla	King mackerel	Fish	Coastal
Scomberomorus maculatus	Atlantic spanish mackerel	Fish	Pelagic
Scomberomorus regalis	Cero	Fish	Coastal
Selar crumenophthalmus	Bigeye scad	Fish	Coastal
Sparisoma aurofrenatum	Redband parrotfish	Fish	Coastal
Sparisoma chrysopterum	Redtail parrotfish	Fish	Coastal
Sparisoma rubripinne	Yellowtail parrotfish	Fish	Coastal
Sparisoma viride	Stoplight parrotfish	Fish	Coastal
Sphyraena barracuda	Great barracuda	Fish	Coastal
Sphyraena picudilla	Southern sennet	Fish	Coastal
Tetrapturus georgii	Roundscale spearfish	Fish	Pelagic
Tetrapturus pfluegeri	Longbill spearfish	Fish	Pelagic
Thalassoma bifasciatum	Bluehead wrasse	Fish	Coastal
Thunnus alalunga	Albacore tuna	Fish	Pelagic
Thunnus albacares	Yellowfin tuna	Fish	Pelagic
Thunnus atlanticus	Blackfin tuna	Fish	Pelagic
Thunnus obesus	Bigeye tuna	Fish	Pelagic
Thunnus thynnus	Atlantic bluefin tuna	Fish	Pelagic
Trachinotus falcatus	Permit	Fish	Coastal
Tursiops truncatus	Common bottlenose dolphin	Marine mammal	Pelagic

Appendix A.2. Method of fuzzy logic expert system to calculate the risk and vulnerability of fishes to climate change and fishing

We adapted published algorithms documented in Jones and Cheung (2017) and Cheung *et al*. (2005) to calculate indices of vulnerabilities and risk of impacts to climate change (including ocean acidification) and fishing (for Part B of the report), respectively, for exploited marine fishes. Vulnerability was determined by the intrinsic sensitivity and adaptive capacity of the species to the stressors (fishing and climate change) while risk of impact was a combination of the degree of exposure to hazards from the stressors and the species' vulnerability. Vulnerability and risk of impacts were expressed here as quantitative indices that scale from 1 to 100, with 100 being the most vulnerable or at risk to the stressor(s). Descriptions of the indices calculation are summarized in the following.

Calculating vulnerability and risk of impacts

We predicted a species' vulnerability using a fuzzy logic algorithm that was subdivided into three components (Cheung *et al.*, 2005):

(1) Fuzzification: Indicators of exposure to fishing and climate change and species' biological and ecological traits were categorized into one or more levels simultaneously, with the degree of membership to the levels being defined by fuzzy membership functions:

The definition of rules used to classify into different categories to calculate an overall index of exposure to climate hazard (*ExV*) and the levels of attributes used to define categories of sensitivity and adaptive capacity.

	Categories and their resulting linguistic level			
Exposure	Low	Moderate	High	Very High
Exposure value (*ExV*)	1 > *ExV*	0.5 < *ExV* < 2	1 < *ExV* < 3	2 < *ExV*
Sensitivity	Low	Moderate	High	Very High
Temperature tolerance (TT, °C)	7 > *TT*	3 < *TT* < 10	7 < *TT* < 14	10 < *TT*
Maximum body length (BL, cm)	40 > BS	20 < *BS* < 60	40 < *BS* < 80	60 < *BS* < 80
Maximum body length & high coral reef association			20 < *BS* < 60 and coral reef association >1	40 > BS and coral reef association >1
Taxonomic group (ocean acidification)	Fishes, crustaceans, sea cucumbers	Fishes, crustaceans, sea cucumbers	Crustaceans, molluscs, sea urchins	Molluscs, sea urchins
Adaptive Capacity	Low	Moderate	High	Very High
Latitudinal breadth (LB, degree)	19 > *LB*	10 < *LB* < 50	19 < *LB* < 70	70 < *LB*
Depth range (DR, m)	35 > *DR*	10 < *DR* < 200	35 < *DR* < 570	200 < *DR*
Fecundity (Fec, eggs or pups per year)	500 > *Fec*	500 < *Fec* < 10000	1000 < *Fec* < 100000	10000 < *Fec*
Habitat specificity (HS)	0.5 < *HS*	0.25 < *HS* < 0.75	0.1 < *HS* < 0.5	0.25 > *HS*

Attributes, levels and the fuzzy membership functions of different life history attributes and the Ocean Health Index (fisheries) for calculating the vulnerability and risk of impacts of marine species to fishing.

Attributes	Levels	Functions*	Values at limits	Values at full membership
Maximum body size	Small	Trapezoidal	< 50 cm	< 20 cm
	Medium	Triangular	20 – 75 cm	50 cm
	Large	Triangular	50 – 150 cm	100 cm
	Very large	Trapezoidal	> 100 cm	> 150 cm
von Bertalanffy growth parameter K	Low	Trapezoidal	< 0.2 $year^{-1}$	< 0.005 $year^{-1}$
	Medium	Triangular	0.005 – 0.5 $year^{-1}$	0.2 $year^{-1}$
	High	Triangular	0.2 – 0.8 $year^{-1}$	0.5 $year^{-1}$
	Very high	Trapezoidal	> 0.5 $year^{-1}$	> 0.8 $year^{-1}$
Natural mortality rate	Low	Trapezoidal	< 0.2 $year^{-1}$	< 0.005 $year^{-1}$
	Medium	Triangular	0.005 – 0.5 $year^{-1}$	0.2 $year^{-1}$
	High	Triangular	0.2 – 0.8 $year^{-1}$	0.5 $year^{-1}$
	Very high	Trapezoidal	> 0.5 $year^{-1}$	> 0.8 $year^{-1}$
Age at maturity	Small	Trapezoidal	< 3 years	< 1 year
	Medium	Triangular	1 – 5 years	3 years
	Large	Triangular	3 – 7 years	5 years
	Very large	Trapezoidal	> 5 years	> 7 years
Maximum age	Small	Trapezoidal	< 5 years	< 2 year
	Medium	Triangular	2 – 15 years	5 years
	Large	Triangular	5 – 35 years	15 years
	Very large	Trapezoidal	> 15 years	> 35 years
Geographic range	Small	Trapezoidal	<3168 km^2	< 1584 km^2
	Medium	Triangular	1584 – 5730 km^2	3168 km^2
	Large	Triangular	3168 – 14335 km^2	5730 km^2
	Very large	Trapezoidal	> 5730 km^2	> 14335 km^2
Spatial aggregation strength	Low	Trapezoidal	< 40	< 20
	Medium	Triangular	20 – 60	40
	High	Triangular	40 – 80	60
	Very high	Trapezoidal	> 60	> 80
Annual fecundity	Very low	Trapezoidal	< 20 egg ind^{-1}	< 10 egg ind^{-1}
	Low	Triangular	10 – 100 egg ind^{-1}	50 egg ind^{-1}
	Not low	Trapezoidal	> 50 egg ind^{-1}	> 100 egg ind^{-1}
Ocean Health Index (fisheries)	Low	Trapezoidal	< 0.25	< 0.05
	Medium	Triangular	0.05 – 0.5	0.25
	High	Triangular	0.25 – 0.75	0.5
	Very high	Trapezoidal	> 0.5	> 0.75

* These functions refer to the shape of the curves when mapping the fuzzy membership functions. See Figure 2 for a visualisation of these functions

For fishing hazard, we used the fisheries components of the Ocean Health Index (OHI-fisheries) to represent the fishing hazards to fishes' population viability (Halpern *et al.*, 2012). The OHI index is considered a measure of ocean health across countries and high seas regions worldwide and consists of multiple components organised into four dimensions: status, resilience, pressures and trend. OHI-fisheries represents the amount of catches that were sustainably harvested. It was calculated based on the population biomass of each reported fisheries stock relative to the biomass at the stock's maximum sustainable yield. For each exclusive economic zones (EEZs) and the high seas (sub-divided by ocean basin), the overall OHI-fisheries index was calculated from the geometric mean of the values for all stocks weighted by each stock's catch (Halpern *et al.*, 2012). The original OHI-fisheries index published in Halpern *et al*. (2012), and applied at a global scale, scales between 0 and 1, with 0 indicating that no fish stocks are at sustainable levels. The OHI index is available for a number of countries, but not all. Thus, in instances where country-specific data was available we used those values, otherwise we applied the average estimated OHI-fisheries index across 267 maritime countries (0.49) from the assessment conducted in 2016 as the status-quo scenario (Halpern *et al.*, 2017; see also http://ohi-science.org/ohi-global/). In addition, we evaluated two idealized future fishing scenarios: a sustainable scenario in which all considered regions have an OHI-fisheries index value that is doubled (with a maximum value of 1); and an over-fishing scenario in which all considered regions have an OHI-fisheries index that is halved. Fishing hazards were categorized into low, medium, high and very high based on the OHI-fisheries index and the fuzzy membership functions for each category (Table S1).

Climate hazards are indicated by the changes in annual average physical and biogeochemical ocean conditions by the mid- and end of the 21st century under two different scenarios (see Jones and Cheung, 2017 for details). Attributes representing climate hazards included sea water temperature, oxygen concentration and hydrogen ion concentration (sea surface and bottom for pelagic and demersal species, respectively). Outputs of projected changes in these variables were from three fully coupled Earth system models: the Geophysical Fluid Dynamic Laboratory ESM2G (GFDL-ESM2G), the Institute Pierre Simon Laplace CM5A-MR (IPSL-CM5A-MR) and the Max Planck Institute ESM-MR (MPI-ESM-MR). We regridded the Earth system model outputs onto a 0.5 ^{o} latitude x 0.5^{o} longitude grid of the world ocean. In each cell, we expressed the local climate hazard as changes in mean condition of each variable relative to annual variability of the historical period of the Earth system model simulations (standard deviation of annual values from 1951 – 2000) for two future periods: the mid-21st century (average of 2041 – 2060) and the end of the 21st century (average of 2081 – 2100). As we considered the actual temperature and the variability experienced by the species during the historical period as the baseline, climate variability was not needed in the model itself. We considered two greenhouse gas scenarios: the "business-as-usual" - Representative Concentration Pathway (RCP) 8.5 scenario and the "strong mitigation" – RCP2.6 scenario.

We determined exposure to climate or fishing hazards for each species based on its geographic range. We obtained current range boundary for each species as predicted using the Sea Around Us method (Jones *et al.*, 2012). The range boundary was defined based on latitudinal and depth ranges, as well as expert-delineated occurrence range boundaries such as those published in FAO species catalogues. The range boundary was then subsequently gridded on a 0.5° latitude x 0.5° longitude spatial resolution. The exposure to hazard of each species was based on the climate and fishing hazards level in the grid cells where the species was expected to occur.

Life history and biological characteristics that represented species' sensitivity and adaptive capacity included: maximum body size, von Bertalanffy growth parameter K, age at maturity, longevity, fecundity, an index of spatial aggregation behavior, temperature preferences, geographic range, latitudinal range, depth range, taxonomic group and association to specific habitats (see Cheung *et al*., 2005 and Jones and Cheung, 2017 for details). Data for these attributes were obtained from FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.org). Missing data was allowed in the fuzzy logic framework. However, since maximum body size is an important predictor of the vulnerability of marine fishes to fishing and climate change, we used it as a minimum requirement for the analysis.

(2) Fuzzy reasoning: The levels of fishing and climate change as well as species' biological and ecological traits were classified into levels of exposure to hazards, sensitivity and adaptive capacity. Consequently, these levels were combined to determine species' vulnerability and risk of impacts based

on pre-defined heuristic rules. We used published heuristic rules to determine the vulnerability of marine fishes to climate change (Jones and Cheung, 2017) and fishing (Cheung *et al*., 2005).

Actions defined by each rule were operated when a threshold value of membership was exceeded (threshold degree of membership = 0.2, as used by Jones and Cheung (2017) and Cheung *et al*. (2005)), thereby defining the minimum required membership of the premise that an expert would expect for a particular rule to be triggered. The algorithm accumulated the degree of membership associated with each level of conclusions from the rules using an algorithm called MYCIN (see Cheung *et al*., 2005), where:

$$AccMem_{(i+1)} = AccMem_{(i)} + Membership_{(i+1)} \times (1 - AccMem_{(i)}) \quad \text{eq. 1}$$

where *AccMem* is the accumulated membership of a particular conclusion (e.g., high vulnerability) and *i* denote one of the rules that has led to this conclusion. This algorithm facilitates the consideration of multiple lines of evidence (e.g., the vulnerabilities of the species and the exposure to climate hazards) to determine the final degree of membership of the conclusion. The joint climate-fishing risk of impacts was based on the Euclidean distance between the predicted climate change and fishing risks of impacts, e.g., if risk of impact from climate change is high and risk of impact from fishing is high, then the joint climate-fishing risk of impact is high (Table 1).

(3) Defuzzification: Vulnerability and risk of impacts were expressed on a scale from 1 to 100, 100 being the most vulnerable and at risk, respectively. Index values (*Indval*) correspond to each vulnerability category (*x*) were: Low = 1, Moderate = 25, High = 75 and Very high = 100. The final index (*FlnInd*) of risk of impacts or vulnerability was calculated as the average of the index values weighted by their accumulated membership (Cheung *et al.*, 2015):

$$FlnInd = \frac{\sum_{x=1}^{4} AccMem_x \cdot Indval_x}{\sum_{x=1}^{4} AccMem_x} \quad \text{eq. 2.}$$

A.3 Life history variables used in calculating the climate risk index with the fuzzy logic model and to derive species vulnerabilities to climate change. Life history information and ecological data for all species were collated from published databases including FishBase, SeaLifeBase and the Sea Around Us database. The list is sorted by decreasing order of calculated climate vulnerabilities of the species. NA - not available. The fuzzy logic algorithm could accommodate missing variables.

Scientific name	Lmax (cm)	Fecundity (eggs per year)	Latitudinal range (degree)	Depth range (m)	Habitat specificity	Vulnerabilities (100 = most vulnerable)
Lutjanus cyanopterus	131	NA	37	37	0.75	93
Lutjanus jocu	105	NA	51	38	1	90
Lutjanus analis	94	NA	64	70	0.75	90
Scarus coeruleus	120	NA	63	22	0.5	90
Mycteroperca tigris	101	NA	65	30	0.5	89
Lachnolaimus maximus	91	288097	80	27	0.5	88
Scarus coelestinus	77	NA	57	70	0.5	88
Mycteroperca interstitialis	84	NA	62	148	0.75	88
Lutjanus vivanus	83	NA	48	152	0.5	88
Caranx latus	92	NA	64	139	0.75	88
Caranx lugubris	100	NA	60	342	0.75	88
Lutjanus griseus	89	NA	49	175	0.75	88
Mycteroperca venenosa	100	NA	65	135	0.5	87
Lutjanus buccanella	75	NA	45	180	0.5	87
Scarus vetula	61	NA	41	22	0.5	87
Etelis oculatus	100	NA	49	350	0.5	86
Apsilus dentatus	65	NA	20	200	0.5	82
Epinephelus guttatus	76	549086	30	98	0.5	81
Ocyurus chrysurus	86	NA	47	179	1	80
Lutjanus purpureus	100	NA	43	314	NA	80
Caranx ruber	65	NA	52	34	0.75	78
Epinephelus striatus	122	NA	69	89	0.25	77
Hyporthodus flavolimbatus	115	NA	70	211	NA	75
Thunnus atlanticus	120	NA	66	950	0.25	75
Rhomboplites aurorubens	60	NA	61	260	0.5	74
Carangoides bartholomaei	100	NA	67	50	0.5	74
Lutjanus mahogoni	48	NA	45	100	0.5	73
Lutjanus synagris	60	NA	65	390	0.75	73

Scientific name	Lmax (cm)	Fecundity (eggs per year)	Latitudinal range (degree)	Depth range (m)	Habitat specificity	Vulnerabilities (100 = most vulnerable)
Elagatis bipinnulata	180	NA	73	149	0.75	72
Sparisoma viride	51	NA	40	47	0.75	71
Isostichopus badionotus	50	NA	40	65	0.5	69
Acanthocybium solandri	250	NA	83	11	NA	68
Lutjanus apodus	55	NA	44	61	0.5	67
Sphyraena picudilla	58	NA	70	64	0.75	66
Halichoeres radiatus	51	NA	56	52	0.5	66
Sargocentron coruscum	15	NA	25	29	0.5	66
Haemulon macrostomum	43	NA	66	20	0.5	65
Sparisoma rubripinne	39	NA	30	14	0.75	64
Haemulon bonariense	43	NA	42	170	0.5	64
Actinopyga agassizii	35	NA	40	54	0.5	64
Hirundichthys affinis	30	NA	0	20	NA	64
Panulirus argus	45	NA	60	89	0.5	64
Tetrapturus pfluegeri	282	NA	75	199	NA	63
Trachinotus falcatus	122	NA	67	36	0.5	63
Haemulon carbonarium	36	NA	67	22	0.5	63
Lobatus gigas	35	NA	42	71	0.75	61
Tetrapturus georgii	184	NA	0	200	NA	61
Scarus taeniopterus	35	NA	67	23	0.5	61
Holothuria (Halodeima) floridana	20	NA	40	2	0.5	61
Haemulon parra	41.2	NA	61	27	0.5	61
Coryphaena hippurus	210	299684	85	84	0.1	61
Caranx hippos	124	NA	78	349	0.75	60
Haemulon album	65	1326650	66	40	0.5	60
Holothuria (Halodeima) mexicana	25	NA	40	20	0.5	60
Balistes vetula	60	NA	78	273	0.5	59
Scomberomorus maculatus	101	459674	26	25	NA	59
Acanthurus chirurgus	39	NA	90	23	0.5	59
Haemulon melanurum	33	NA	45	47	0.5	59
Cephalopholis fulva	41	136967	65	149	0.75	58
Selar crumenophthalmus	73	NA	71	169	0.25	58

Scientific name	Lmax (cm)	Fecundity (eggs per year)	Latitudinal range (degree)	Depth range (m)	Habitat specificity	Vulnerabilities (100 = most vulnerable)
Scomberomorus regalis	183	597863	41	19	0.75	57
Holocentrus adscensionis	50	NA	55	179	1	57
Kajikia albida	300	NA	90	149	NA	56
Sparisoma chrysopterum	42	NA	40	14	0.75	56
Scarus iseri	11.7	NA	59	22	0.5	55
Haemulon chrysargyreum	23	NA	66	25	0.5	55
Scomberomorus cavalla	184	919510	70	135	0.75	55
Astichopus multifidus	25	NA	40	50	0.5	54
Sargocentron vexillarium	18	NA	80	20	0.5	54
Epinephelus adscensionis	50	NA	64	119	0.75	54
Thalassoma bifasciatum	25	NA	41	40	0.5	53
Calamus calamus	48	NA	70	74	0.75	53
Opisthonema oglinum	38	NA	76	16	0.5	52
Makaira nigricans	500	NA	85	NA	NA	50
Sphyraena barracuda	200	NA	80	99	0.25	49
Caranx crysos	70	251766	58	99	NA	46
Clepticus parrae	25	NA	27	39	0.75	46
Acanthurus bahianus	38	NA	76	38	0.75	46
Pterois volitans	38	NA	83	53	0.75	46
Hemiramphus brasiliensis	55	NA	56	NA	NA	45
Thunnus obesus	250	4274342	95	249	NA	44
Haemulon plumierii	43	141308	62	37	0.75	43
Holocentrus rufus	29	NA	38	31	0.75	42
Thunnus albacares	265	2462113	97	249	0.25	39
Istiophorus albicans	315	NA	90	199	NA	39
Katsuwonus pelamis	120	400000	120	259	NA	39
Thunnus alalunga	155	2449490	105	NA	0.25	39
Pristipomoides aquilonaris	56	NA	56	346	0.5	38
Thunnus thynnus	458	NA	94	984	0.25	38
Myripristis jacobus	20	NA	60	99	1	36
Haemulon	25	NA	67	59	0.75	36

Scientific name	Lmax (cm)	Fecundity (eggs per year)	Latitudinal range (degree)	Depth range (m)	Habitat specificity	Vulnerabilities (100 = most vulnerable)
flavolineatum						
Priacanthus arenatus	50	NA	84	190	0.5	36
Decapterus punctatus	30	NA	69	99	0.75	35
Sparisoma aurofrenatum	23	NA	65	18	0.75	35
Haemulon sciurus	36	108397	39	29	0.5	34
Cephalopholis cruentata	42.6	NA	42	170	0.5	34
Acanthurus coeruleus	39	NA	57	38	0.5	31
Haemulon aurolineatum	20	48466	76	29	0.75	31
Hippocampus erectus	51.4	NA	82	72	0.5	30
Neoniphon marianus	16	NA	17	69	0.5	29
Mulloidichthys martinicus	34	NA	65	48	0.5	29
Haemulon striatum	28	NA	68	90	0.5	28
Hemiramphus balao	40	NA	55	4495	0.5	27
Abudefduf saxatilis	22.9	NA	78	20	0.5	27
Decapterus macarellus	46	NA	80	399	NA	24
Pseudupeneus maculatus	25	NA	63	89	0.5	19

A.4. Estimated temperature preference (in °C) (mean), variability (standard deviation) for selected fishes, invertebrates. The temperature preference profile (TPP) of each species overlays estimated species distributions with annual seawater temperature and calculates the area-corrected distribution of relative abundance across temperature for each year from 1971 to 2000, subsequently averaging annual temperature preference profiles (TPP). The estimated TPP was used in the DBEM to predict the thermal physiological performance of a species (aerobic scope) in each area.

Scientific name	Mean (°C)	SD (°C)
Abudefduf saxatilis	13.1	9.1
Acanthocybium solandri	24.5	1.4
Acanthurus bahianus	25.6	1.4
Acanthurus chirurgus	14.1	9.5
Acanthurus coeruleus	14.2	9.5
Actinopyga agassizii	23.2	5.5
Apsilus dentatus	20.8	6.5
Astichopus multifidus	13.2	9.2
Balistes vetula	19.5	7.7

Scientific name	**Mean (ºC)**	**SD (ºC)**
Calamus calamus	25.1	1.8
Carangoides bartholomaei	16.1	7.6
Caranx crysos	21.8	2.7
Caranx hippos	22.1	2.5
Caranx latus	24.5	2
Caranx lugubris	24.4	2
Caranx ruber	25.2	1.7
Cephalopholis cruentata	21.2	6.9
Cephalopholis fulva	25.5	1.5
Clepticus parrae	25.1	1.7
Coryphaena hippurus	24.2	1.4
Decapterus macarellus	24.4	2.1
Decapterus punctatus	18	4.3
Elagatis bipinnulata	24.8	2.7
Epinephelus adscensionis	24.4	2.4
Epinephelus guttatus	25.3	1.8
Epinephelus striatus	25.2	1.6
Etelis oculatus	16.5	6.2
Haemulon album	24.6	1.4
Haemulon aurolineatum	22.1	3.2
Haemulon bonariense	22.5	5.6
Haemulon carbonarium	21.9	6.6
Haemulon chrysargyreum	22.2	5.8
Haemulon flavolineatum	25.7	1.1
Haemulon macrostomum	22.1	5.5
Haemulon melanurum	20.1	6
Haemulon parra	21.9	6.4
Haemulon plumierii	24.4	2.8
Haemulon sciurus	25.5	1.4
Haemulon striatum	20.4	5
Halichoeres radiatus	12.2	9.3
Hemiramphus balao	11.8	6.7
Hemiramphus brasiliensis	23.5	2.5
Hippocampus erectus	18.8	4.4
Hirundichthys affinis	24.5	1.9
Holocentrus adscensionis	24.6	2.3
Holocentrus rufus	25.2	1.6
Holothuria (Halodeima) floridana	23.5	4.4

Scientific name	**Mean (ºC)**	**SD (ºC)**
Holothuria (Halodeima) mexicana	24.3	4.5
Hyporthodus flavolimbatus	18.6	5.3
Isostichopus badionotus	13.1	9.1
Istiophorus albicans	24.1	1.1
Kajikia albida	24.5	1.5
Katsuwonus pelamis	24.8	1.5
Lachnolaimus maximus	25	1.8
Lobatus gigas	22.1	3
Lutjanus analis	24.8	2.1
Lutjanus apodus	25.7	1.2
Lutjanus buccanella	17.8	7.3
Lutjanus cyanopterus	24.8	1.8
Lutjanus griseus	23.7	2.3
Lutjanus jocu	25.4	1.6
Lutjanus mahogoni	21.8	6.7
Lutjanus purpureus	22.1	3.9
Lutjanus synagris	24	2.4
Lutjanus vivanus	20.5	4.8
Makaira nigricans	24.9	1.5
Megaptera novaeangliae	25.2	1.6
Mulloidichthys martinicus	24.5	1.6
Mycteroperca interstitialis	23.9	2.1
Mycteroperca tigris	25.6	1.6
Mycteroperca venenosa	24.7	2.1
Myripristis jacobus	25	2
Neoniphon marianus	25.1	1.5
Ocyurus chrysurus	25.3	1.6
Opisthonema oglinum	21.7	2.8
Panulirus argus	13.3	9.2
Priacanthus arenatus	19.3	5.1
Pristipomoides aquilonaris	18.5	4.9
Pseudupeneus maculatus	24.6	2.4
Pterois volitans	24.5	2.1
Rhomboplites aurorubens	18.3	4.2
Sargocentron coruscum	21.6	6.3
Sargocentron vexillarium	20.6	7.5
Scarus coelestinus	10.9	9.1
Scarus coeruleus	10.9	9

Scientific name	**Mean (ºC)**	**SD (ºC)**
Scarus iseri	13.1	9.8
Scarus taeniopterus	12.9	9.6
Scarus vetula	13.2	9.7
Scomberomorus cavalla	24.3	2.2
Scomberomorus maculatus	22.6	2.3
Scomberomorus regalis	25.3	1.3
Selar crumenophthalmus	23.8	2.9
Sparisoma aurofrenatum	25.6	1.1
Sparisoma chrysopterum	25.7	0.9
Sparisoma rubripinne	25.5	1.5
Sparisoma viride	25.6	1
Sphyraena barracuda	25	2
Sphyraena picudilla	24.1	2
Tetrapturus georgii	24.5	1.4
Tetrapturus pfluegeri	24.5	1.5
Thalassoma bifasciatum	13.3	9.4
Thunnus alalunga	24.2	1.2
Thunnus albacares	24.5	1.4
Thunnus atlanticus	24.5	1.3
Thunnus obesus	24.6	1.3
Thunnus thynnus	24.2	1.2
Trachinotus falcatus	20.2	5.6
Tursiops truncatus	24.7	2.2

A.5. Calculated climate risk index of the 106 species of exploited fishes and invertebrates in the Caribbean region under RCP2.6 and RCP8.5 by 2050. In this risk assessment framework, climate risk consists of three components: exposure to climate hazards, sensitivity to climate hazards, and species capacity to adapt to climate changes. Details of how the climate risk index was evaluated is provided in Appendix A.2

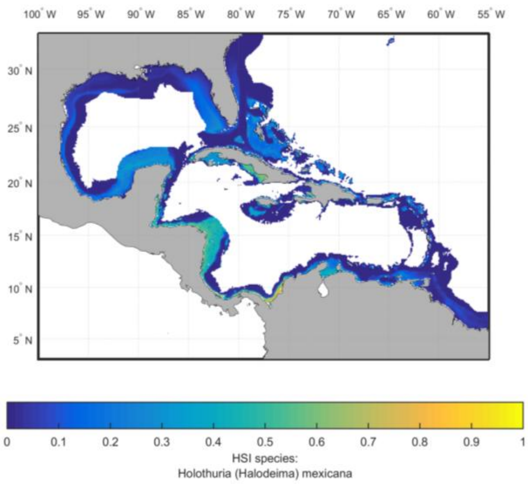
Scientific name	**RCP2.6**	**RCP8.5**
Istiophorus albicans	*98*	*100*
Scomberomorus maculatus	*98*	*100*
Epinephelus striatus	*98*	*100*
Mycteroperca tigris	*98*	*100*
Mycteroperca venenosa	*98*	*100*
Hemiramphus brasiliensis	*97*	*100*
Sphyraena barracuda	*97*	*100*
Cephalopholis fulva	*97*	*100*
Caranx ruber	*97*	*100*
Haemulon album	*97*	*100*
Lutjanus analis	*97*	*100*
Haemulon sciurus	*97*	*100*
Lutjanus apodus	*97*	*100*
Haemulon plumierii	*97*	*100*
Thunnus alalunga	*96*	*100*
Scomberomorus regalis	*96*	*100*
Coryphaena hippurus	*96*	*100*
Ocyurus chrysurus	*96*	*100*
Epinephelus guttatus	*96*	*100*
Lutjanus cyanopterus	*96*	*100*
Lutjanus jocu	*96*	*100*
Lutjanus griseus	*96*	*100*
Caranx lugubris	*96*	*100*
Haemulon flavolineatum	*96*	*100*
Acanthurus bahianus	*96*	*100*
Pterois volitans	*96*	*100*
Thunnus thynnus	*95*	*100*
Thunnus albacares	*95*	*100*
Katsuwonus pelamis	*95*	*100*
Thunnus obesus	*95*	*100*

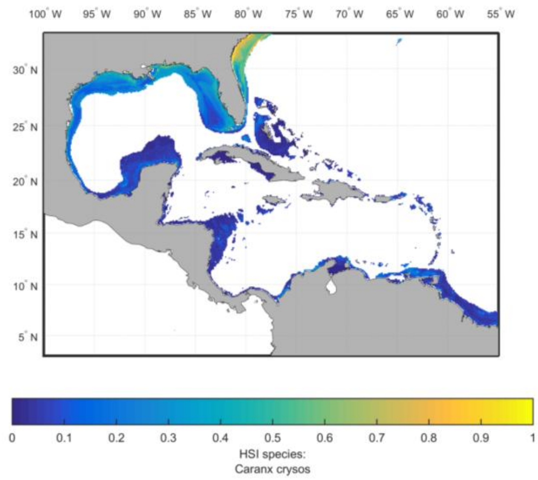
Scientific name	**RCP2.6**	**RCP8.5**
Makaira nigricans	*95*	*100*
Scomberomorus cavalla	*95*	*100*
Tetrapturus pfluegeri	*95*	*100*
Acanthocybium solandri	*95*	*100*
Elagatis bipinnulata	*95*	*100*
Thunnus atlanticus	*95*	*100*
Epinephelus adscensionis	*95*	*100*
Caranx latus	*95*	*100*
Clepticus parrae	*95*	*100*
Calamus calamus	*95*	*100*
Lachnolaimus maximus	*95*	*100*
Sparisoma chrysopterum	*95*	*100*
Sparisoma rubripinne	*95*	*100*
Sparisoma viride	*95*	*100*
Sparisoma aurofrenatum	*95*	*100*
Decapterus macarellus	*95*	*100*
Kajikia albida	*95*	*100*
Holocentrus rufus	*95*	*100*
Mycteroperca interstitialis	*95*	*100*
Caranx crysos	*94*	*100*
Caranx hippos	*94*	*100*
Lutjanus synagris	*94*	*100*
Hirundichthys affinis	*94*	*100*
Pseudupeneus maculatus	*94*	*100*
Haemulon aurolineatum	*94*	*100*
Tetrapturus georgii	*94*	*100*
Holocentrus adscensionis	*94*	*100*
Neoniphon marianus	*94*	*100*
Opisthonema oglinum	*93*	*100*
Selar crumenophthalmus	*93*	*100*
Myripristis jacobus	*93*	*100*
Sphyraena picudilla	*92*	*100*
Mulloidichthys martinicus	*92*	*100*
Lobatus gigas	*78*	*85*
Holothuria (Halodeima) floridana	*77*	*81*

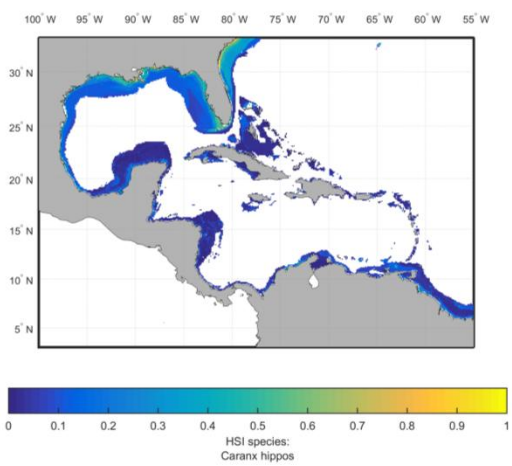
Scientific name	**RCP2.6**	**RCP8.5**
Apsilus dentatus	*76*	*82*
Trachinotus falcatus	*71*	*79*
Lutjanus mahogoni	*71*	*77*
Holothuria (Halodeima) mexicana	*71*	*76*
Sargocentron vexillarium	*71*	*78*
Haemulon macrostomum	*70*	*76*
Haemulon parra	*70*	*77*
Sargocentron coruscum	*70*	*80*
Haemulon chrysargyreum	*69*	*75*
Balistes vetula	*69*	*76*
Cephalopholis cruentata	*69*	*75*
Etelis oculatus	*69*	*75*
Carangoides bartholomaei	*69*	*76*
Haemulon carbonarium	*68*	*73*
Actinopyga agassizii	*68*	*69*
Panulirus argus	*67*	*73*
Scarus coelestinus	*67*	*73*
Scarus coeruleus	*67*	*73*
Hippocampus erectus	*67*	*71*
Halichoeres radiatus	*67*	*73*
Scarus vetula	*67*	*73*
Acanthurus chirurgus	*67*	*73*
Scarus taeniopterus	*67*	*73*
Abudefduf saxatilis	*67*	*73*
Thalassoma bifasciatum	*67*	*73*
Scarus iseri	*67*	*73*
Acanthurus coeruleus	*67*	*73*
Astichopus multifidus	*67*	*73*
Isostichopus badionotus	*67*	*73*
Lutjanus buccanella	*65*	*75*
Haemulon striatum	*61*	*68*
Hemiramphus balao	*61*	*65*
Pristipomoides aquilonaris	*60*	*65*
Priacanthus arenatus	*60*	*67*
Haemulon melanurum	*60*	*67*

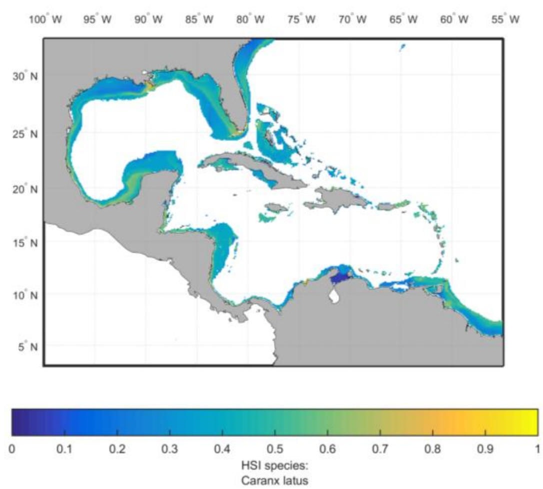
Scientific name	**RCP2.6**	**RCP8.5**
Lutjanus purpureus	*59*	*64*
Decapterus punctatus	*58*	*65*
Lutjanus vivanus	*58*	*63*
Haemulon bonariense	*55*	*59*
Rhomboplites aurorubens	*54*	*62*
Hyporthodus flavolimbatus	*53*	*58*

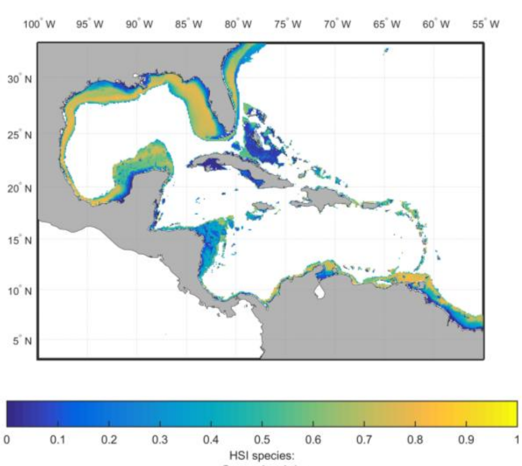
A.6. Projected habitat suitability index (HSI) of the 110 selected species in the Caribbean Sea region based on current ocean conditions (1970 to 2000 period). High resolution of all the maps are available through the data-portal created for this project.

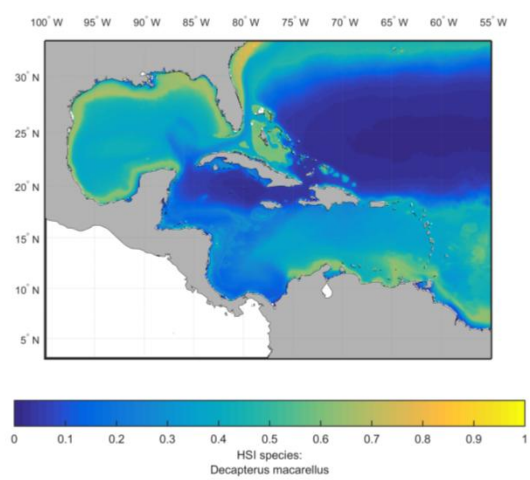


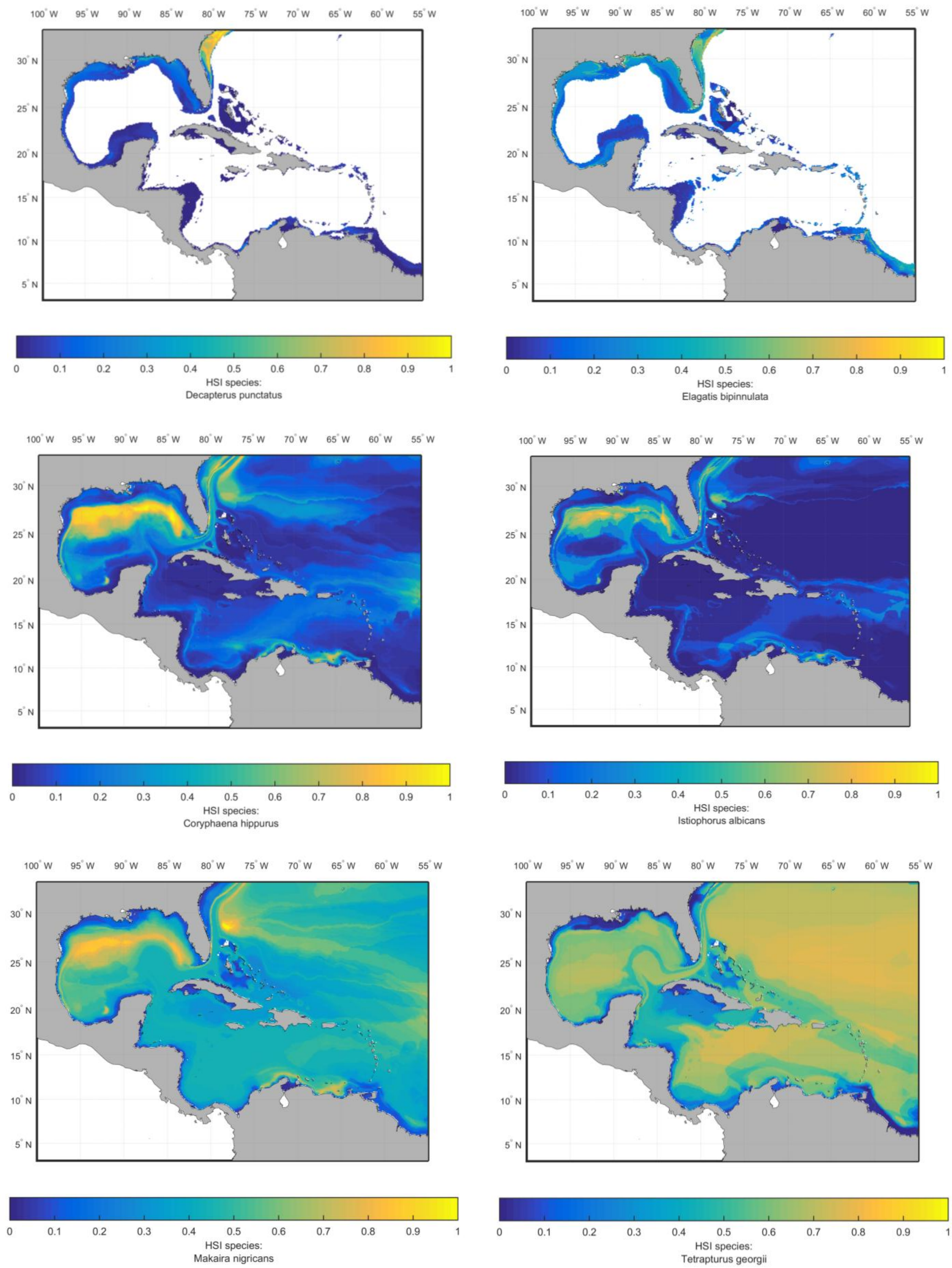








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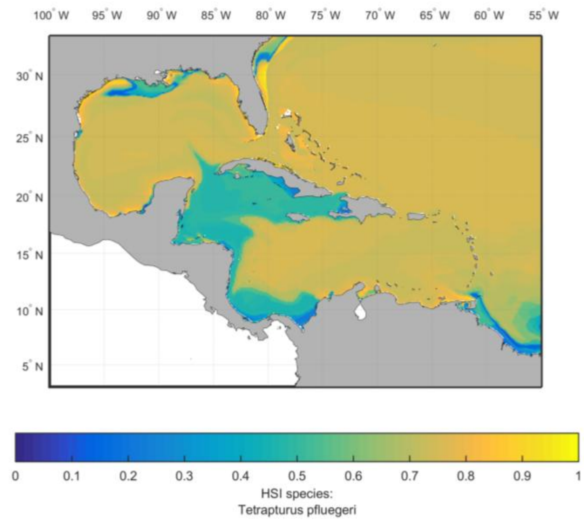
95° W
90° W
85° W
80° W
75° W
70° W
65° W
60° W
55° W
30° N
25° N
20° N
15° N
10° N
5° N
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
HSI species:
Decapterus punctatus
HSI species:
Elagatis bipinnulata
HSI species:
Coryphaena hippurus
HSI species:
Istiophorus albicans
HSI species:
Makaira nigricans
HSI species:
Tetrapturus georgii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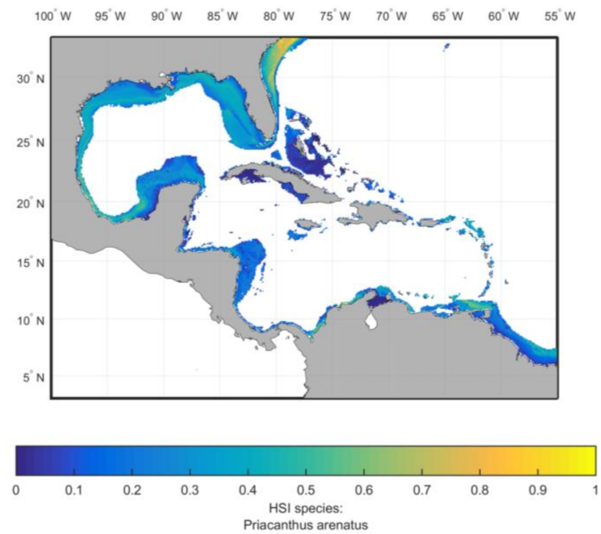
HSI species:
Tetrapturus pfluegeri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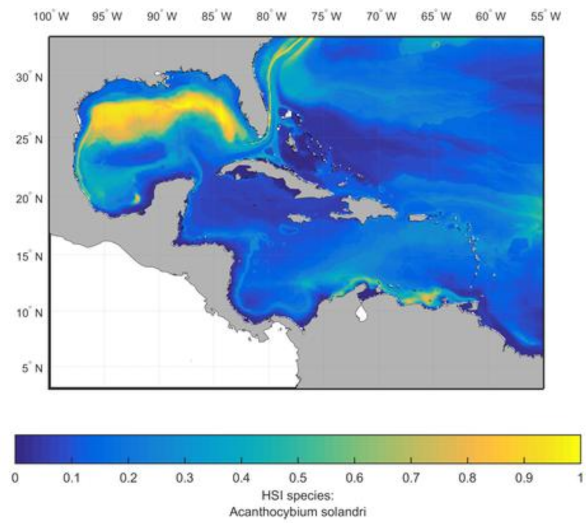
HSI species:
Priacanthus arenatus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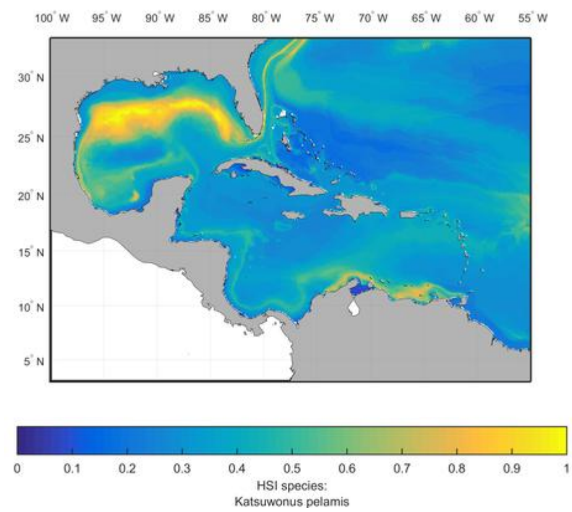
HSI species:
Acanthocybium solandri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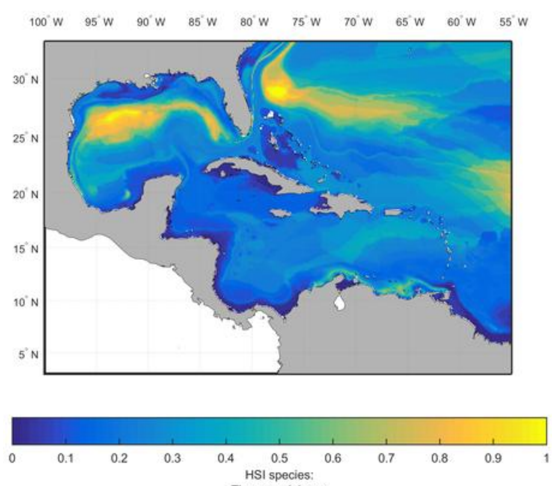
HSI species:
Katsuwonus pelamis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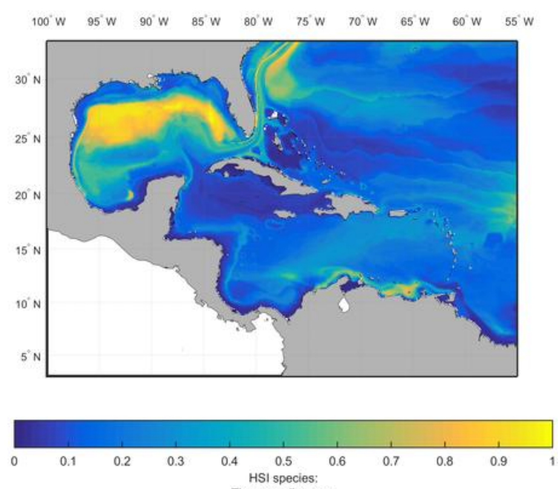
HSI species:
Thunnus alalunga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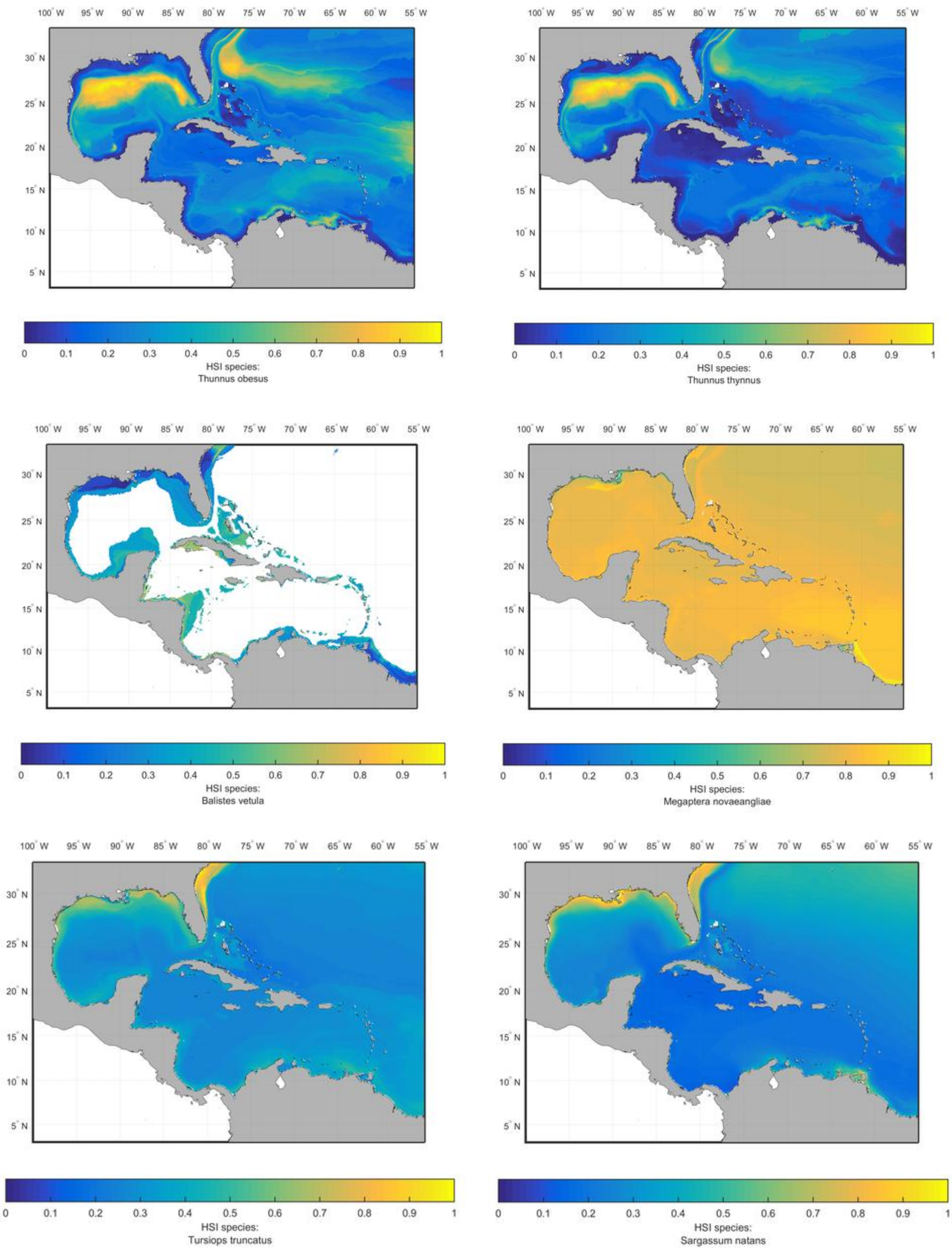
HSI species:
Thunnus albacares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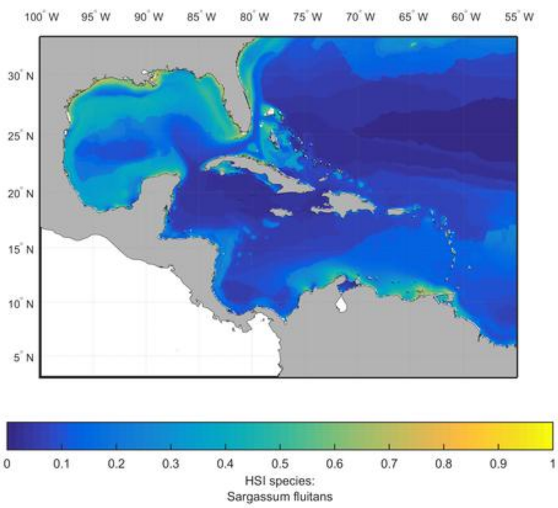
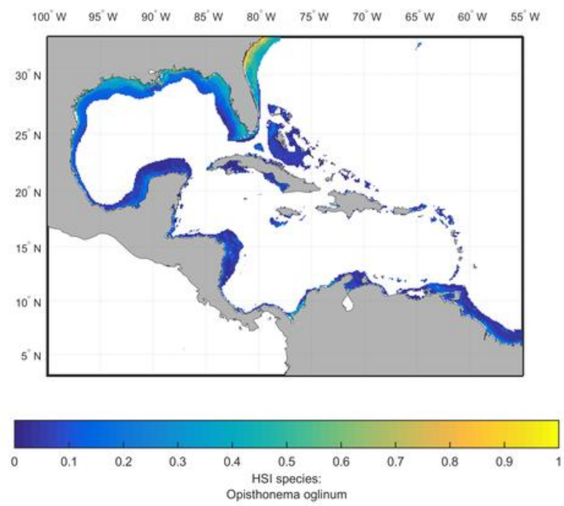
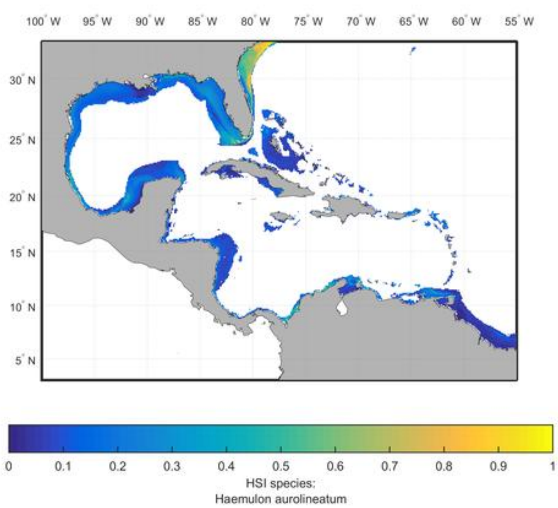
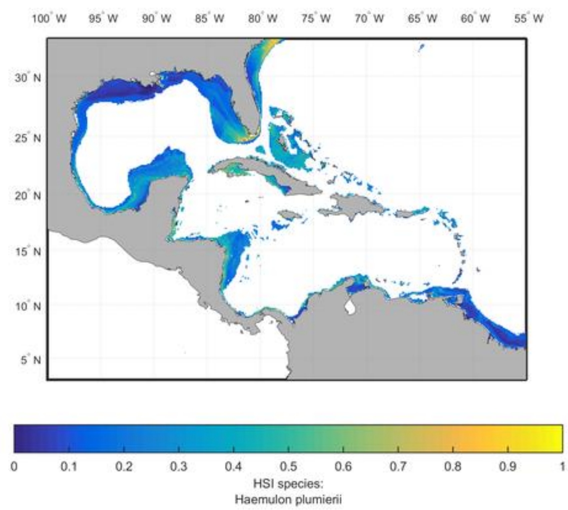
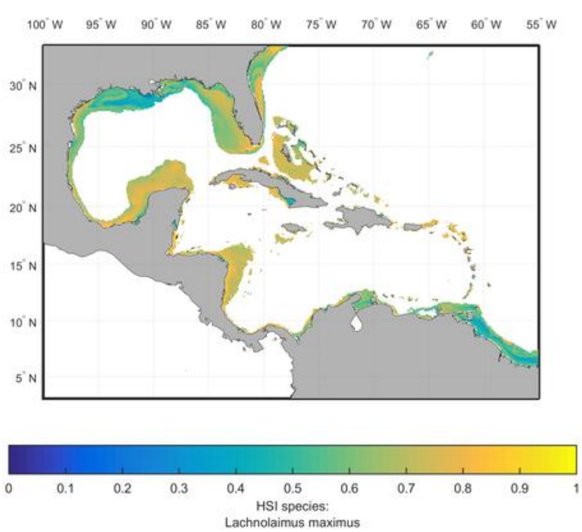
HSI species:
Thunnus obesus
HSI species:
Thunnus thynnus
HSI species:
Balistes vetula
HSI species:
Megaptera novaeangliae
HSI species:
Tursiops truncatus
HSI species:
Sargassum natans


HSI species:
Sargassum fluitans


HSI species:
Opisthonema oglinum


HSI species:
Haemulon aurolineatum


HSI species:
Haemulon plumierii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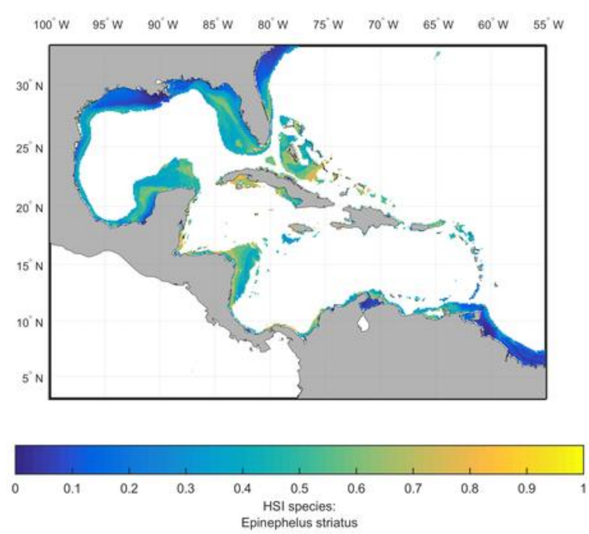
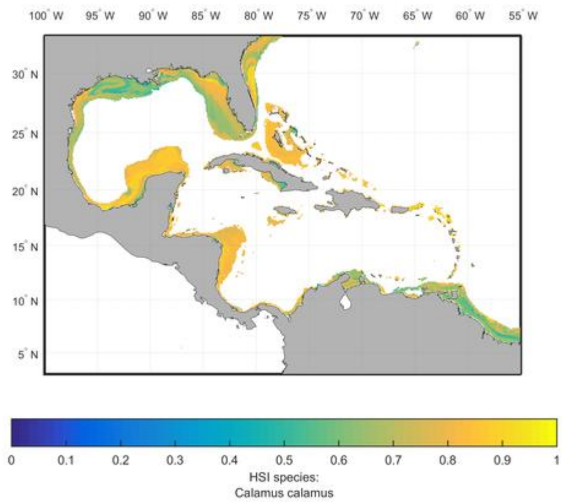
Lachnolaimus maximus


HSI species:
Epinephelus striatus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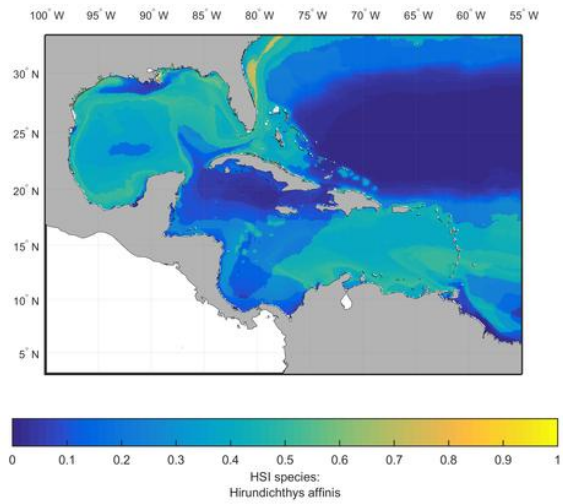
HSI species:
Calamus calamus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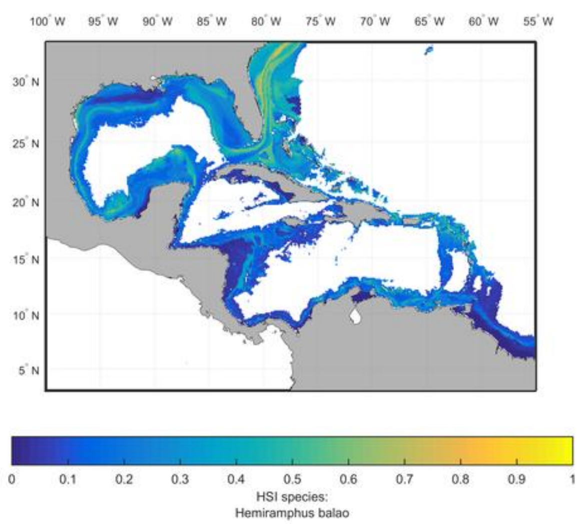
HSI species:
Hirundichthys affinis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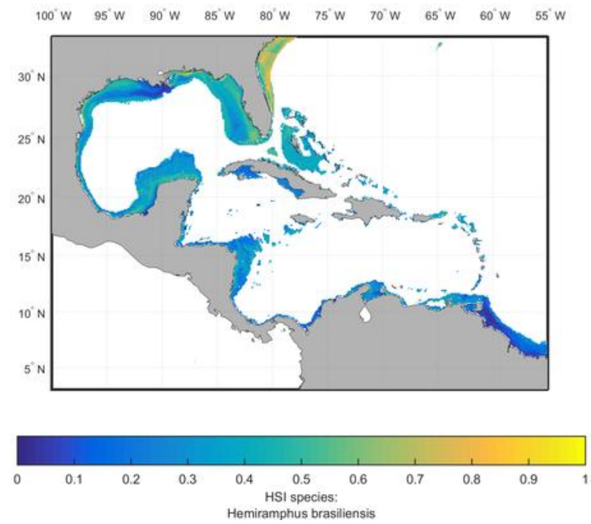
HSI species:
Hemiramphus balao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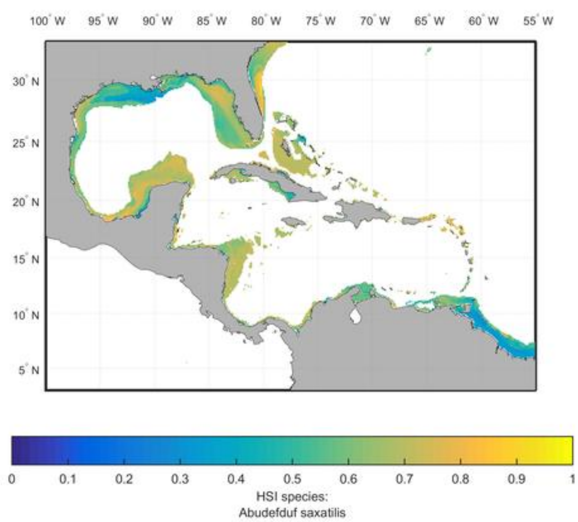
HSI species:
Hemiramphus brasiliensis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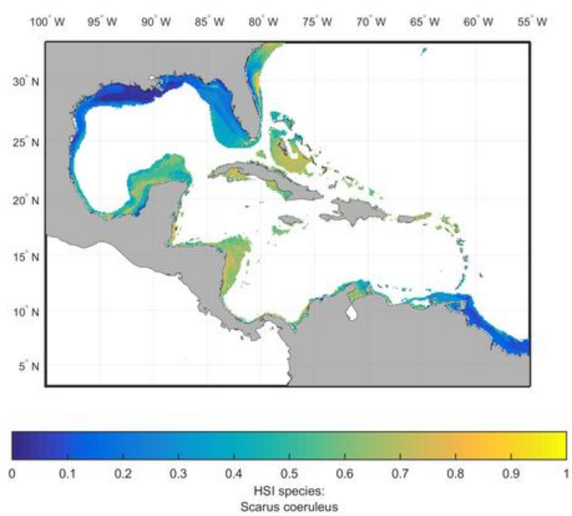
HSI species:
Abudefduf saxatilis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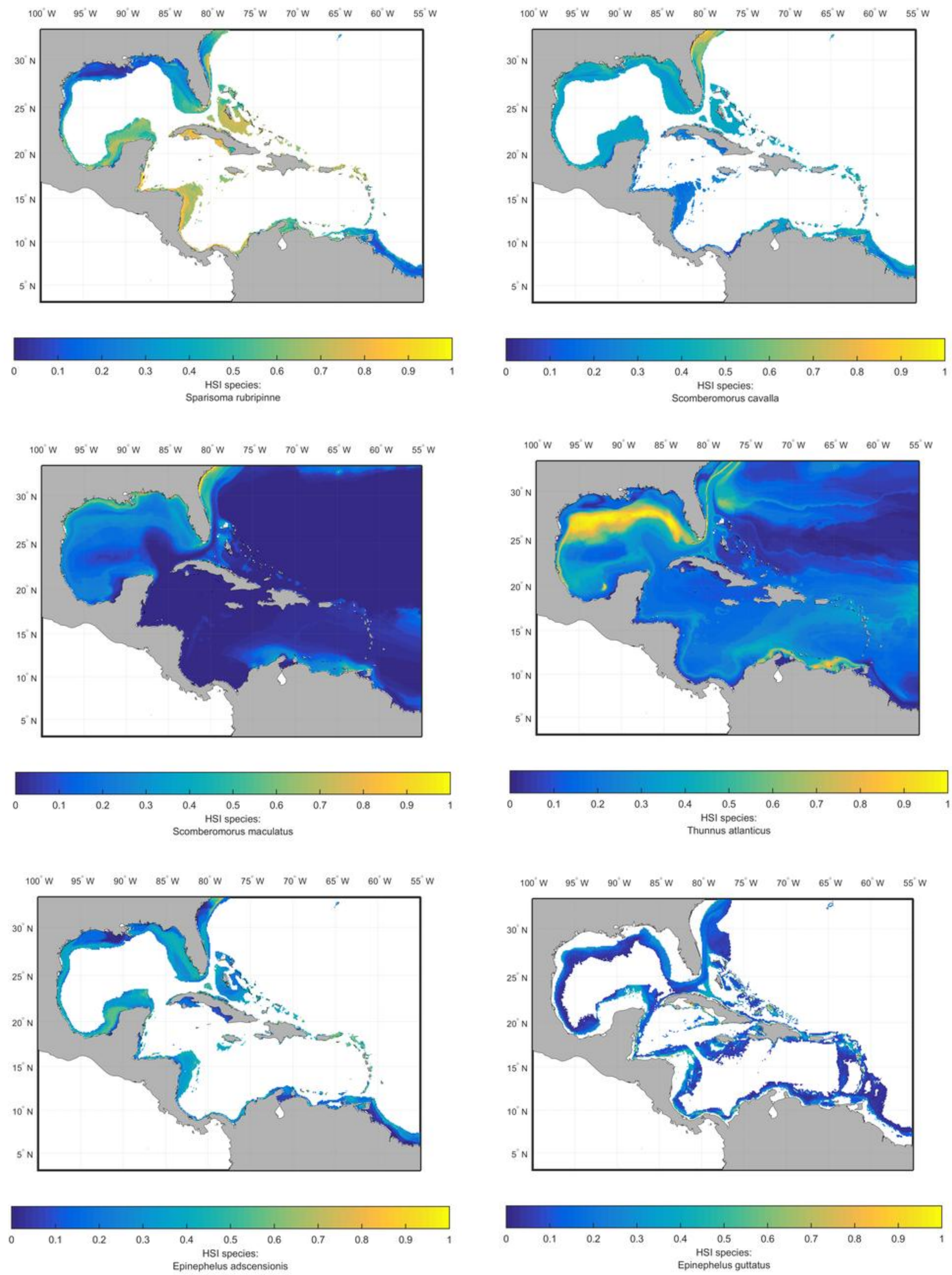
HSI species:
Scarus coeruleus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HSI species:
Sparisoma rubripinne
HSI species:
Scomberomorus cavalla
HSI species:
Scomberomorus maculatus
HSI species:
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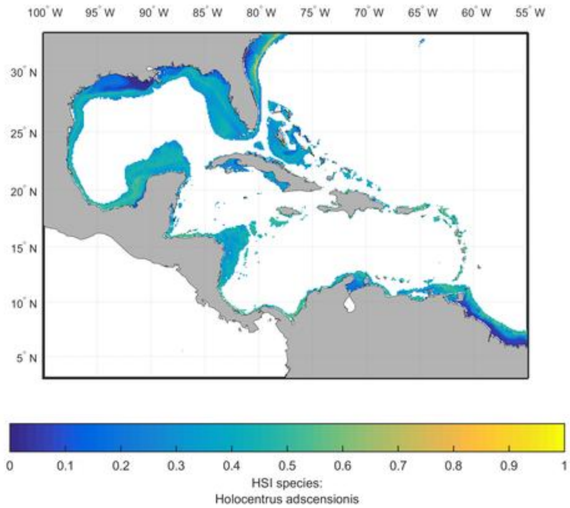
HSI species:
Epinephelus adscensionis
HSI species:
Epinephelus guttatus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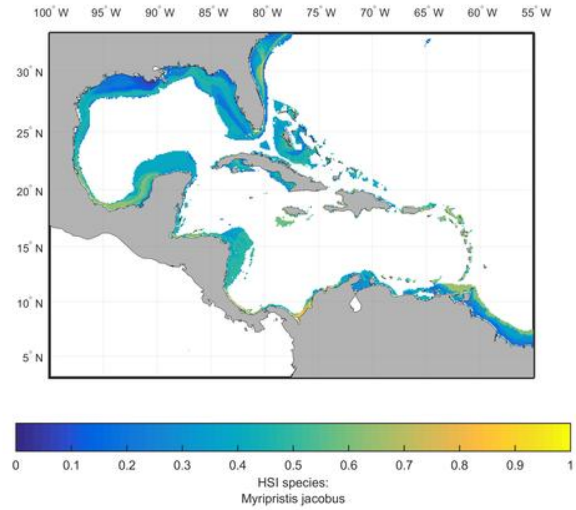
HSI species:
Holocentrus adscensionis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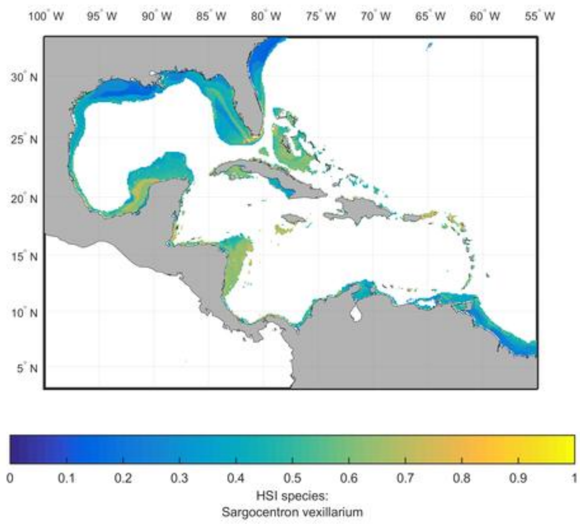
HSI species:
Myripristis jacobus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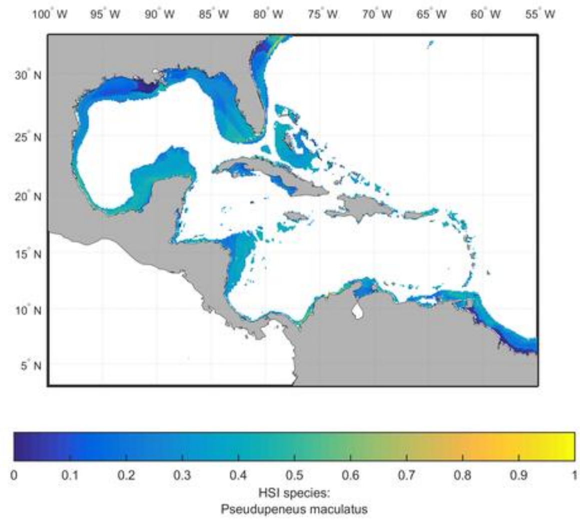
HSI species:
Sargocentron vexillarium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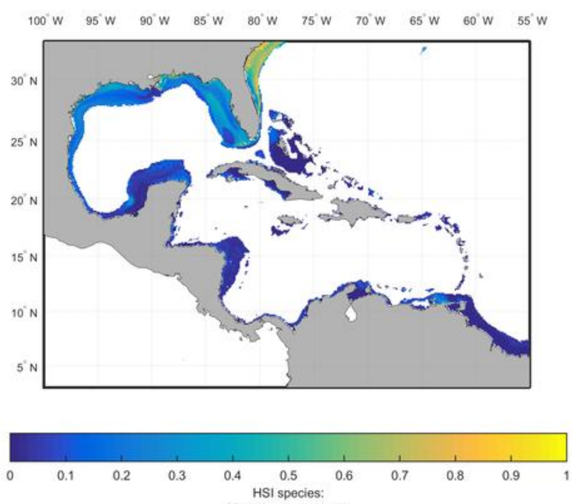
HSI species:
Pseudupeneus maculatus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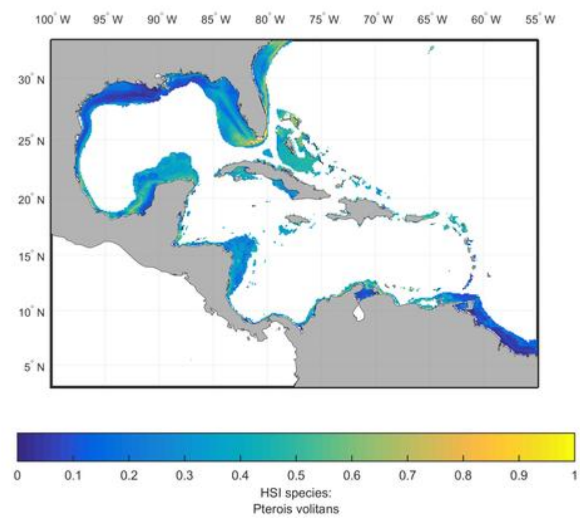
HSI species:
Hippocampus erectus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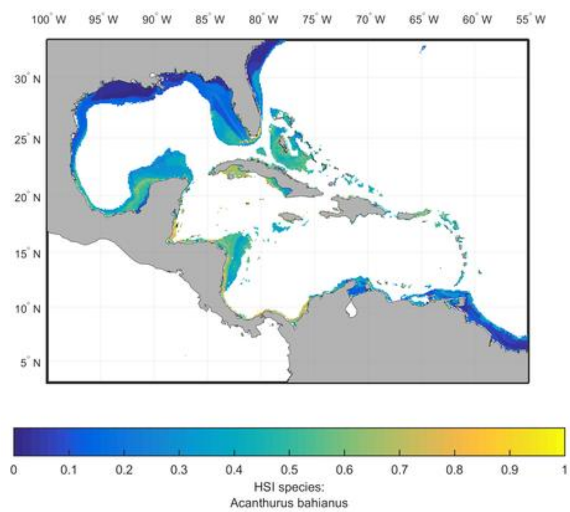
HSI species:
Pterois volitans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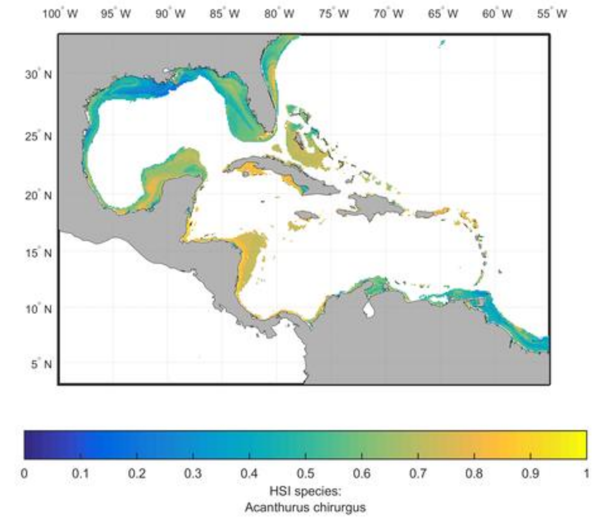
HSI species:
Acanthurus bahianus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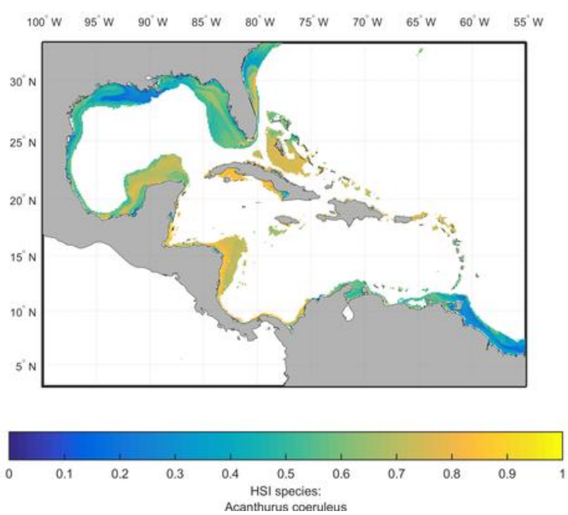
HSI species:
Acanthurus chirurgus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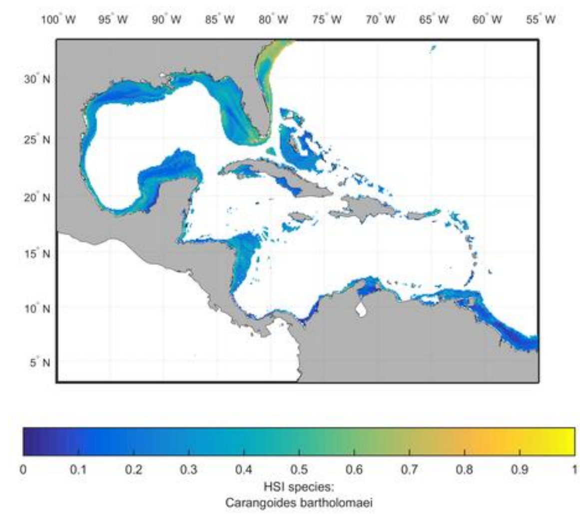
HSI species:
Acanthurus coeruleus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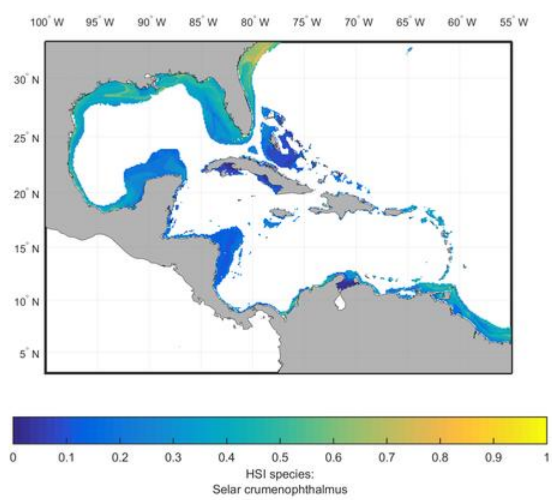
HSI species:
Carangoides bartholomaei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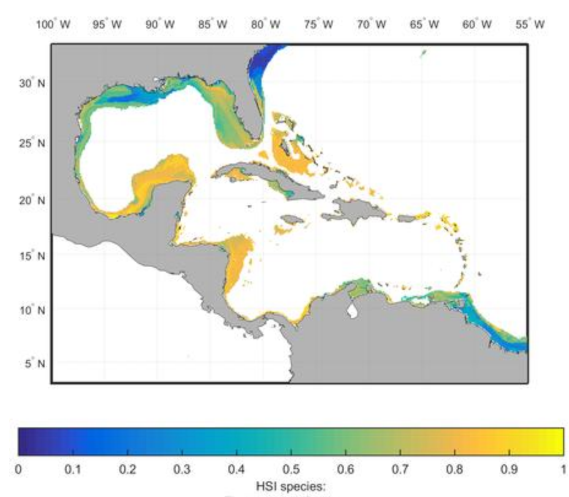
HSI species:
Selar crumenophthalmus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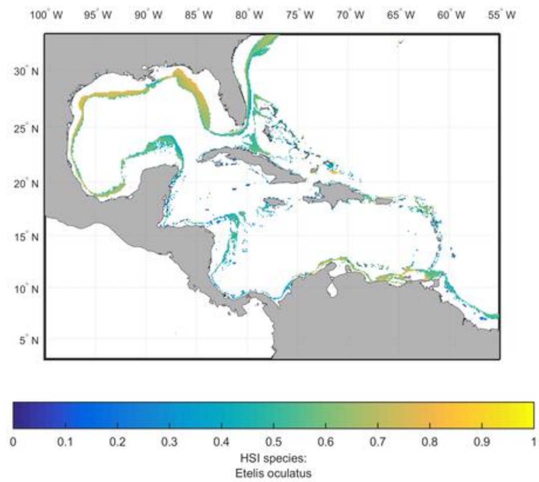
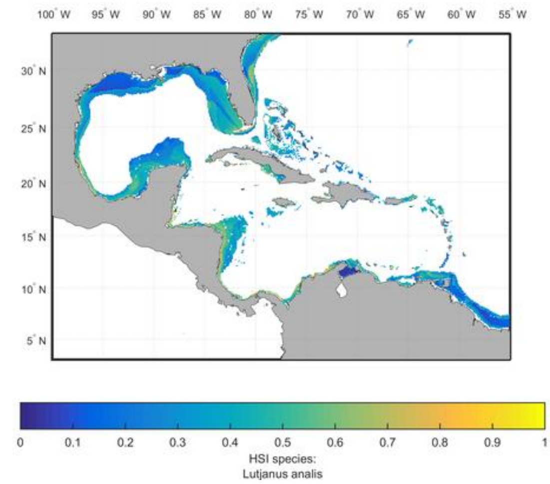
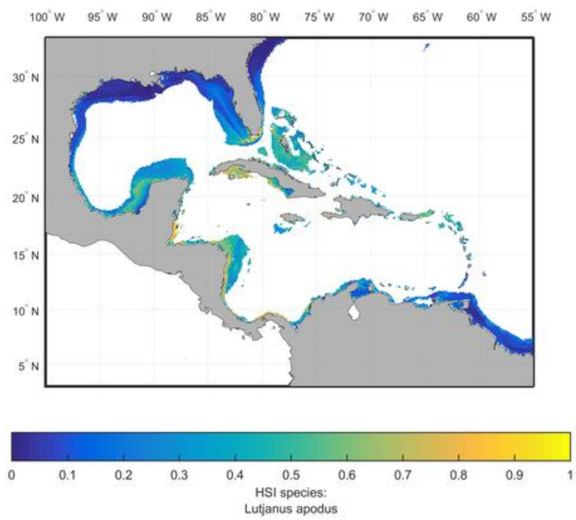
HSI species:
Thalassoma bifasciatum


HSI species:
Etelis oculatus


HSI species:
Lutjanus analis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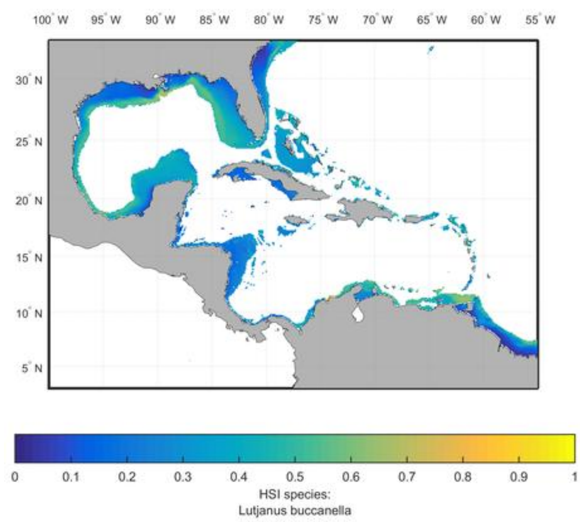
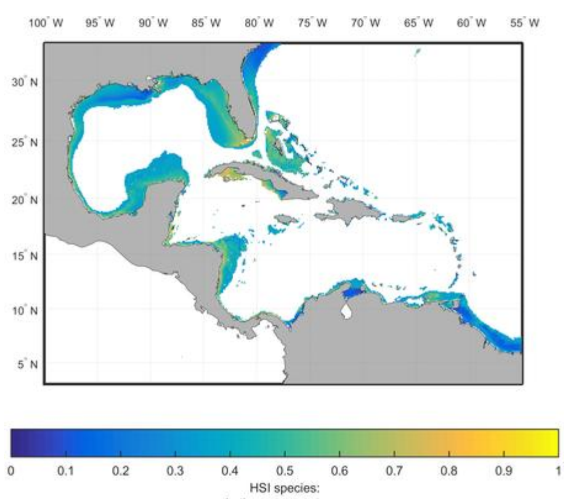
Lutjanus apodus


HSI species:
Lutjanus buccanella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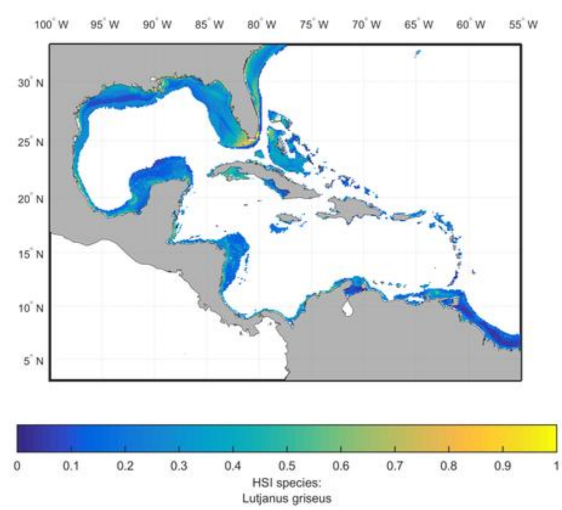
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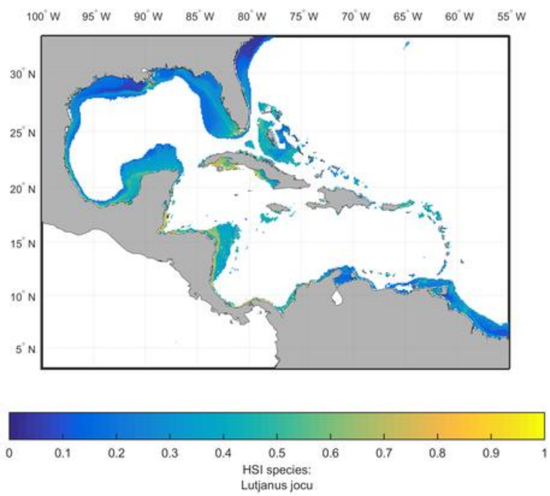
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25° N
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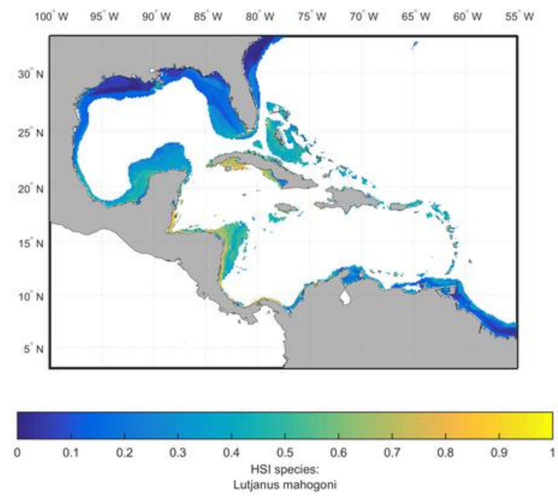
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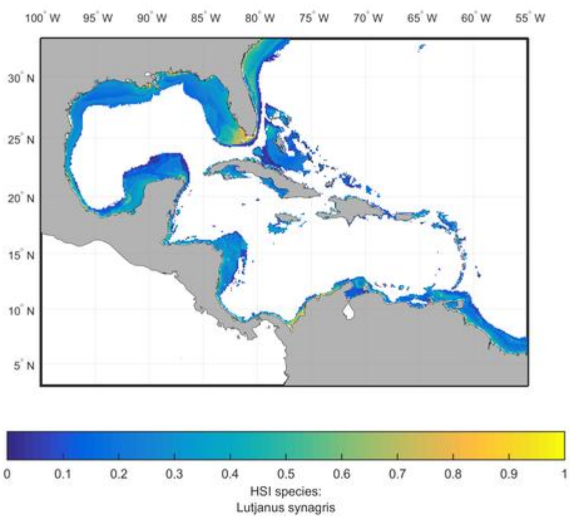
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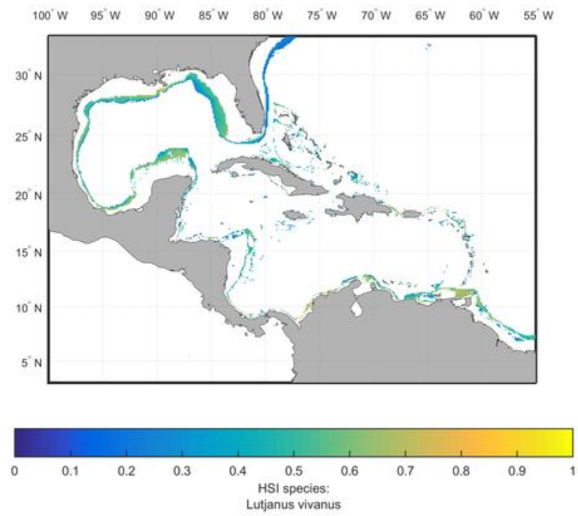
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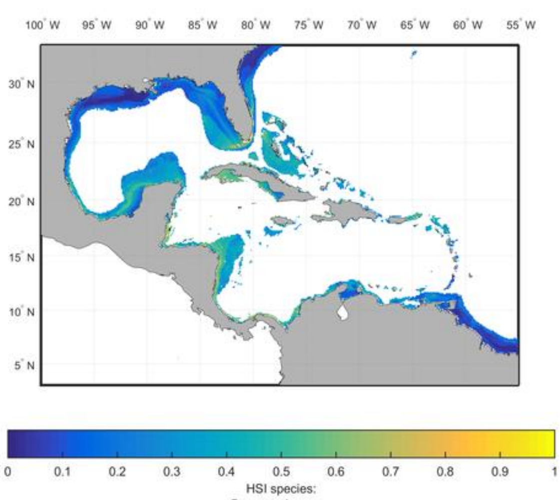
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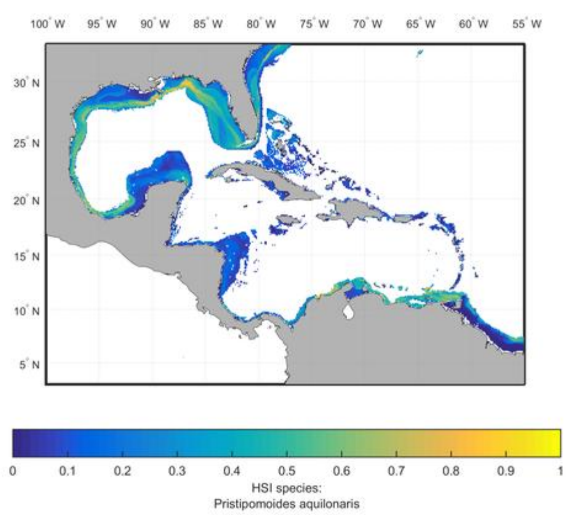
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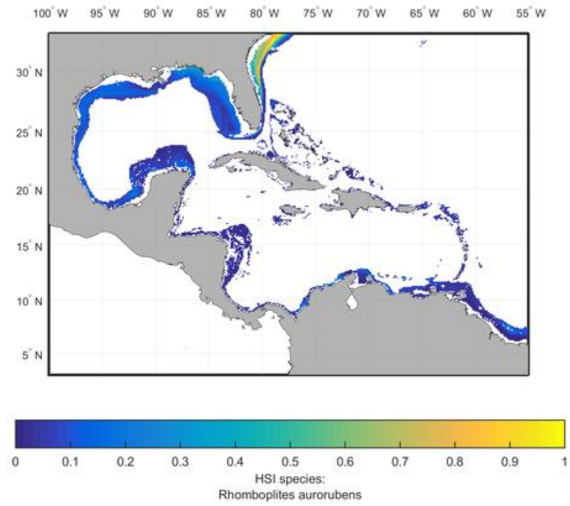
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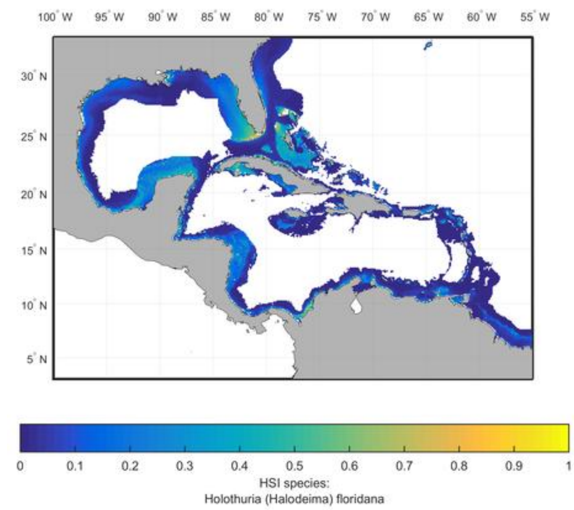
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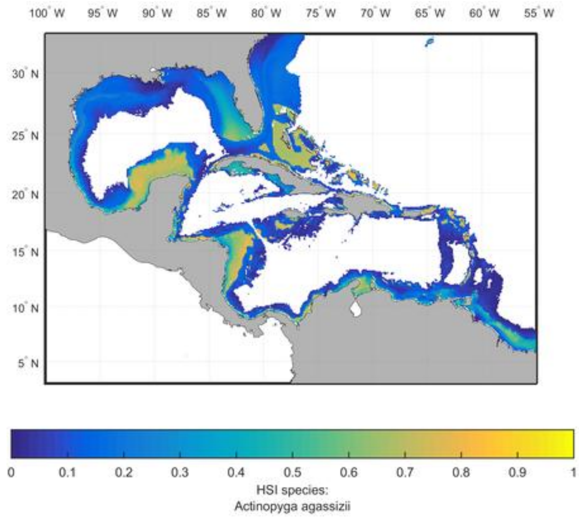
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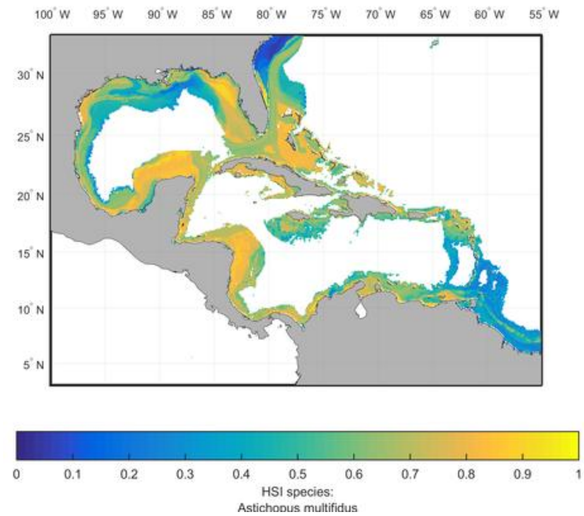
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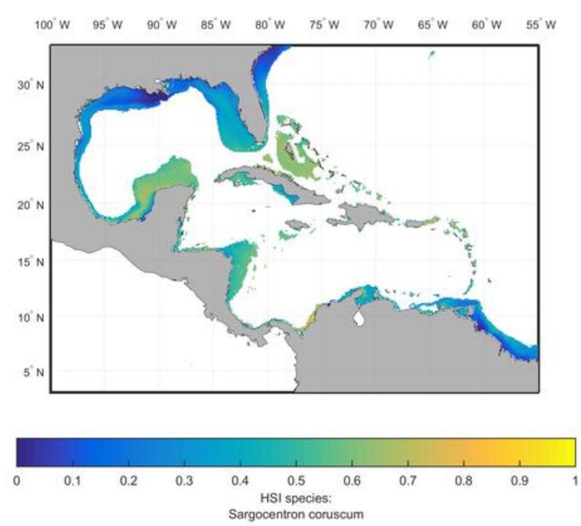
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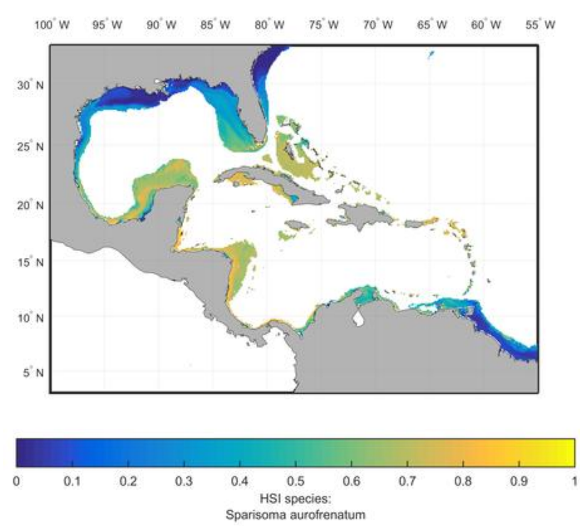
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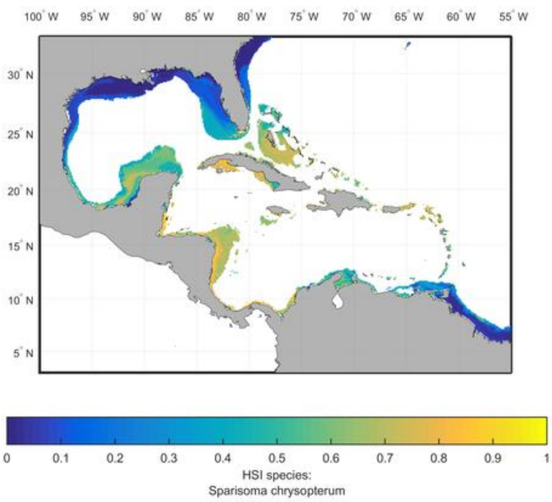
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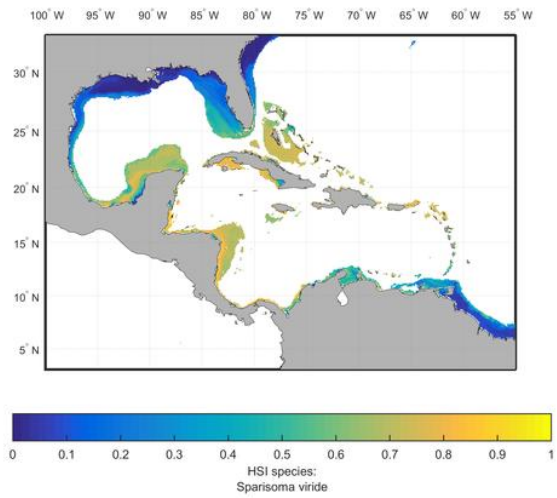
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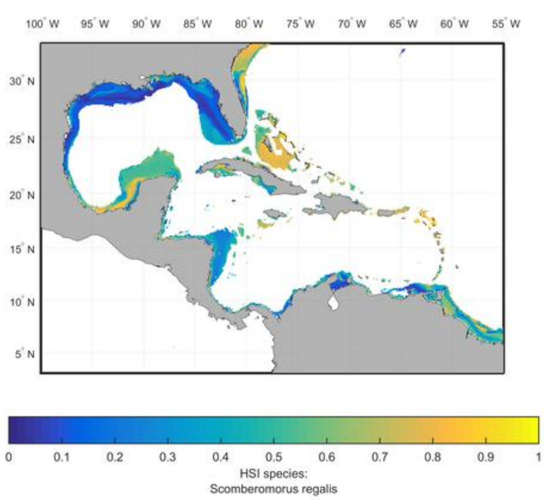
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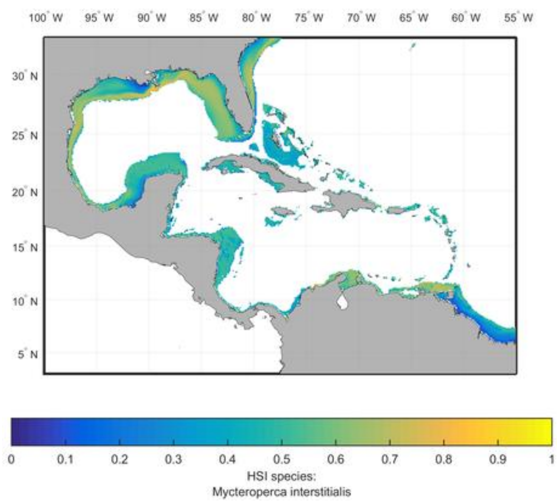
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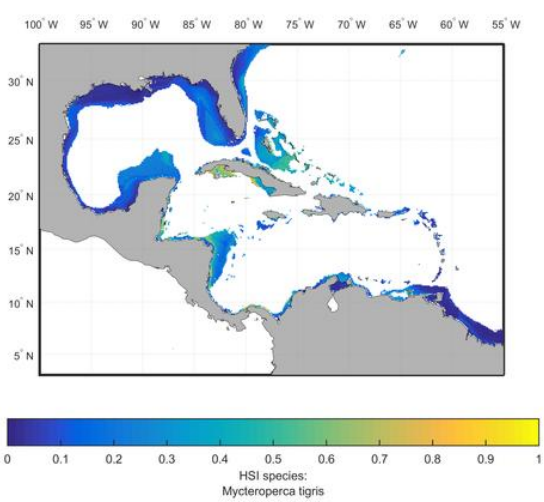
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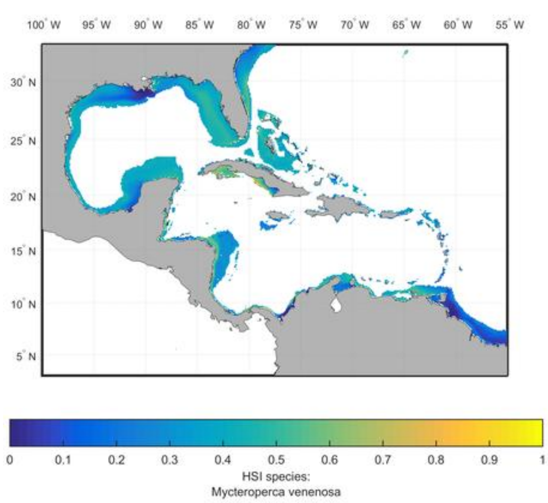
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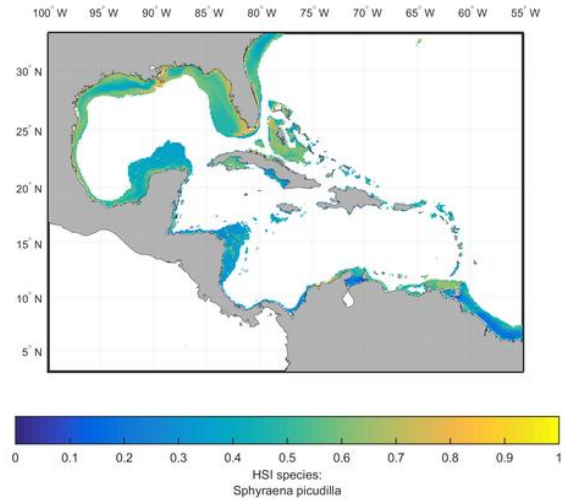
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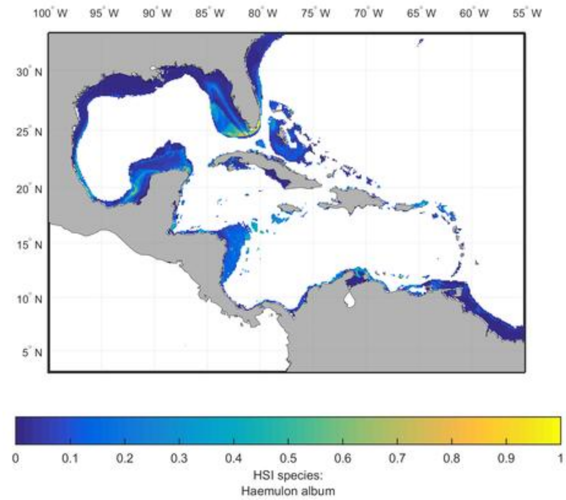
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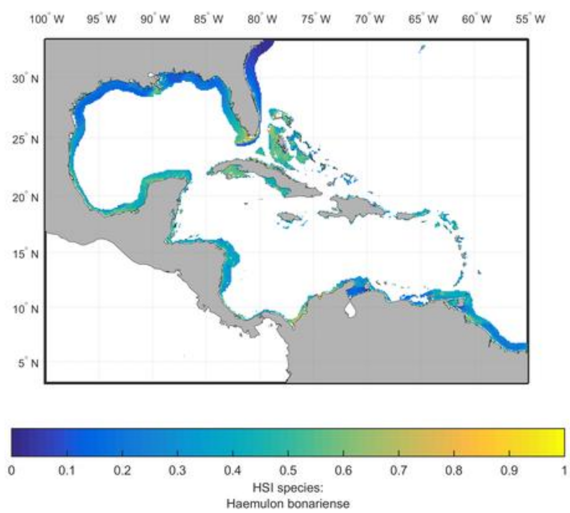
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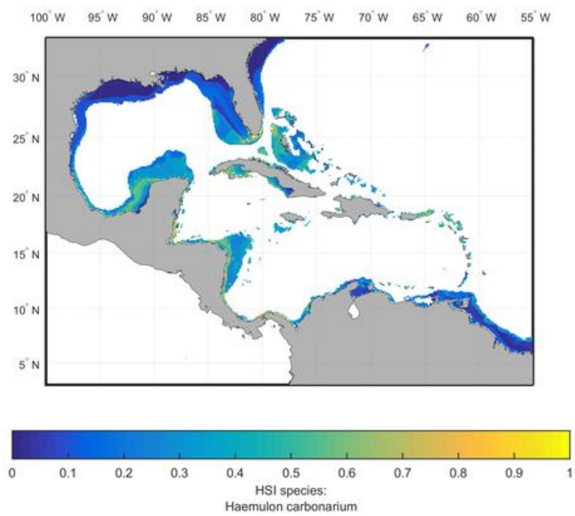
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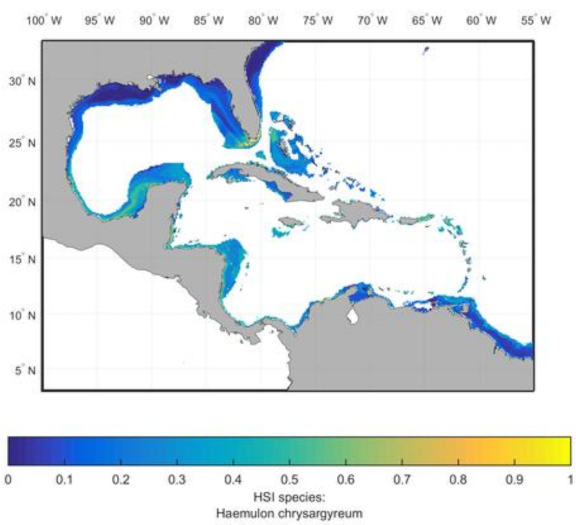
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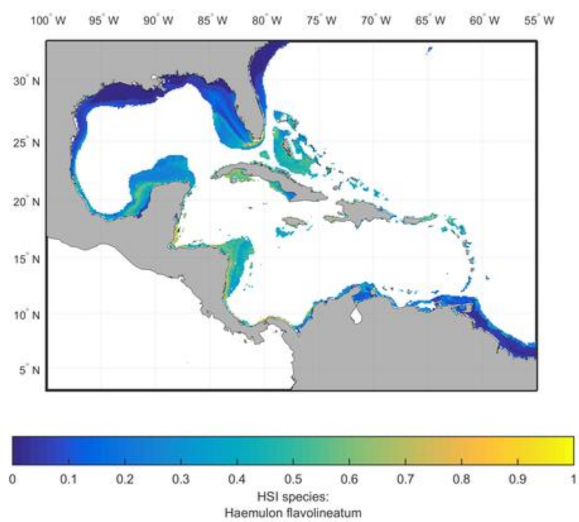
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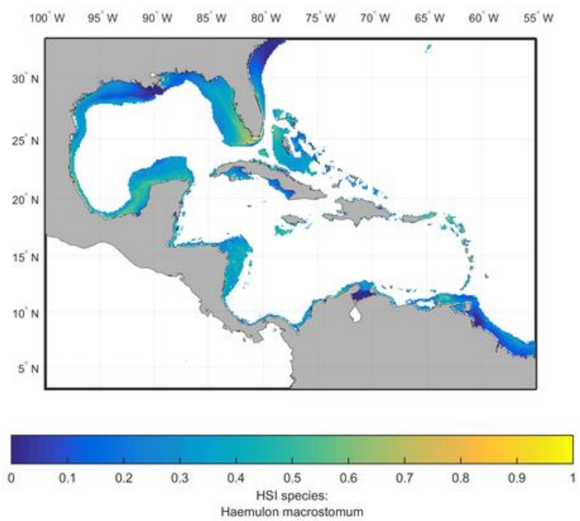
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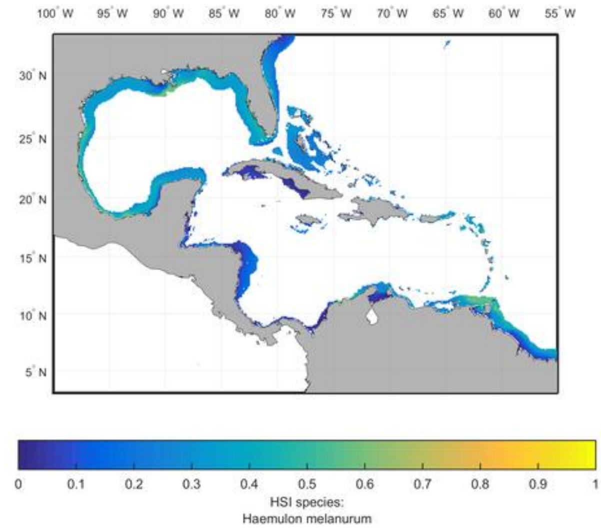
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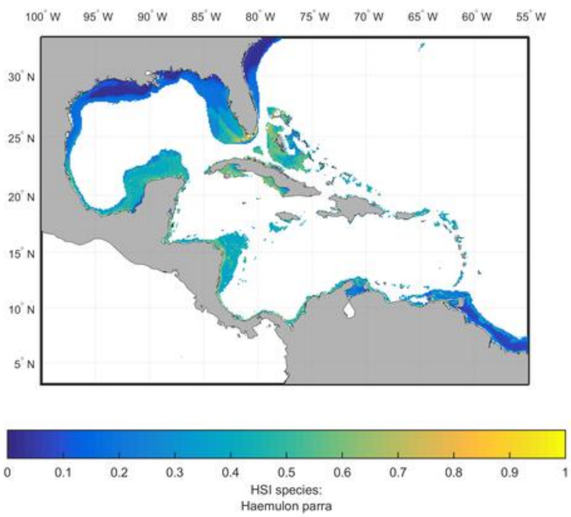
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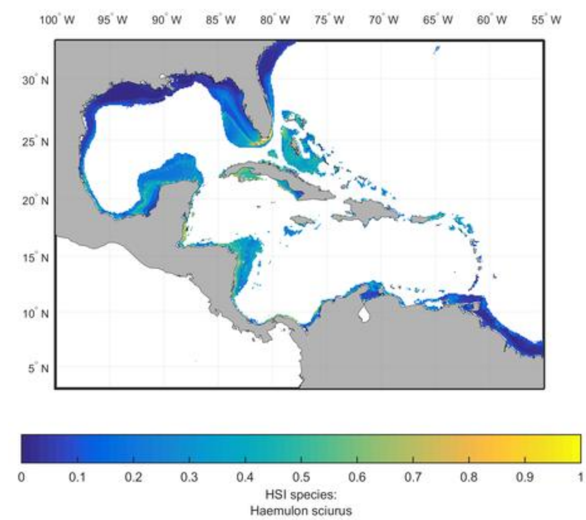
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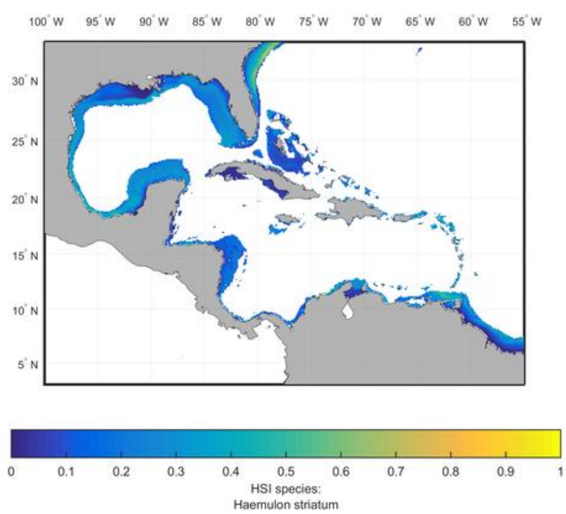
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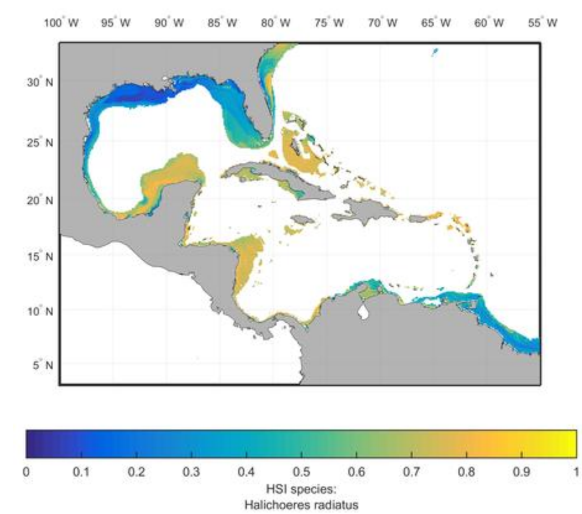
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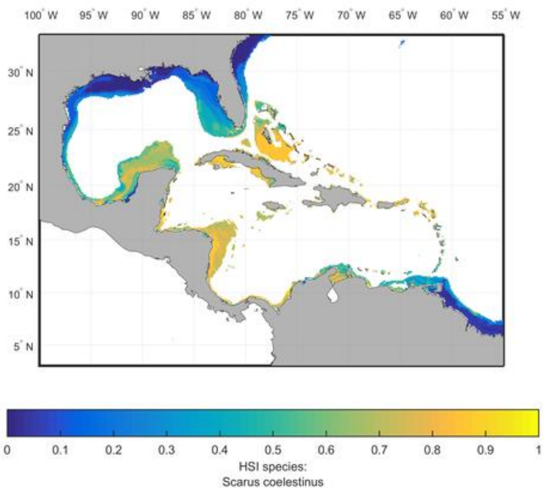
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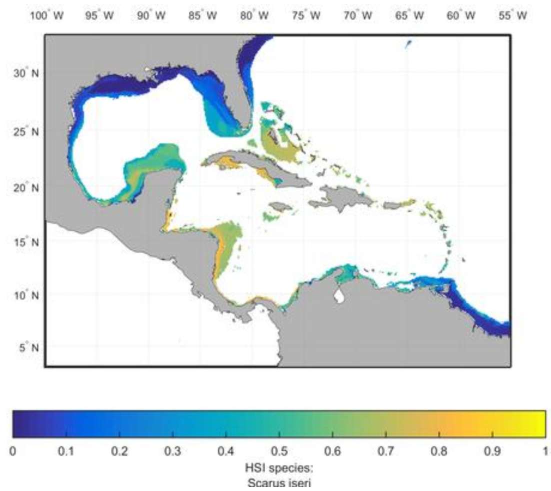
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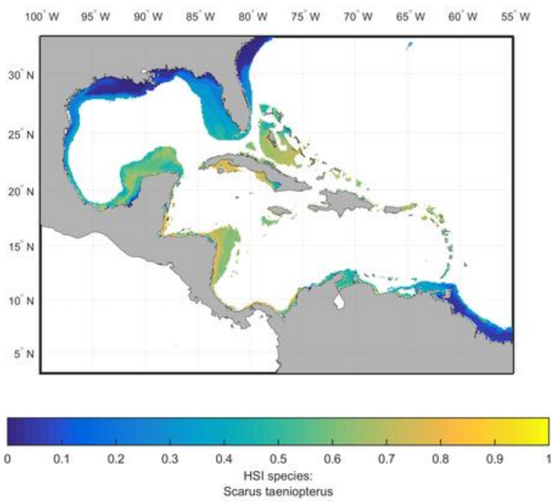
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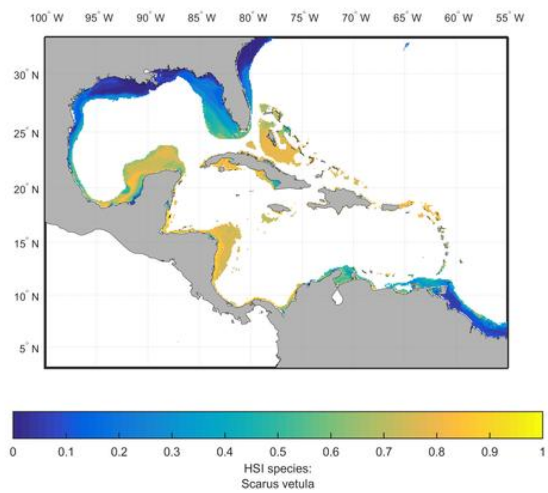
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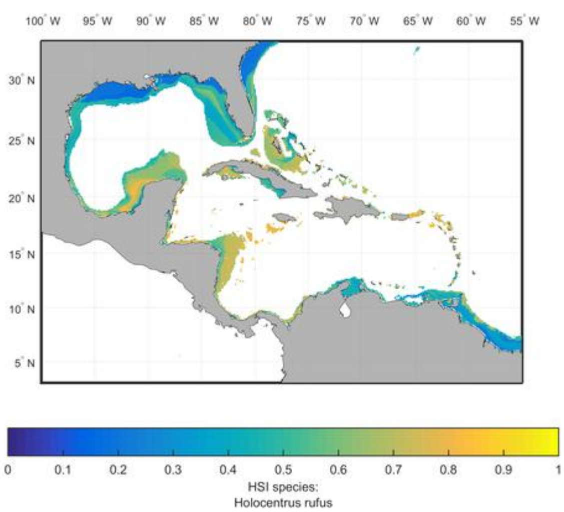
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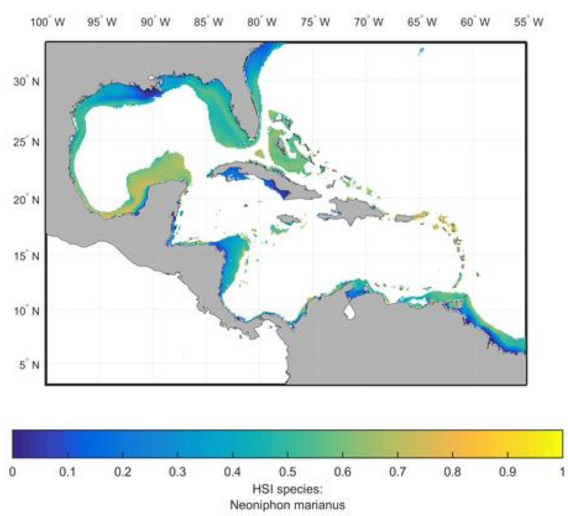
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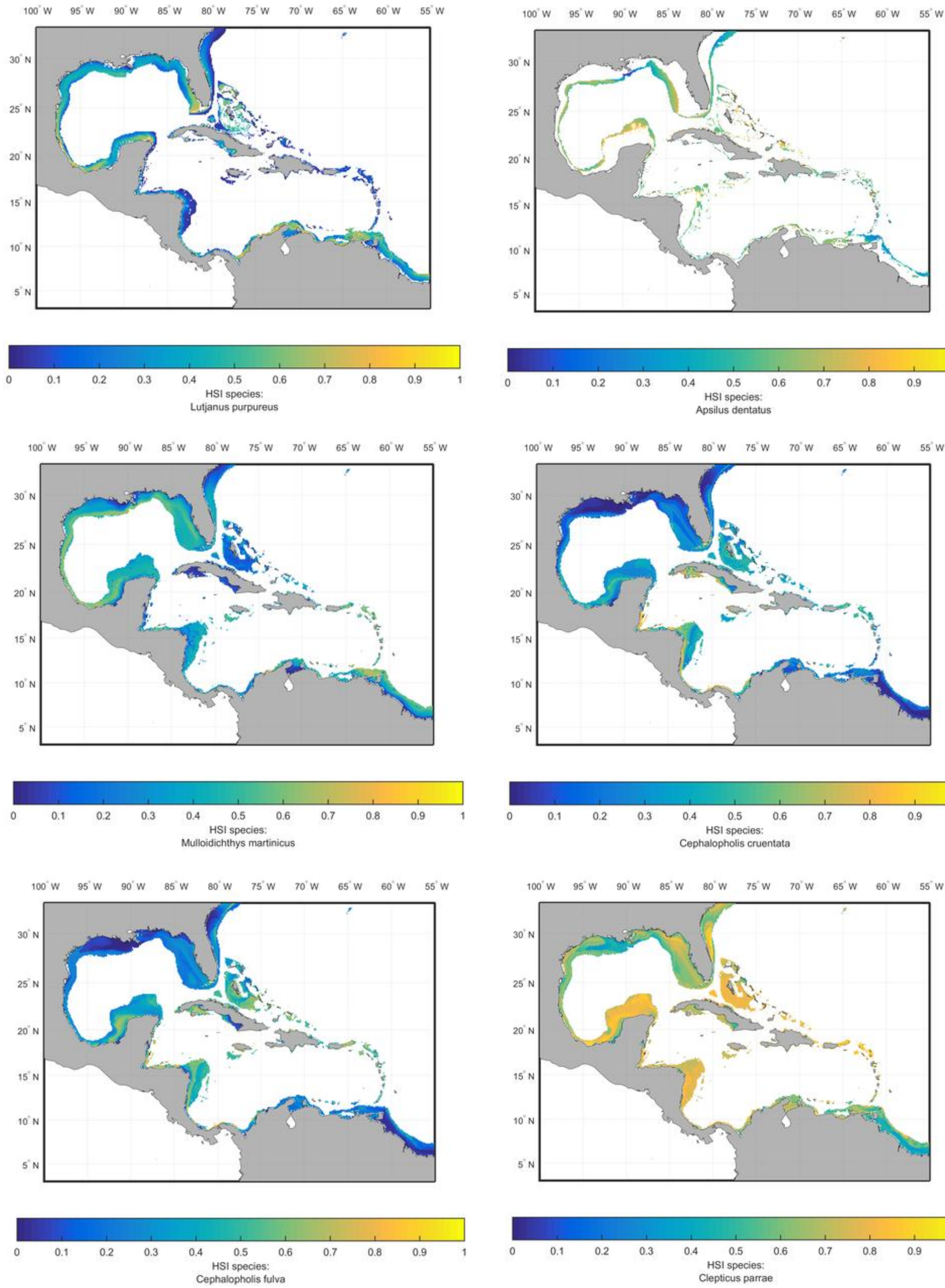
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HSI species:
Lutjanus purpureus
HSI species:
Apsilus dentatus
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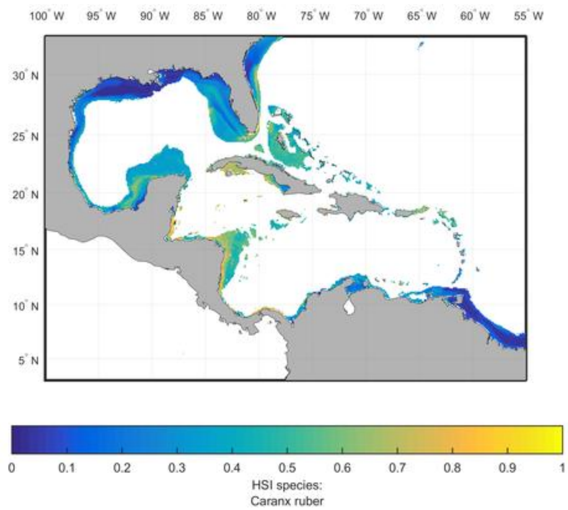
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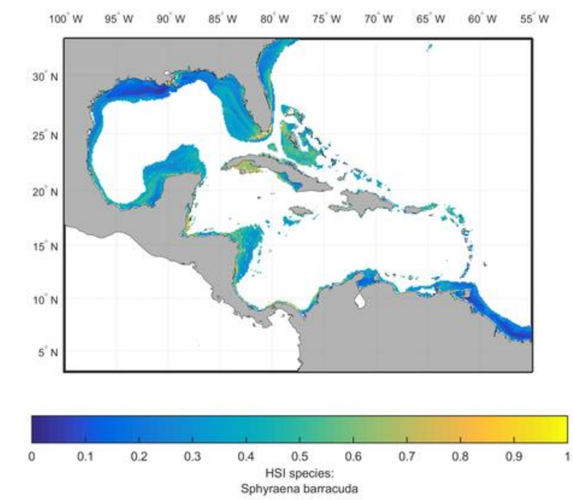
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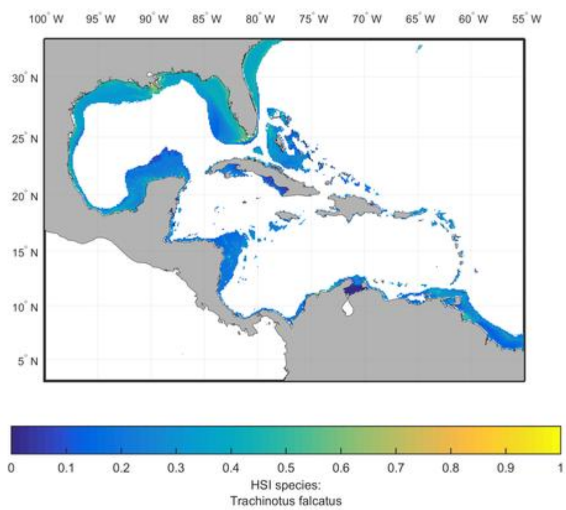
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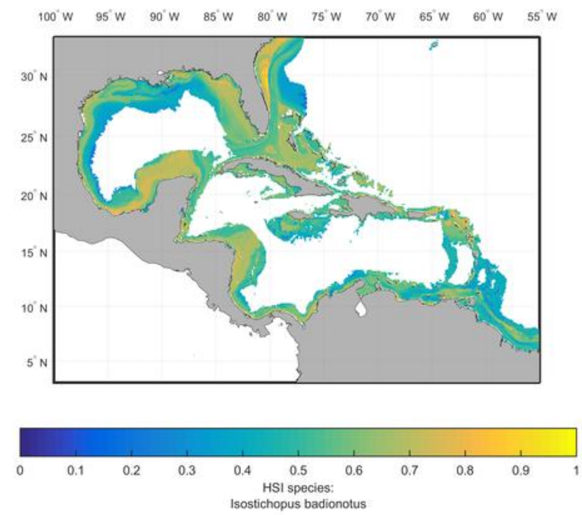
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HSI species:
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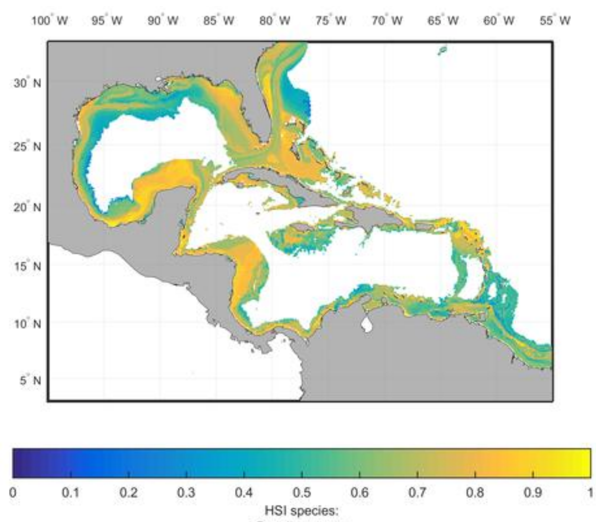
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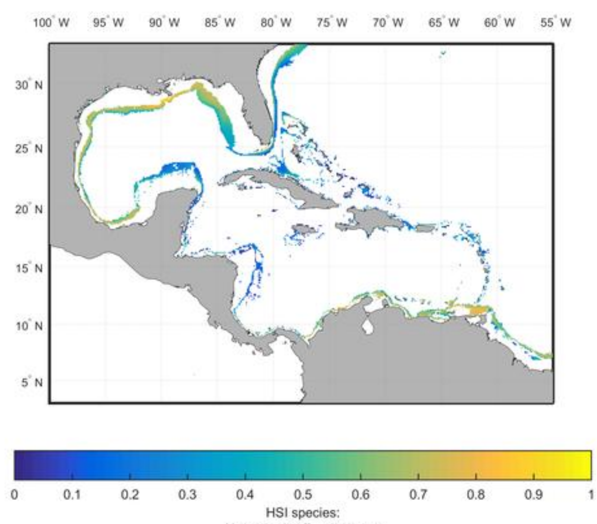
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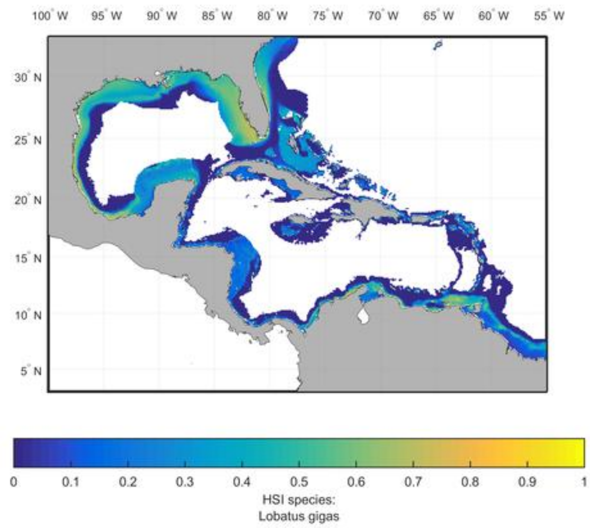
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HSI species:
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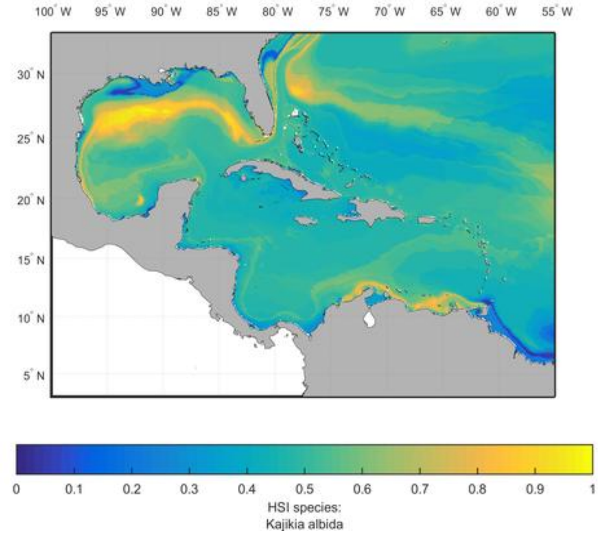
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HSI species:
Kajikia albida

B. CLIMATE CHANGE EFFECTS ON CARIBBEAN MARINE ECOSYSTEMS AND FISHERIES - NATIONAL PROJECTIONS FOR SIX CASE STUDY COUNTRIES: JAMAICA, HAITI, DOMINICA, ST. LUCIA, ST. VINCENT AND THE GRENADINES, AND GRENADA

William W. L. Cheung[1], Gabriel Reygondeau[1], Colette C.C. Wabnitz[1], Natascia Tamburello[2], Susan Singh-Renton[3], Allena Joseph[4]

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Vancouver, British Columbia, Canada, V6T 1Z4
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Abstract

Overall, climate change is projected to have similarly high risk and projected impacts[2] on marine biodiversity and fisheries across all of the case study countries (Dominica, Grenada, Haiti, Jamaica, Saint Lucia, Saint Vincent and the Grenadines). The magnitude of risks and impacts are generally above the average determined for the Caribbean region as a whole (see research paper A as part of this Collection). Pelagic species (oceanic and reef) consistently had the highest risk and projected impacts (e.g., *Thunnus thynnus*, *Istiophorus albicans*) as they are generally exposed to the larger projected changes in ocean conditions at the sea surface, relative to changes in sea bottom. However, some of the demersal species (e.g., *Holothuria* (*Halodeima*) *mexicana* and *Holothuria floridana*) have a limited geographic range, rendering them also highly sensitive to climate impacts, and contributing to the high climate risks and projected impacts for some of the demersal groups. The projected large decrease in maximum catch potential and high level of species turnover (local invasion and extinction) suggest that the future of fisheries in these case study countries is characterized by exposure to large uncertainties in the availability of fisheries resources. Such high risks apply to resources that are targeted by both larger-scale pelagic fisheries and the smaller-scale reef fisheries. Opportunities for climate risk reduction of fisheries resources exist through an integrated ecosystem-based approach to management that will need to consider a ridge to reef lens. In other words, sustainable measures will need to be put in place that consider land-use patterns, habitat alterations, pollution as well as improvements in the exploitation status of fisheries resources in the six case study countries. The latter is considered an immediate threat to sustainability for

[2] Risk: determined for a species (or a system) by its vulnerability as well as the potential occurrence of climate-related ocean changes (i.e., hazards such as warming, ocean acidification); projected impacts: qualitative or quantitaive projections of future negative consequences of climate change.

the majority of species considered and, as shown by our indicator analyses, more sustainable fishing scenarios could substantially support a reduction in the climate risk of fisheries-important species. In contrast, overfishing, combined with high CO_2 concentrations, could devastate fisheries.

The high level of ecological risks and impacts across the case study countries suggest that any major differences in climate risks at the country level would depend on the sensitivity and adaptive capacity of the associated social-economic system.

1 INTRODUCTION

This report is part of the deliverables under Work Package 1 for the project *Fishery-Related Ecological and Socio-economic Impact Assessments and Monitoring System*. Specifically, this report addresses the following components of the overarching objectives of Work Package 1:

- Assess the ecological impacts of climate change and variability on the Caribbean region's fisheries resources; and
- Develop tools and methods for fisheries and marine ecosystem analyses and assessments to quantify the current and future impacts of climate change and variability on fisheries production.

This report complements and expands on the regional results presented in Part A and focuses on country-level findings for each of the six selected highly climate-vulnerable nations of the Commonwealth of Dominica, Grenada, Haiti, Jamaica, Saint Lucia and Saint Vincent and the Grenadines (SVG).

1.1 **Fisheries and Marine Resources**

In all six countries, fisheries activities, largely small-scale and artisanal in nature, provide an important number of goods and services that are important to human well-being, such as high protein food, livelihood opportunities and household income. Caribbean coral reefs specifically have been estimated to generate between USD$3.1 and 4.6 billion annually from fisheries, tourism and shoreline protection (Burke and Maidens, 2004; Burke and Kushner, 2011). In Jamaica, fish consumption was estimated to be one of the highest per capita in the Americas (27.1 kg/year in 2013) and fisheries were estimated to employ just under 24,000 fishers in 2015 (FAO, 2017). Key target species include pelagics (coastal and oceanic), shelf and slope demersals, reef fish, and high-value benthic invertebrates, such as spiny lobster (*Panulirus argus*) and queen conch (*Lobatus gigas*).

However, the health of corals reefs and associated ecosystems such as seagrass beds and mangroves from which case study countries' communities derive essential goods and services, is degrading rapidly under the mounting pressure of many human activities. Coastal development, growing coastal and tourism populations, sewage as well as poor land management practices resulting in sedimentation and nutrient loading have become important issues for many of the islands (Sweeney and Corbin, 2011). Overfishing (particularly of herbivores and including illegal, unreported and unregulated (IUU) activities), disease, and ineffective management pose further threats to the ecological balance of Caribbean coastal environments (Burke *et al*., 2004; Gill *et al*., 2017; CRFM *et al*., 2017). Primarily as a result of a combination of these threats, and exacerbated by climate change (see below), recent studies estimate that the Caribbean region has lost more than 50% of its coral reef cover since the 1970s (Mumby *et al*., 2014; Jackson *et al*., 2014). Rates of loss for mangroves and seagrass beds as a result of overexploitation, coastal development, nutrient and sediment pollution, introduction of non-native species, and global climate change are comparable (Waycott *et al*., 2009). Decline in the health of these habitats will lead to further losses in fishery productivity (Cinner *et al*., 2012), in turn negatively affecting artisanal reef fisheries and the communities that depend on them for livelihoods and food security (Munday *et al*., 2008; Cinner *et al*., 2013; Sale *et al*., 2014). They also significantly undermine the ability of coastal ecosystems to cope with climate change hazards.

1.2 **Climate Change Challenges**

Climate change and increased climate variability are expected to adversely impact the fisheries sector in all six island states. Such changes, manifested through increases in water temperature, declines in oxygen concentration and increase in acidity as well as other changes in ocean physical and chemical conditions, are affecting and will continue to affect fishes and invertebrates by altering the size, abundance, distribution, availability and productivity of fish populations (Perry *et al*., 2005; Pörtner *et al*., 2007; McIlgorm *et al*., 2010; Cheung *et al*., 2013). Mass coral reef bleaching events, which are becoming more severe and more common, have led to the increasing incidence of disease and death among various coral species (Levas *et al*., 2018; Buglass *et al*. 2016), in turn negatively impacting the important fishery species that depend on these habitats for refuge, food and reproduction as well as dependent industries important for local livelihoods and income (McField, 2017). Current carbonate production rates of coral reefs throughout the region have been estimated to be at least 50% lower compared to historical levels and a number of sites registering negative growth rates (Perry *et al*., 2013). Burke *et al*. (2004) estimated that the further degradation of Caribbean reefs could cost the region US$95-140 million per year in losses to coral reef-associated fisheries, US$100-300 million per year through declines in dive tourism, and US$140-420 million per year as a result of reduced shoreline protection services. The recent massive influxes of *Sargassum* have also severely affected fisheries production and livelihoods throughout the region (Doyle and Franks, 2015; Hinds *et al*., 2016; Siuda *et al*., 2016).

In addition to direct effects on important fish and invertebrate fishery species themselves, climate change – through ocean warming, sea-level rise, increased hurricane intensity (Uhrin, 2016), and changes in rainfall patterns (McLean *et al*., 2015) – will have important negative impacts on the habitats, which these species depend on (i.e., coral reefs, mangroves and seagrass beds) (Stephenson and Jones, 2017). Climate change will also substantially reduce the safety of fishers at sea (Badjeck *et al*., 2010; FAO Western Central Atlantic Fishery Commission, 2018). All six islands focused on in this study are dependent on fisheries, tourism and associated industries, but they have different vulnerabilities and will experience different impacts from climate change (Blasiak *et al*., 2017).

Coastal communities, especially those that rely heavily on fishing, have been identified as particularly vulnerable to climate change. Recognizing this threat, the region recently developed a Protocol on Climate Change Adaptation and Disaster Risk Management in Fisheries and Aquaculture[3], building on the existing Caribbean Community Common Fisheries Policy (CCCFP) (CRFM, in press). Three studies (Pérez-Ramírez, 2017; Oxenford and Monnereau, 2018; Monnereau and Oxenford, 2018) provide relatively detailed assessments, based on (limited) current observations, data and climate projections of likely impacts on fish, shellfish and fisheries in the Caribbean. These studies and others before them (e.g., Nurse and Charlery, 2014) conclude that most species, the associated fishery sector and dependent coastal communities are all highly vulnerable to climate change. Oxenford and Monnereau (2018) in particular highlight that reef-associated species are likely to be the most vulnerable of the fishery groups considered, as a result, in part, of the combination of observed negative climate change impacts on associated habitats, their current overexploited nature, and pressures on associated coastal ecosystems.

[3] The Protocol is a result of technical cooperation between the Caribbean Regional Fisheries Mechanism (CRFM) and the Global Environment Facility (GEF)-funded Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of the Food and Agriculture Organisation of the United Nations (FAO).

In response to evidence-based concerns, and in an effort to minimize climate change impact on and support for fisheries dependent livelihoods, Jamaica has set aside $22.8 million to plan and execute a *Fisheries Ecosystem Adaptation Strategies and Technologies project*. The initiative seeks to "enhance marine protected areas (MPAs) ecosystem services via reduction of human-induced stressors and increased sustainable resource use; apply climate adaptation measures to minimize impacts on MPA ecosystems from land-based sources of pollution; and minimize climate change impact on fishing livelihoods" (Patterson, 2018).

A better understanding of the projected impacts on and the likely vulnerability of key species of interest to climate change throughout the EEZ of the 6 island nations of interest in this study, is a significant step toward assisting countries and stakeholders to strengthen and develop adaptive capacity to climate change impacts and improve resilience of marine ecosystems and the fisheries sector. Doing so would significantly contribute to maintaining the flow of ecosystem services to dependent communities (Knowlton and Jackson 2008) and support livelihoods and well-being in the face of impending changes.

This study sought to undertake a comprehensive assessment of climate change impacts on 110 marine species and associated fisheries. These species were identified as important based on their catches[4] and stakeholder feedback. Specifically, by integrating multiple modelling approaches, we (1) project future ocean conditions; (2) assess the impacts of environmental changes to key marine species; (3) determine selected species future vulnerability as a result of projected environmental changes, as well as the species' sensitivity and adaptive capacity to these changes; and (4) estimate climate change impacts on future fisheries production. The modelling assessment and its outputs are based on a high resolution - previously unavailable - global coupled ocean-atmospheric climate model. All findings are reported at the scale of individual case study countries.

2 METHODS

Projected climate impact indicators were derived for the six selected case study countries: Commonwealth of Dominica, Jamaica, Grenada, Haiti, Saint Lucia, and Saint Vincent and the Grenadines (SVG) (Figure 1). Boundaries for each country's Exclusive Economic Zone was based on the digital map available at http://www.marineregions.org/downloads.php (Figure 1).

[4] Total catch volumes were based on estimates provided in the Sea Around Us catch database (www.seaaroundus.org).

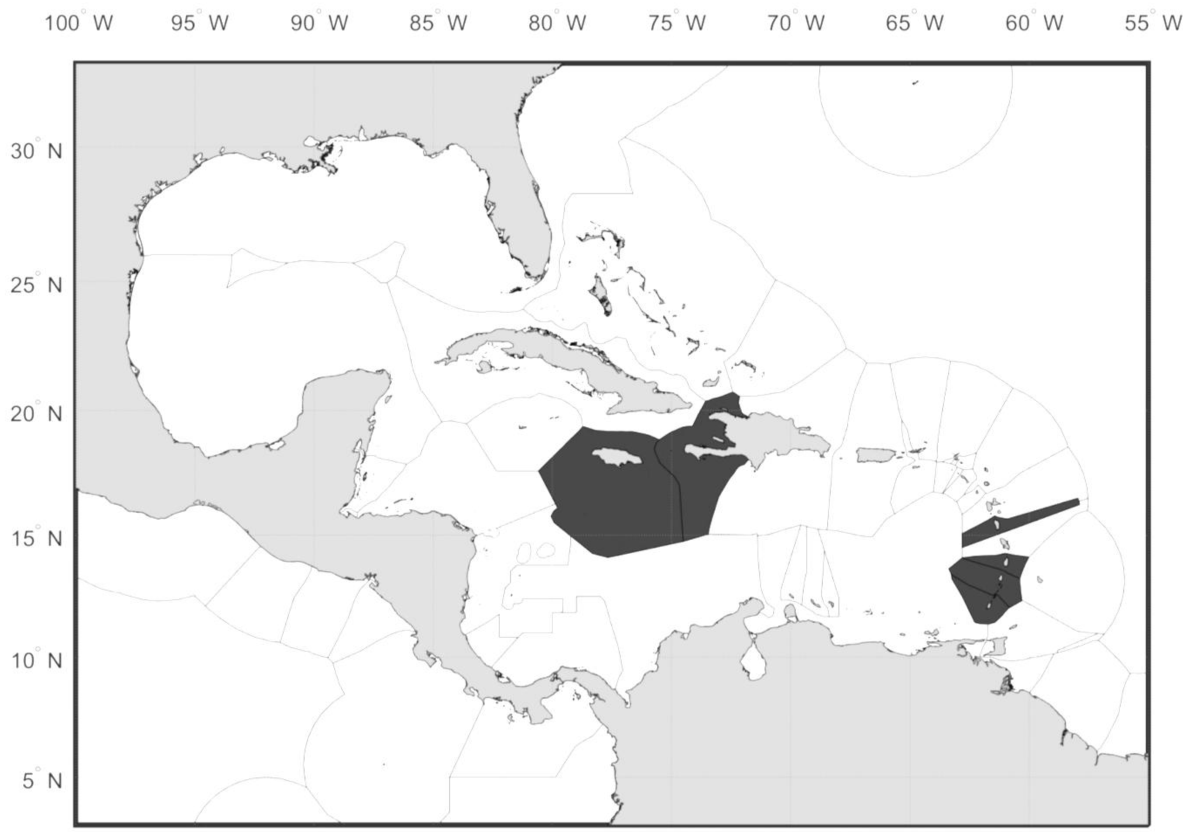


Figure 1. Exclusive Economic Zone (EEZ) boundaries for the Caribbean Sea region. The dark area covers the EEZs of the six case study countries.

For each country, we calculated indicators to evaluate the vulnerability, risk and impact of marine biodiversity and fisheries resources to anthropogenic climate change. Impact indicators include the climate vulnerability and risk indices of selected species; the projected changes in habitat suitability[5] index of these species; the changes in habitat suitability for key species assemblages (e.g., reef and reef pelagics); and the projected changes in maximum catch potential for each case study country. Country-specific indicators were calculated from the average of the indicator values across the grid cells of a given country's EEZ. See paper A in this Collection for details of how individual indicators were calculated.

We also calculated projected changes in ocean variables that are most relevant to the selected marine species in each of the six case study countries' EEZ. These ocean variables include temperature and salinity both at sea surface and bottom. To match the scale of the case study countries' EEZ and to ensure the relevance of model outputs to assess climate risks and impacts, projected changes in ocean variables were based on the high resolution GFDL CM2.6 Earth System Model (0.1° x 0.1° spatial resolution). Such ocean projections were used to calculate all indicators, except the changes in maximum catch potential (0.5° x 0.5° spatial resolution). Calculation of the latter was undertaken using the Dynamic Bioclimate Envelope Model (DBEM), which currently is limited to using input data at the coarser resolution, as provided by other Earth System Models (the Geophysical Fluid Dynamic Laboratory Earth System Model 2G (GFDL ESM 2G), the Institut Pierre-Simon Laplace Climate Model (IPSL-CM5A-MR),

[5] Defined as the physical environmental habitat of a species (e.g., salinity and temperature), not the biogenic habitat features in which it may be found (i.e., seagrass or reef).

and the Max Planck Institute Earth System Model (MPI-ESM-MR) (see WP1 deliverable report A). Therefore the DBEM cannot integrate the outputs from GFDL CM2.6 at present.

We report projections under two time-frames of simulation that correspond to two greenhouse gas concentration scenarios. The GFDL CM2.6 outputs were driven by an idealized carbon emission scenario, with an annual increase in atmospheric CO_2 concentration until the concentration is doubled relative to pre-industrial level over a 70-year timeframe, and then CO_2 is maintained at stable levels for another 10 years (see paper A). We used the average of year 31 to 40 and year 61 to 70 of the simulation to represent the lower and higher CO_2 concentration scenarios, respectively. These time-frames correspond to an atmospheric CO_2 concentration of 400 ppm and 535 ppm, respectively. Results reported according to these time frames are herein referred to be under the low and high CO_2 concentration scenarios (RCP2.6 and RCP 8.5 respectively).

The methodology used to calculate all impact indicators were described in research paper A in this Collection. We therefore refer readers to the methodology described therein.

3 CASE STUDIES

3.1 Commonwealth of Dominica

3.1.1 Fisheries catch time series and climate change challenges

3.1.1.1 Fisheries

Dominica's fishery is predominantly artisanal in nature and diverse, targeting a wide range of demersal species along the island's steep and narrow shelf, and focusing on offshore large pelagic species (Figure 2). Fishery activities are highly seasonal. During the high season (January through June), fishers target pelagic species such as tuna, marlin, dolphinfish, and kingfish using troll lines, gillnets, as well as hand lines, while during the low season (July to December) they mainly fish for demersal species with handlines and fish pots (Anderson and Mathes, 1985). All catches are sold locally for local consumption (including by tourists), with fishers processing and selling the fish themselves (Sebastian, 2002). Reef fish species, including snappers, groupers, grunts and parrotfish are considered overexploited (Guiste and Gobert, 1996; Sebastian 2002).

Reconstructed catch efforts[6] for Dominica were extracted from the *Sea Around Us* database. These efforts are part of a global, country-by-country initiative to add comprehensive, but conservative catch estimates for all unreported fisheries components to the official landings statistics reported by FAO on behalf of countries (Zeller *et al*., 2016). For Dominica, efforts included three sectors: subsistence, artisanal, and recreational. Subsistence fishing is characterized by fishing aimed at providing food rather than generating an income, while artisanal fishing is carried out primarily to "make money", with catches usually sold on local markets (or exported). Recreational fishing typically characterizes fishing activities carried out for purposes of enjoyment rather than for consumption or sale.

[6] Catch reconstruction efforts by the Sea Around Us combine official reported data and estimates of unreported data (including major discards), with reference to individual EEZs. Official reported data are mainly extracted from the Food and Agriculture Organization of the United Nations (FAO) FishStat database. Country-level catch reconstructions are as independent from each other as possible (to avoid systematic biasing), but follow the general and well-established reconstruction principles by starting in 1950, covering all fisheries sectors that exist in a country, and including at least minimal estimates of discards for major fisheries (Zeller et al. 2016). Reconstructions provide both the reported catches as well as best estimates of unreported catches, all segregated by industrial (large-scale, commercial), artisanal (small-scale, commercial), recreational and subsistence (both small-scale, non-commercial) sectors, where applicable. Reconstructions also estimate the volume of discards from major fisheries in each country (fish caught, but discarded at sea) as part of a global discard analysis (Zeller et al. 2018).

Total reconstructed catches[7] (also referred to as total catches) amounted to approximately 96,290 tonnes for the period 1950 to 2014 (Figure 2). Unreported catches over the same time period were estimated at 42,911 tonnes (44.6% of total reconstructed catches), with average annual unreported catches amounting to 660 tonnes. The subsistence sector in Dominica represented 60% of total reconstructed catches, while artisanal catches, supplying mainly the tourist market, accounted for 35%. Reconstructed catches fluctuated between a low of 810 tonnes in 1979 and a high of 1,900 tonnes in 1967, with annual reconstructed catches averaging around 1,481 tonnes. Catches suffered severe declines in 1979 as a result of damages from Hurricane David in August of that year (Goodwin *et al*., 1985; Anon, 2000; Anon 2008). Fisheries catches of Dominica were dominated by ballyhoo (19.3% *Hemiramphus brasiliensis*), a small schooling coastal halfbeak species that is commonly used as bait to catch large offshore pelagic fish (LeGore, 2007). Catches of large migratory pelagics including 'dorado' or dolphinfish (9.6%), tunas (10.2%), and billfishes (3.9%) were important. Together, large and medium pelagics accounted for 48% of total catches. Catches of species such as snappers (8.4%), seabasses and hinds (7.5%), as well as squirrelfish (3%) were also common and, taken together, reef-associated species made up 10.2% of total catches.

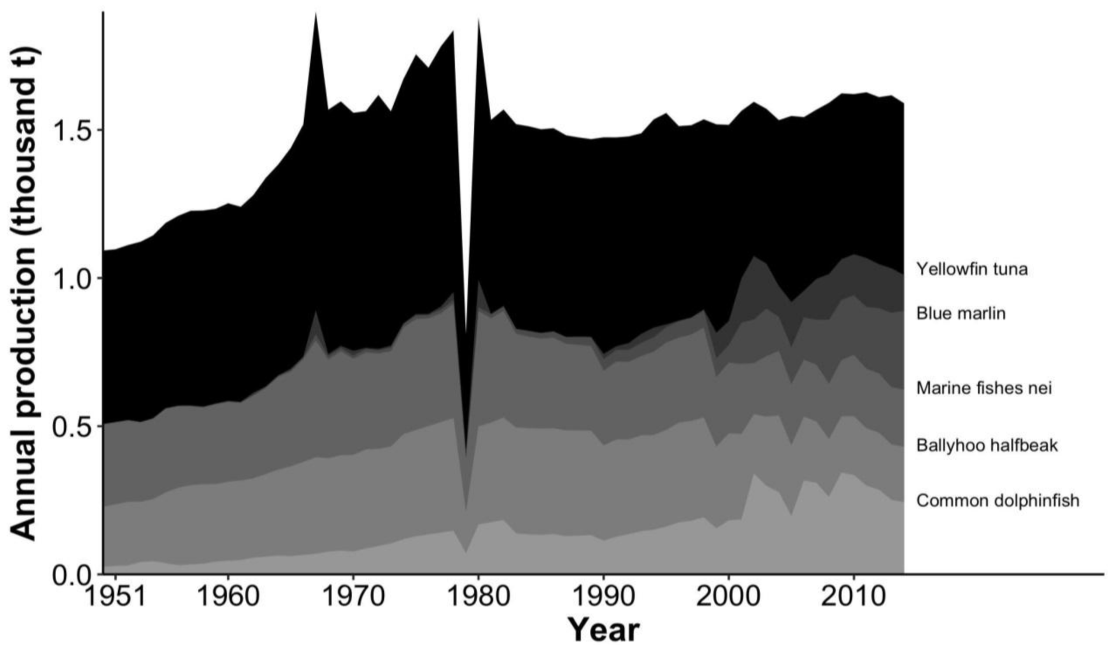


Figure 2. Reconstructed catches for Dominica's EEZ from 1950 to 2014. Total catches are plotted in black, while key species groups contributing to those catches over time are plotted in different shades of grey. Data source: Sea Around Us (www.seaaroundus.org).

3.1.1.2 <u>Climate change</u>

Dominica is particularly exposed to meteorological hazards, with climate change projected to increase the likelihood of severe weather events (Herring *et al*., 2016). Tropical Storm Erika, which struck the island of Dominica in August 2015, destroyed the majority of aquaculture centres (FAO Western Central Atlantic Fishery Commission, 2018). Sublittoral habitats were also severely impacted, affecting inshore fisheries production potential (Steiner, 2015). The passage of Hurricane Maria through the island two years later in September 2017 had a catastrophic impact on most fishing vessels, fishing gear, vendor equipment, and coastal infrastructure (e.g., ice machines, freezer storages, fuel pumps), and consequently

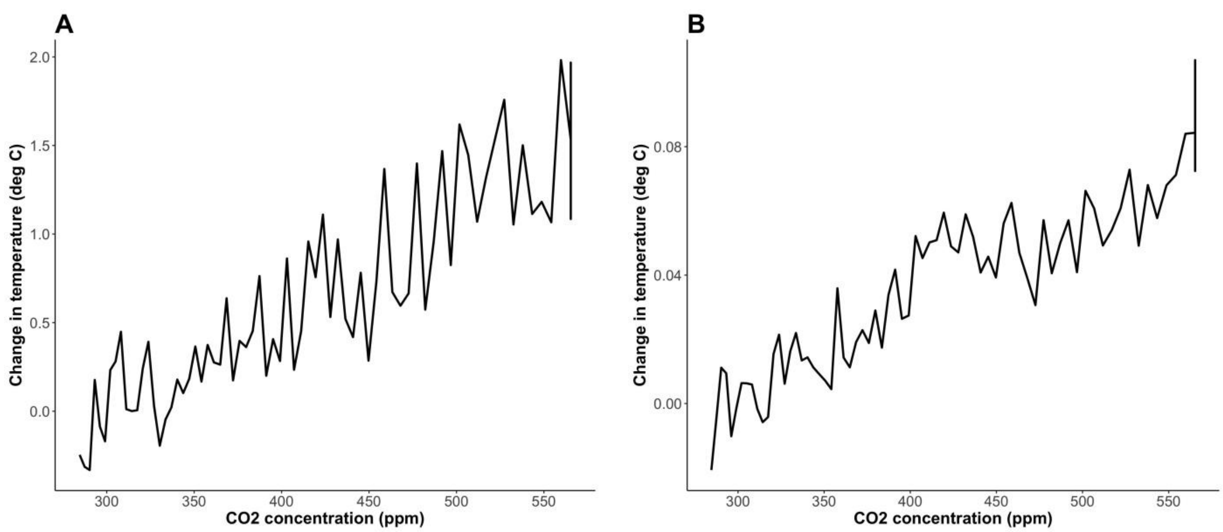
[7] Reconstruction steps and data sources for Dominica's catch reconstruction efforts are described in detail Ramdeen *et al*. (2014), and we therefore only provide a succinct updated summary of the study's findings in this report.

on fishing and fish-selling activities (FAO, 2018; Commonwealth of Dominica, 2017). It was estimated that the storm caused US$1.3 billion in total damages and losses (equivalent to 224 percent of the country's annual economic output) (The World Bank, 2017). Damages and losses to the country's fisheries sector alone were evaluated at US$3 million, affecting the basic livelihoods of approximately 2,200 fishers and others dependent on the sector with needs totalling US$3 million (Commonwealth of Dominica, 2017).

Together with tourism, Dominica relies on agriculture for its economy. However, severe damage sustained by the sector as a result of major storms has led to dramatic declines in crop production. As a result, a large number of farmers have moved into fisheries, increasing dependence on the sector for income, livelihoods and as a source of protein (Anon 2006) and increasing its vulnerability to climate change impacts. Hurricane Maria in particular decimated the agricultural sector likely exacerbating this trend.

Reconstruction of the country post hurricane Maria has led to a number of organizations and philanthropies - including the EU, the World Bank, the Clinton Foundation, Irish billionaire Denis O'Brien, and the FAO/GEF-funded CC4FISH, in line with the country's National Resilient Development Strategy - releasing funding to support efforts to reduce disaster risk and climate change adaptation across all sectors.

Increasing atmospheric CO_2 concentration was projected to increase ocean temperature and salinity in the EEZ of the Commonwealth of Dominica (Figure 3). Based on the projections from the coupled ocean-atmospheric climate model GFDL CM 2.6, sensitivity of sea surface and sea bottom temperature to atmospheric CO_2 concentration was 0.59^{o}C per 100 ppm CO_2 and 0.03^{o}C per 100 ppm CO_2, respectively. Sea surface salinity was also projected to increase at a rate of 0.134 unit per 100 ppm CO_2, but decrease at a rate of 0.002 unit per 100 ppm CO_2 at sea bottom.



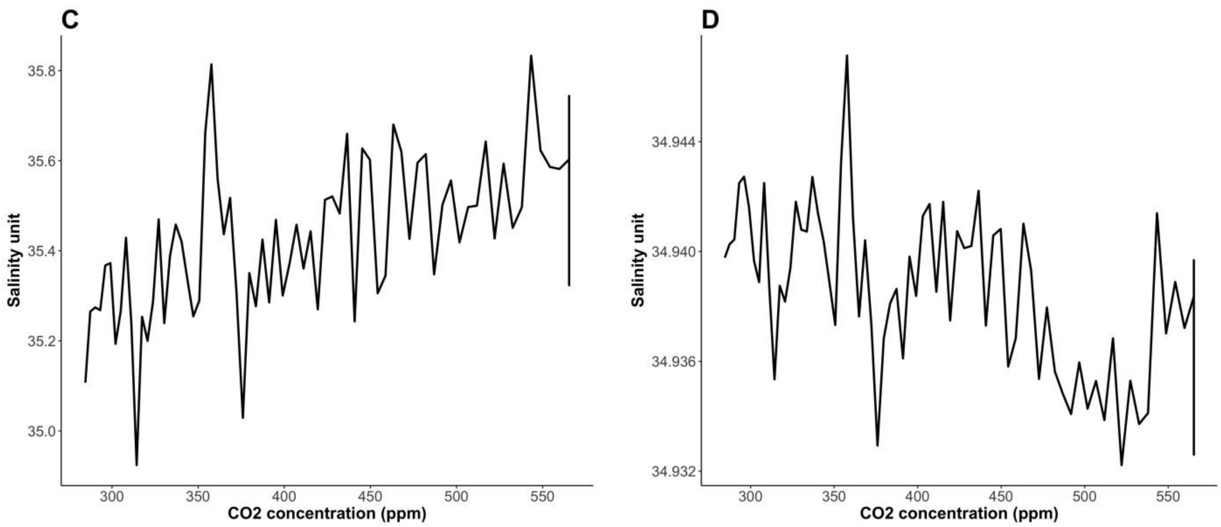


Figure 3. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (°C), (B) sea bottom temperature (°C), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels for the EEZ of Dominica.

3.1.2 Vulnerability of exploited species

Vulnerability of selected fish species occurring in the Commonwealth of Dominica was evaluated as moderate (Table 1). A total of 42 of the overall selected project species were reported to occur in the EEZ of Dominica (i.e., in the Changing Ocean Research Unit global marine biodiversity database), with a median climate vulnerability index of 56.4 (25th and 75th quartiles = 44.5 and 65.5, respectively, with 100 = maximum vulnerability). Amongst the 42 species, the ones with the highest vulnerability index were blue parrotfish (*Scarus coeruleus*, index =90), midnight parrotfish (*Scarus coelestinus*, index = 88), and hogfish (*Lachnolaimus maximus*, index = 88). Those with the lowest vulnerability index were mackerel scad (*Decapterus macarellus*, index = 24), sergeant major (*Abudefduf saxatilis*, index = 27) and balao halfbeak (*Hemiramphus balao*, index = 27).

Table 1. Vulnerability and risk of impacts of selected fish species in the Commonwealth of Dominica. Vul : vulnerabilities, Risk : risk of impact, Status-quo :current exploitation status, OverF : overfishing scenario, Sust : sustainable fishing scenario. The Ocean Health Index-Fisheries components for 2016 were used as the status quo. For the idealized sustainable fishing scenario, the OHI-fisheries index value was doubled (with a maximum value of 1) for all regions considered. For the idealized over-fishing scenario the OHI-fisheries index that was halved for all regions considered (see also paper A in this Colletion Appendix A.2 for further details). The methods for calculating vulnerability and risk of impacts are described in paper A.

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Sphyraena picudilla	*Southern sennet*	66	96	96	86	100	100	87
Caranx latus	*Horse eye jack*	88	93	95	87	93	94	87
Sparisoma viride	*Stoplight parrotfish*	71	89	92	81	91	93	86
Scarus coeruleus	*Blue parrotfish*	90	89	91	80	89	91	81
Calamus calamus	*Porgy*	53	89	91	85	94	96	87
Tetrapturus pfluegeri	*Longbill spearfish*	63	85	89	76	87	90	81
Scarus coelestinus	*Midnight*	88	86	88	76	87	89	77

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
	parrotfish							
Sparisoma aurofrenatum	*Redband parrotfish*	35	86	88	77	90	93	83
Thunnus obesus	*Bigeye tuna*	44	83	87	69	85	90	80
Thunnus atlanticus	*Blackfin tuna*	75	82	86	69	83	87	69
Tetrapturus georgii	*Roundscale spearfish*	61	82	86	70	87	90	79
Hirundichthys affinis	*Fourwing flyingfish*	64	80	85	66	85	89	71
Scarus vetula	*Queen parrotfish*	87	79	85	63	80	85	64
Sphyraena barracuda	*Great barracuda*	49	79	84	64	86	89	76
Lachnolaimus maximus	*Hogfish*	88	77	84	55	77	84	55
Acanthurus chirurgus	*Doctorfish*	59	78	84	74	80	86	78
Thunnus thynnus	*Atlantic bluefin tuna*	38	78	83	62	85	88	71
Coryphaena hippurus	*Common dolphinfish*	61	74	83	60	82	88	70
Hemiramphus balao	*Balao halfbeak*	27	82	83	65	82	83	65
Scarus taeniopterus	*Princess parrotfish*	61	82	83	75	83	85	78
Scarus iseri	*Striped parrotfish*	55	78	83	73	79	85	76
Scomberomorus regalis	*Cero*	57	76	82	60	84	88	72
Sparisoma chrysopterum	*Redtail parrotfish*	56	79	82	61	86	89	69
Pterois volitans	*Red lionfish*	46	76	82	61	84	88	72
Scomberomorus cavalla	*King mackerel*	55	73	81	55	83	87	68
Kajikia albida	*White marlin*	56	76	81	60	84	87	72
Makaira nigricans	*Blue marlin*	50	74	80	60	82	87	71
Selar crumenophthalmus	*Bigeye scad*	58	76	80	61	82	87	69
Clepticus parrae	*Creole wrasse*	46	77	80	60	86	87	72
Decapterus punctatus	*Round scad*	35	78	80	63	78	80	65
Thunnus albacares	*Yellowfin tuna*	39	72	79	55	82	86	69
Acanthocybium solandri	*Wahoo*	68	74	79	53	82	85	64
Sparisoma rubripinne	*Yellowtail parrotfish*	64	71	78	47	77	83	54
Thunnus alalunga	*Albacore tuna*	39	71	76	51	81	83	64
Katsuwonus pelamis	*Skipjack tuna*	39	70	76	51	82	83	65

Scientific name	**Common name**	**Vul**	**Risk: Status quo-2.6**	**Risk: OverF-2.6**	**Risk: Sust-2.6**	**Risk: Status quo-8.5**	**Risk: OverF-8.5**	**Risk: Sust-8.5**
Panulirus argus	*Caribbean spiny lobster*	64	63	73	48	66	75	51
Halichoeres radiatus	*Puddingwife wrasse*	66	64	72	46	66	74	48
Isostichopus badionotus	*Three rowed sea cucumber*	69	62	71	41	64	73	43
Decapterus macarellus	*Mackerel scad*	24	61	68	31	78	78	48
Abudefduf saxatilis	*Sergeant major*	27	58	66	43	60	69	44
Thalassoma bifasciatum	*Bluehead wrasse*	53	57	65	39	60	68	41
Acanthurus coeruleus	*Blue tang*	31	44	58	26	46	61	27

Risk of impacts as a result of fishing and climate change were evaluated as high to very high for the EEZ of Dominica under status quo fishing and both RCP2.6 and RCP8.5 scenarios (Table 1). Across the 42 selected species occurring in the EEZ of Dominica, the average risk of impact index were 77.5 (25th and 75th quartiles = 72.3 and 82.0, respectively) and 82.5 (25th and 75th quartiles = 79.3 and 86.0, respectively) under RCP2.6 and RCP8.5, respectively, and status quo fishing scenario (i.e., an Ocean Health Index (fisheries) value of 0.26, meaning ~ 26% of fish stocks were considered to be sustainably exploited). Under a sustainable fishing scenario (i.e., Ocean Health Index (fisheries) value that is twice the current value, meaning a high proportion of fish stocks are sustainably exploited), the risk of impact index decreased to 61.0 and 70.5 under RCP2.6 and RCP8.5, respectively. In contrast, under a scenario of increased overfishing, the risk of impact index increased to 82.5 and 97.0 under RCP 2.6 and RCP8.5, respectively.

Amongst the 42 selected species occurring in Dominica's EEZ, those with the highest risk of impact index included southern sennet (*Sphyraena picudilla*), horse eye jack (*Caranx latus*) and stoplight parrotfish (*Sparisoma viride*) (Table 1). These species registered a higher risk of impact as a result of their relatively higher vulnerability to fishing and climate change. Those with the lowest risk of impact index included Sergeant major (*Abudefdul saxatillis*), bluehead wrasse (*Thalassoma bifasciatum*) and blue tang (*Acanthurus coeruleus*).

3.1.3 Projected changes in habitat suitability

Changes in ocean conditions under increased atmospheric CO_2 concentration were projected to result in a decrease in selected species' habitat suitability - characterized by the ocean conditions used in the model (Figure 4). Overall, the sum of habitat suitability indices across selected species in the EEZ of Dominica was projected to decrease by 20.25% and 48.90%, under atmospheric CO_2 concentrations similar to the 2030-2039 and 2050-2059 periods under RCP8.5. Species that were projected to have the largest decrease in HSI include sailfish (*Istiophorus albicans*), Spanish mackerel (*Scomberomorus maculatus*) and bluefin tuna (*Thunnus thynnus*) (see data portal[8] (Webb and Stimson, *in prep*) associated with this project for maps of HSI for all individual species).

[8] http://climatesmart.fish/

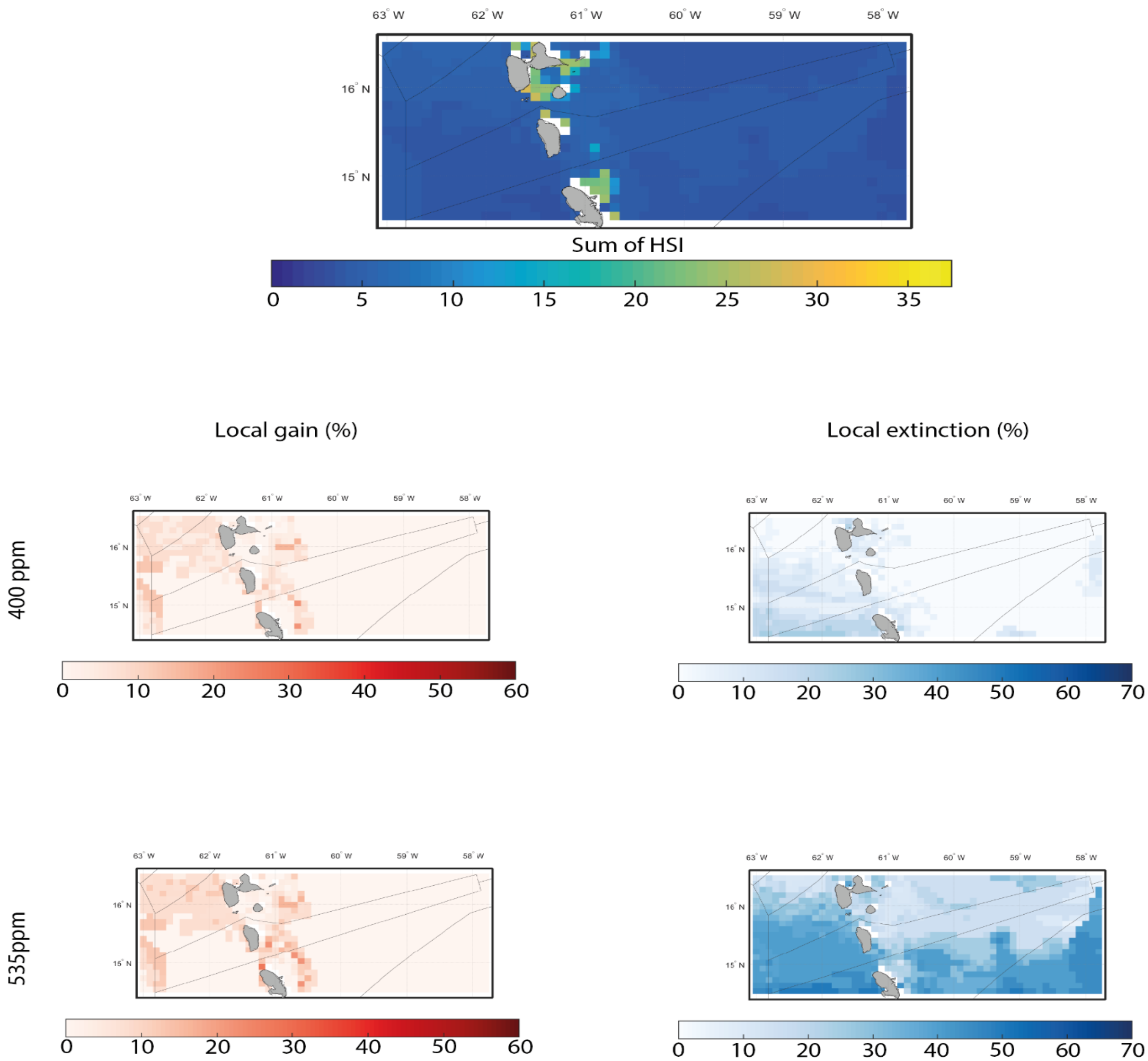


Figure 4. Current habitat suitability index and projected climate risk for marine biodiversity in the EEZ of the Commonwealth of Dominica. Sum of HSI for the current period (1970 to 2000) across the selected species (top). Climate risk represented as projected change of: percentage of species gained relative to current species richness with atmospheric CO_2 concentration of 400 ppm (upper left) and 535 ppm (lower left), and percentage of species local losses (extinction) relative to current species richness under the 400 ppm (upper right) and 535 ppm (lower right) CO_2 concentration scenarios.

3.1.4 Projected changes in fisheries catches

Maximum catch potential (MCP) – a proxy of maximum sustainable yield - was projected to decrease in the EEZ of Dominica across time periods and scenarios (Figure 5). We projected that catch potential will decline by 5% to 15% and 15% to 30% by 2030-2039 and 2050-2059 relative to the 1970-2000 period, respectively, under RCP2.6. The projected declines in MCP almost doubled for both time periods under RCP8.5.

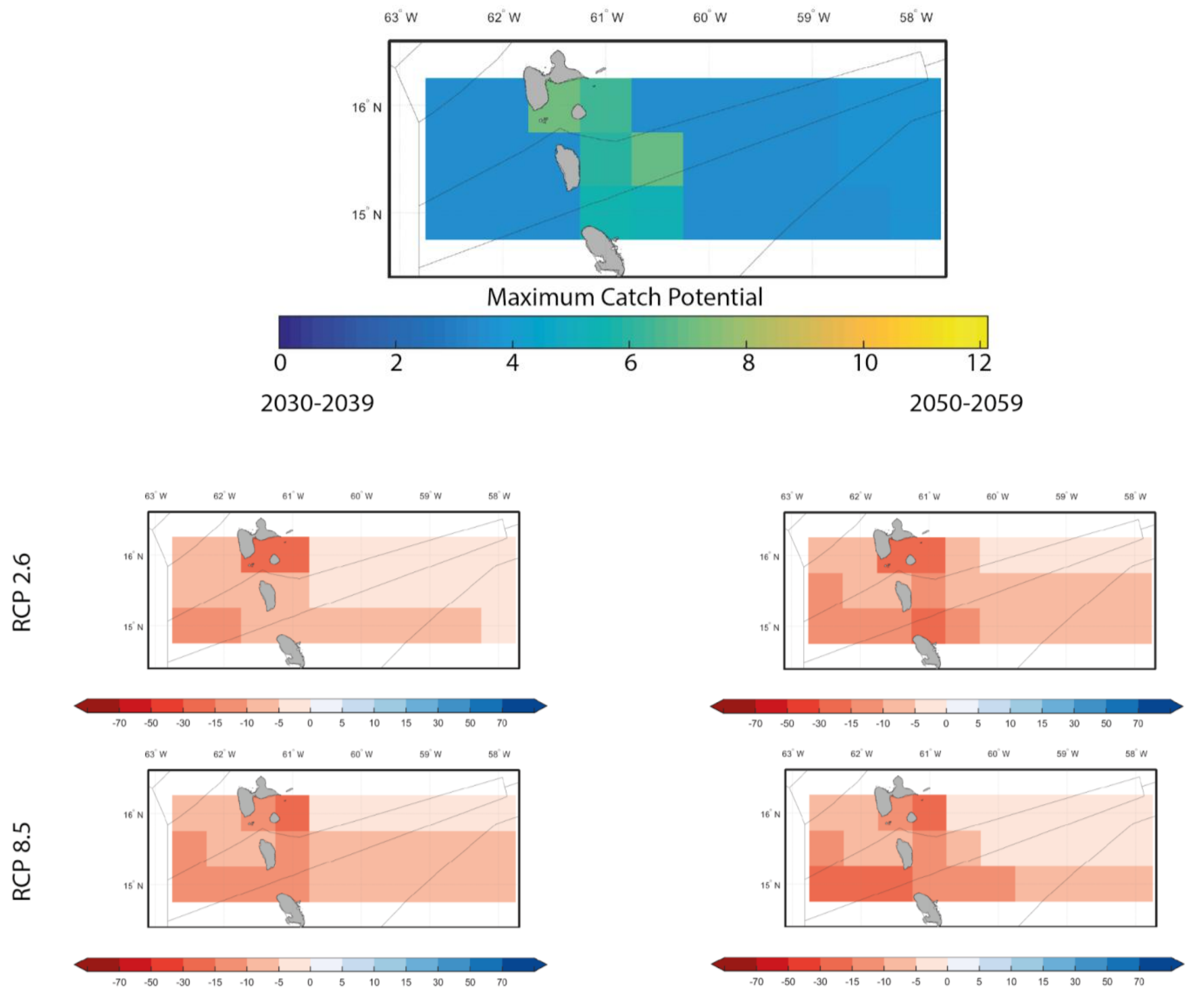


Figure 5. Projected changes in maximum catch potential using the Dynamic Bioclimate Envelope Model (DBEM) under RCP2.6 and RCP8.5 by 2030-2039 and 2050-2059 relative to 1970-2000. The results represent ensemble-average projections across outputs driven by three Earth system models (GFDL, IPSL, MPI – see paper A in this Collection): (top panel) projected distribution of current maximum catch potential, (middle row) projected distribution of maximum catch potential under RCP2.6, (bottom row) projected distribution of maximum catch potential under RCP8.5, (left) timeframe is 2030-2039 and (right) timeframe is 2050-2059.

3.1.5 <u>Synthesis of key risks</u>

Overall, key risks of climate impacts on marine species and fisheries were estimated across all species and RCPs with variations across species groups (Figure 6). Vulnerability and risk index were estimated to be generally high for all species, particularly ocean pelagics, groupers, and parrotfish because of their large-body size and high exposure to climate hazards. Ocean pelagics were also projected to have the largest decrease in habitat suitability index. However, invasion and local extinction were high across all species groups, and were higher under the high CO_2 concentration scenario. Declines in maximum catch potential were projected to be high by the 2050s under RCP8.5 across most species groups. Parrotfish and other reef fish stand out as an exception as an insufficient number of species were included in DBEM for these two groups of fishes, thus the results may not be representative for the average responses of these groups.

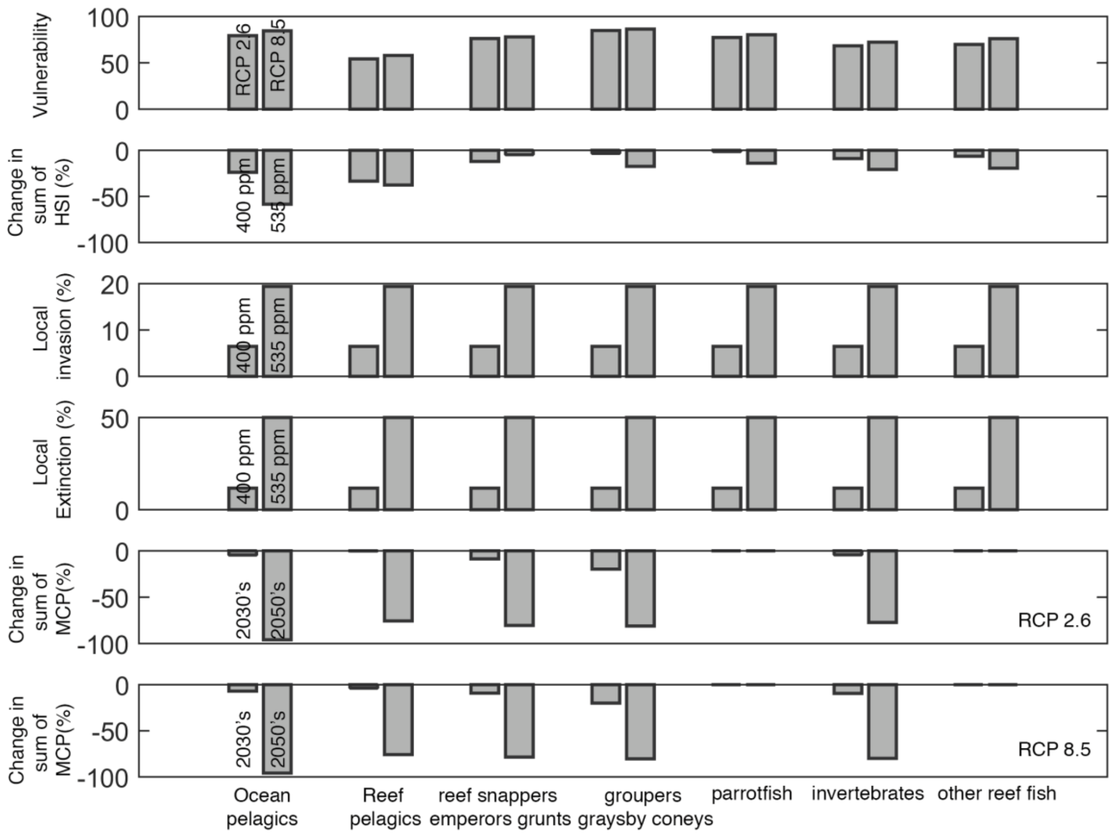


Figure 6. Projected climate risk indicators for the Commonwealth of Dominica across different groups of marine species. The climate risk indicators include vulnerability index for species' groups, change in the sum of habitat suitability index (HSI) across species groups, rate of local invasion and local extinction[9], and changes in maximum catch potential (MCP).

3.2 **Grenada**

3.2.1 Fisheries catch times series and climate change challenges

3.2.1.1 Fisheries

Grenada has a long history of fisheries development. Fishing offshore for large pelagics and inshore for small pelagics and demersal species using beach seines and handlines, respectively, was common as early as the 1940s (Brown, 1945). At that time, Brown (1945) already pointed to signs of depletion of inshore stocks. Over time, a number of initiatives, through technical assistance programs and government investments in and subsidization of the sector, have focused on promoting the development of Grenada's offshore fisheries (including longlines). The legalization of foreign fishing within Grenada EEZ waters in the 1980s further contributed to the fishing for large pelagics such as tuna and billfishes (Samalsingh *et al*., 1999). A large proportion of catches are sold at local markets, or directly to restaurants and hotels. Much of the catch made up of large pelagics is sold to processing plants and a portion of both demersal and pelagic species' landings is exported.

[9] % invasion represents the % of new species per pixel compared to baseline for a given species group, averaged across all pixels in the EEZ. The same in reverse applies for extinction.

Total reconstructed catches[10] amounted to 128,038 tonnes from 1950 to 2014 (Figure 7), registering peaks and troughs through the years, with an overall increasing trend through time. Reconstructed catches fluctuated between a low of 894 tonnes in 1951 and a high of 3,509 tonnes in 2011, with annual reconstructed catches averaging around 1,970 tonnes. Over the entire time period, the artisanal sector was the most important (71.4% of total reconstructed catches), followed by subsistence (20.1%), and industrial fisheries (8.5% - active only since the 1990s). However, while artisanal and industrial fisheries grew over time, the subsistence sector declined. Recreational fisheries accounted for less than 0.1% of total reconstructed catches. Unreported catches for the period 1950-2014 were estimated at 42,869 tonnes (33% of total reconstructed catches), with average annual unreported catches amounting to 660 tonnes, and highest unreported catches registered for 2011. Declines in harvests between 1980 and 1983 can be attributed to a decline in capitalization in the fisheries sector, a lack of maintenance of on-shore refrigeration facilities, an aging fleet, as well as a reduction in skilled labour associated with the artisanal fleet (Finlay 1990; 1991). The latter happened as a result of skilled fishers transferring to semi-industrial vessels; however, as the boats never operated very successfully, a substantial reduction in fishing days occurred (Finlay, 1991). Moreover, political events at the time had a negative impact on tourism, an important fish consumption segment of the population (Mohammed and Lindop, 2015).

Small-scale fisheries that deploy multiple gear types were by far the most common sub-sector throughout Grenada (93.5%), followed by longliners (4.2%). Fisheries catches of Grenada were dominated by bigeye scad (12.5% *Selar crumenophthalmus*), an oceanic species that is commonly targeted both for human consumption and bait to catch large offshore pelagic fish. Catches of large migratory pelagics such yellowfin tuna (11.9% - *Thunnus albacares*, only appearing in the second half of the time period), blackfin tuna (6.2% *Thunnus atlanticus*), billfishes (6.2%) and dolphinfish (4.8% *Coryhaena hippurus*) were important. Together, large and medium pelagics accounted for 48% of total catches. Catches of reef-associated species such as seabasses, groupers and hinds (11.4%), snappers (5.9%), as well as Caribbean spiny lobster (1.6% *Panulirus argus*) were also common and taken together, reef-associated species made up 28.7% of total catches. Through time, while the contribution of the offshore sector to total catches increased, particularly from 2008 onwards, catches in the inshore fishery registered an initial decline, followed by stabilization.

The CITES conference of the parties and Standing Committee currently has a recommendation to suspend trade in conch from Grenada – valid since 2006 (CITES, 2019).

[10] Details regarding method and data sources for the catch reconstruction effort for Grenada are detailed in Mohammed and Lindop (2015) and follow the approach outlined in section 3.1.1 above. Note that while the original study by Mohammed & Lindop did not include discards, the updated Sea Around Us dataset does, accounting for 0.23% of total catches.

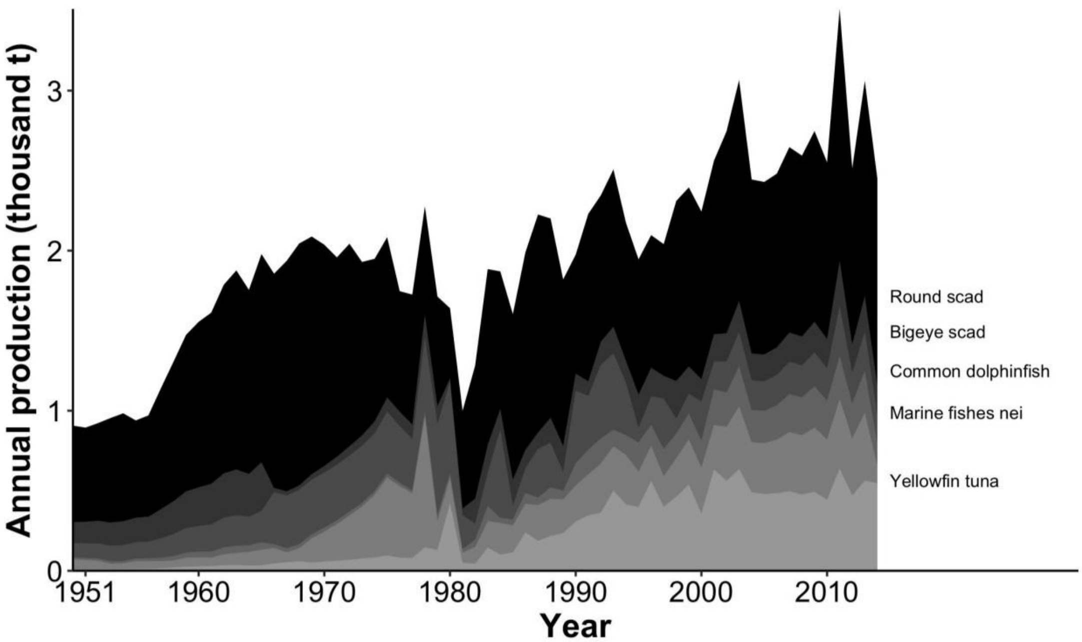


Figure 7. Reconstructed catches for the EEZ of Grenada from 1950-2014. Total catches are plotted in black, while key species groups contributing to those catches over time are plotted in different shades of grey. Data source: Sea Around Us (www.seaaroundus.org) (nei = not elsewhere included).

3.2.1.2 Climate change

Climate change has benefitted from public and political attention in Grenada. Over the last decade a number of initiatives have made progress in developing and supporting the implementation of climate change adaptation programs and their integration into national plans for sustainable development.

As is the case for a number of Small Island Developing States in the region, Grenada has been severely impacted by extreme weather events over the past several decades and stands to be at risk given future hurricane projections, particularly as most of the human infrastructure, transportation, trade as well as tourism facilities are located along the coastal zone. Hurricane Ivan in 2004 caused damage totalling approximately US$900 million and equivalent to 2.5 times the country's annual Gross Domestic Product, also devastating natural systems on and around the island (Peters, 2010). One of the main future climate challenges for Grenada (and other island states throughout the region) will be to strike the right balance between the continued development of coastal areas for commercial purposes, while at the same time ensuring the conservation of coastal ecosystems for the suite of ecosystem services they provide. The current health and integrity of coastal ecosystems have been severely compromised through mangrove clearance, overfishing and pollution for example, to allow for economic development (UNDESA, 2012). Effective management of these resources in the future is of critical importance for both continued economic development and to support the food security and safety of local communities. Over time Carriacou has been an important exporter of reef fish, supplying over 45,360 kg annually in parrotfish to Martinique (UNDESA, 2012). Parrotfish are important reef grazers and sand producers, both critical roles to maintain ecological function of reef systems (Mumby, 2009; Cramer *et al*., 2017). Therefore, sustainable management of grazer species can enhance ecosystem resilience (Mumby *et al*., 2014, Bozec *et al*., 2016), which can be further enhanced by the curtailing of illegal fishing methods (UNDESA, 2012). Grenada's (and the Grenada Bank) reef system is considered to host the most extensive coral reefs and related habitats in the South-eastern Caribbean. For the Windward Islands – which encompass Grenada-, larvae export was found to be greater than larvae imports (Kough *et al*., 2013), therefore likely playing an important role in supplying other areas with larval coral and fish. Thus, effective adaptation and sustainable use of resources on Grenada will be of key importance for ecosystems' health throughout an important part of the region.

Increasing atmospheric CO_2 concentration was projected to increase ocean temperature and salinity in the EEZ of Grenada (Figure 8). Based on the projections from the coupled ocean-atmospheric climate model GFDL CM 2.6, sensitivity of sea surface and sea bottom temperature to atmospheric CO_2 concentration was 0.64 ^{o}C per 100 ppm CO_2 and 0.37 ^{o}C per 100 ppm CO_2, respectively. Both sea surface and sea bottom salinity were also projected to increase, at rates of 0.120 unit per 100 ppm CO_2 and 0.044 unit per 100 ppm CO_2, although the projected sensitivity for sea bottom salinity was low.

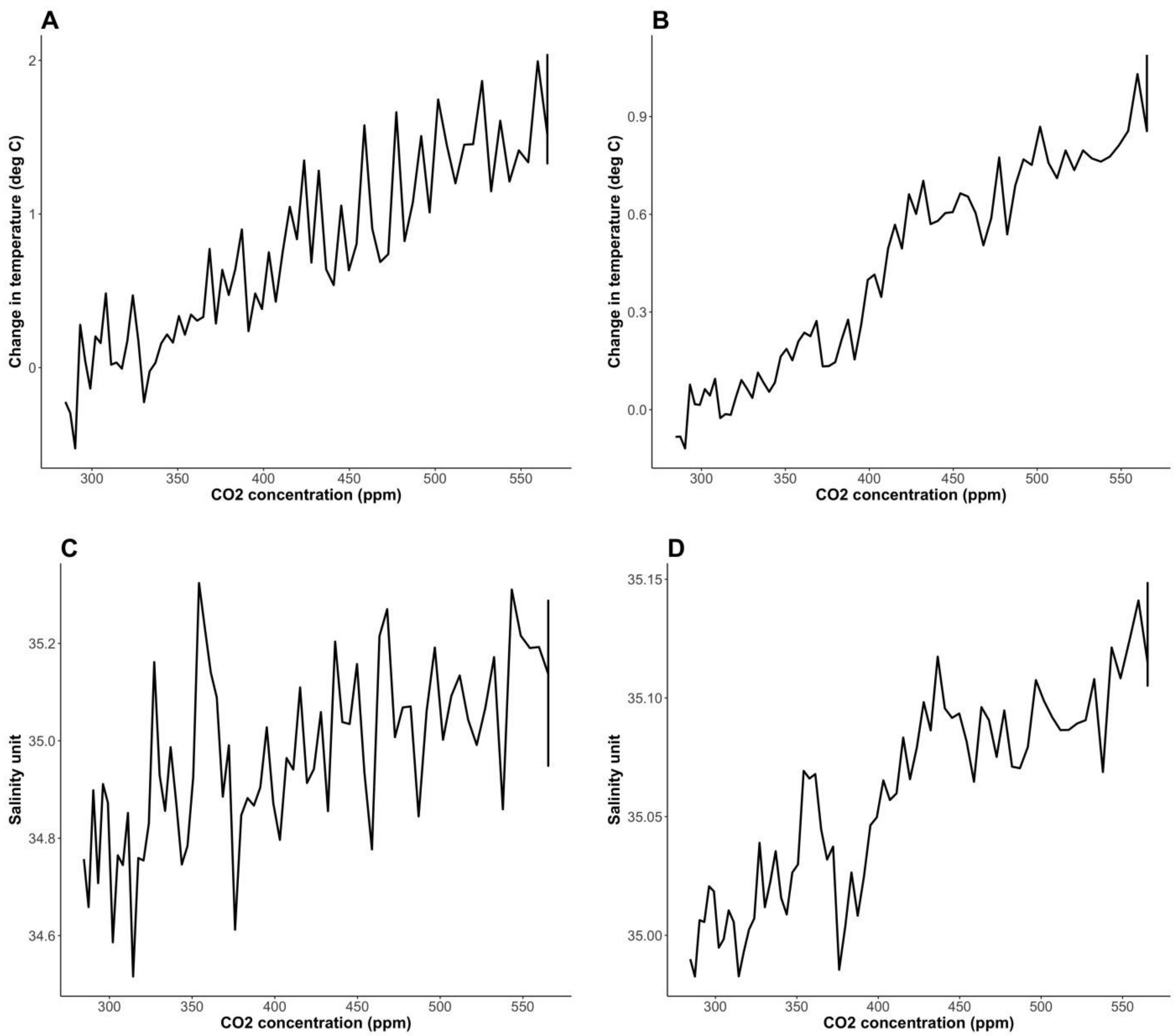


Figure 8. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (^{o}C), (B) sea bottom temperature (^{o}C), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels for the EEZ of Grenada

3.2.2 Vulnerability of exploited species

Vulnerability of selected species occurring in Grenada was evaluated as moderate (Table 2). A total of 66 of the selected study species were reported to occur in the EEZ of Grenada (i.e., in the Changing Ocean Research Unit global marine biodiversity database), with a median climate vulnerability index of 55.0 (25th and 75th quartiles = 42.3 and 64.0, respectively, with 100 = maximum vulnerability). Amongst the

66 species, blue parrotfish (*Scarus coeruleus*, index =90), midnight parrotfish (*Scarus coelestinus*, index = 88), and hogfish (*Lachnolaimus maximus*, index = 88) scored the highest vulnerability index. Mackerel scad (*Decapterus macarellus*, index = 24), sergeant major (*Abudefduf saxatilis*, index = 27) and blue tang (*Acanthurus coeruleus*, index = 31) on the other hand had the lowest vulnerability indices.

Table 2. Vulnerability and risk of impacts of selected species for Grenada. Vul : vulnerabilities, Risk : risk of impact, Status-quo : current exploitation status, OverF : overfishing scenario, Sust : sustainable fishing scenario.

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Ocyurus chrysurus	Yellowtail snapper	80	89	95	81	90	98	86
Epinephelus guttatus	Red hind	81	89	95	82	90	97	85
Caranx latus	Horse eye jack	88	89	93	80	89	93	80
Acanthurus bahianus	Ocean surgeon	46	87	91	76	90	96	83
Calamus calamus	Porgy	53	87	90	77	91	95	83
Sparisoma viride	Stoplight parrotfish	71	84	90	70	88	92	76
Epinephelus adscensionis	Rock hind	54	84	89	67	87	92	79
Scarus coeruleus	Blue parrotfish	90	83	89	65	82	89	65
Tetrapturus pfluegeri	Longbill spearfish	63	79	87	62	84	89	69
Mulloidichthys martinicus	Yellow goatfish	29	75	87	57	84	91	69
Sparisoma aurofrenatum	Redband parrotfish	35	81	87	65	87	91	76
Thunnus obesus	Bigeye tuna	44	76	86	56	83	88	67
Scarus coelestinus	Midnight parrotfish	88	78	86	64	78	86	64
Tetrapturus georgii	Roundscale spearfish	61	76	86	64	82	90	69
Thunnus thynnus	Atlantic bluefin tuna	38	78	85	62	83	88	66
Thunnus atlanticus	Blackfin tuna	75	76	85	60	76	85	61
Haemulon sciurus	Bluestriped grunt	34	79	85	57	85	88	72
Lutjanus mahogoni	Mahagony snapper	73	82	84	65	81	84	65
Hirundichthys affinis	Fourwing flyingfish	64	71	83	59	76	87	64
Scarus taeniopterus	Princess parrotfish	61	79	83	66	80	83	67
Coryphaena hippurus	Common dolphinfish	61	69	81	54	79	87	64
Acanthurus chirurgus	Doctorfish	59	77	81	62	78	81	63

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Caranx crysos	Blue runner	46	66	80	45	77	86	60
Pseudupeneus maculatus	Spotted goatfish	19	65	80	36	77	81	55
Lachnolaimus maximus	Hogfish	88	65	80	50	65	80	50
Sparisoma chrysopterum	Redtail parrotfish	56	70	80	56	78	88	62
Scarus vetula	Queen parrotfish	87	69	80	54	69	80	54
Haemulon plumierii	White grunt	43	66	80	48	77	86	61
Scarus iseri	Striped parrotfish	55	75	80	60	76	80	61
Hemiramphus brasiliensis	Ballyhoo halfbeak	45	64	79	52	73	86	59
Scomberomorus regalis	Cero	57	68	79	51	79	87	63
Kajikia albida	White marlin	56	68	79	52	78	86	62
Makaira nigricans	Blue marlin	50	65	78	51	74	84	59
Scomberomorus cavalla	King mackerel	55	65	78	48	77	86	59
Haemulon chrysargyreum	Smallmouth grunt	55	66	78	49	65	78	49
Clepticus parrae	Creole wrasse	46	68	78	53	79	86	61
Decapterus punctatus	Round scad	35	69	78	55	71	78	55
Thunnus alalunga	Albacore tuna	39	69	77	47	77	82	54
Sphyraena barracuda	Great barracuda	49	64	77	44	76	84	59
Selar crumenophthalmus	Bigeye scad	58	63	77	45	72	84	53
Elagatis bipinnulata	Rainbow runner	72	58	77	43	68	83	51
Epinephelus striatus	Nassau grouper	77	65	77	49	68	80	54
Thunnus albacares	Yellowfin tuna	39	63	76	46	75	84	58
Cephalopholis fulva	Coney	58	59	76	43	73	85	55
Acanthocybium solandri	Wahoo	68	62	76	45	72	83	52
Katsuwonus pelamis	Skipjack tuna	39	62	74	41	75	83	53
Haemulon carbonarium	Caesar grunt	63	59	74	37	58	74	37
Sparisoma	Yellowtail	64	57	74	42	65	80	48

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
rubripinne	parrotfish							
Pterois volitans	Red lionfish	46	62	74	46	71	82	55
Haemulon flavolineatum	French grunt	36	60	73	50	73	87	61
Sargocentron vexillarium	Dusky squirrelfish	54	58	73	34	58	73	35
Holocentrus rufus	Longspine squirrelfish	42	52	70	32	67	82	45
Balistes vetula	Queen triggerfish	59	54	68	34	54	68	34
Holocentrus adscensionis	Squirrelfish	57	44	68	38	57	78	45
Sargocentron coruscum	Reef squirrelfish	66	55	68	36	54	67	37
Panulirus argus	Caribbean spiny lobster	64	55	67	40	56	68	41
Halichoeres radiatus	Puddingwife wrasse	66	54	66	38	56	67	39
Decapterus macarellus	Mackerel scad	24	43	64	20	60	78	33
Myripristis jacobus	Blackbar soldierfish	36	39	64	29	56	79	42
Isostichopus badionotus	Three rowed sea cucumber	69	49	64	34	50	65	35
Abudefduf saxatilis	Sergeant major	27	52	62	36	54	64	38
Haemulon aurolineatum	Tomtate	31	45	61	28	61	78	42
Thalassoma bifasciatum	Bluehead wrasse	53	48	60	32	50	60	34
Astichopus multifidus	Furry sea cucumber	54	43	57	30	43	57	30
Cephalopholis cruentata	Graysby	34	41	55	23	41	55	25
Acanthurus coeruleus	Blue tang	31	35	51	20	37	52	22

Risk of impacts as a result of fishing and climate change were evaluated as moderate to high in the EEZ of Grenada under status quo fishing and both RCP2.6 and RCP8.5 scenarios (Table 2). Across the 66 selected species occurring in the EEZ of Grenada, the median risk of impact index was 65.5 (25th and 75th quartiles = 58.0 and 76.0, respectively) and 75.5 (25th and 75th quartiles = 65.0 and 79.8, respectively) under RCP2.6 and RCP8.5, respectively, and status quo fishing scenario (i.e., an Ocean Health Index (fisheries) value of 0.43; meaning ~ 43% of fish stocks were considered to be sustainably exploited) [see paper A in this Collection]. Under a sustainable fishing scenario (i.e., the Ocean Health Index (fisheries) value is estimated at twice the current value, meaning a high proportion of fish stocks are sustainably exploited), the risk of impact index decreased to 49.5 and 59.0 under RCP2.6 and RCP8.5, respectively. In contrast, under a scenario of further overfishing, the risk of impact index increased to 78.0 and 84.0 respectively under RCP 2.6 and RCP8.5.

Amongst the 66 selected species, those with the highest risk of impact index included yellowtail snapper (*Ocyurus crysurus*), red hind (*Epinephelus guttatus*) and horse eye jack (*Caranx latus*) (Table 2). Those with the lowest risk of impact index included furry sea cucumber (*Astichopus multifidus*), graysby (*Cephalopolis cruentata*) and blue tang (*Acanthurus coeruleus*).

3.2.3 Projected changes in habitat suitability

Changes in ocean conditions under increased atmospheric CO_2 concentrations were projected to result in a decline in habitat suitability for selected species in the EEZ of Grenada (Figure 9). Overall, the sum of habitat suitability index across the selected species in the EEZ of Grenada was projected to decrease by 11.3% and 28%, under atmospheric CO_2 concentrations that would be similar to the 2030-2039 and 2050-2059 periods under RCP8.5. Species that were projected to have the largest decline in HSI included donkey dung sea cucumber (*Holothuria (Halodeima) mexicana*), Atlantic thread herring (*Opisthonema oglinum*) and tomtate grunt (*Haemulon aurolineatum*) (see online data portal associated with this project[11] for maps of HSI for all individual species).

[11] http://climatesmart.fish/

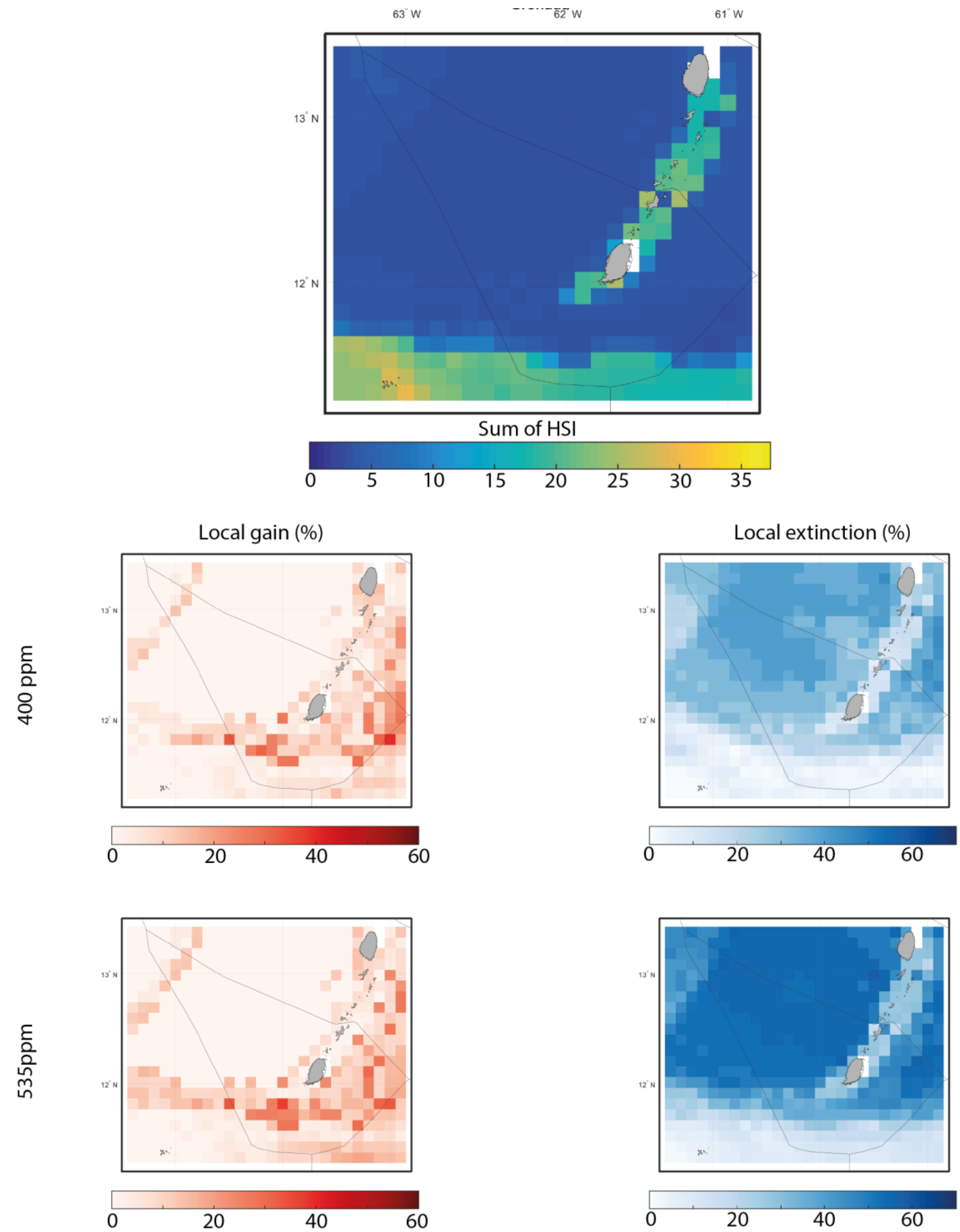


Figure 9. Current habitat suitability index and projected climate risk for marine biodiversity in the EEZ of Grenada. Sum of HSI for the current period (1970 to 2000) across the selected species (top). Climate risk represented as projected change of: percentage of species gained relative to current species richness with atmospheric CO_2 concentration of 400 ppm (upper left) and 535 ppm (lower left), and percentage of species local losses (extinction) relative to current species richness under the 400 ppm (upper right) and 535 ppm (lower right) CO_2 concentration scenarios.

A substantial proportion of Grenada's EEZ was projected to have a high rate of local species gain and loss (Figure 9). The southern and eastern parts of the EEZ were projected to have particularly high rates of local species gains with some areas gaining as much as 50% or more of new species relative to current species richness. In contrast, local extinction rates were projected to be high (>50% relative to current species richness) in the offshore north-western part of the EEZ, partly because of the relatively low current species richness estimated for those areas.

3.2.4 Projected changes in fisheries catches

Maximum catch potential (MCP) was projected to decline in the EEZ of Grenada across time periods and scenarios (Figure 10). We projected that catch potential will decline by 5% to 15% and 15% to 30% by 2030-2039 and 2050-2059 relative to the 1970-2000 period, respectively, under RCP2.6. The projected declines in MCP almost doubled for both time frames under RCP8.5.

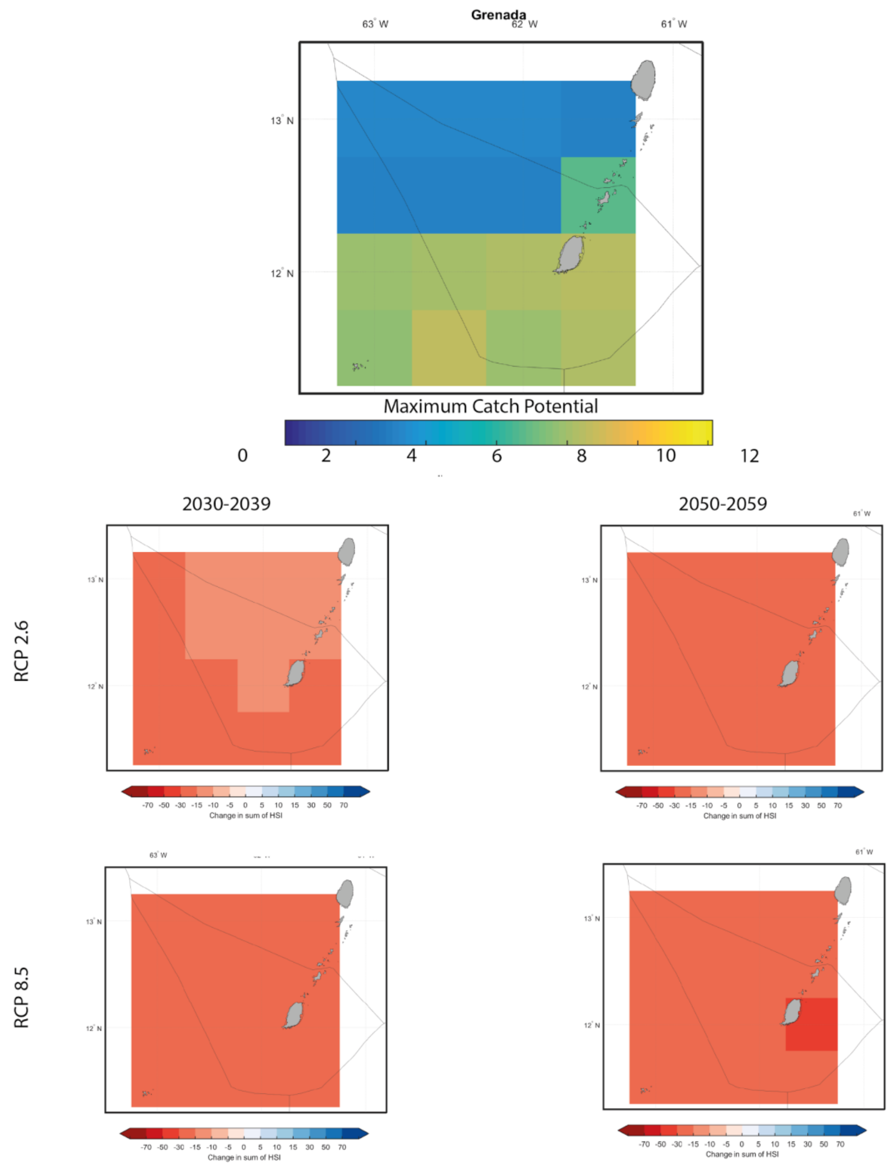


Figure 10. Projected changes in maximum catch potential using the Dynamic Bioclimate Envelope Model (DBEM) under RCP2.6 and RCP8.5 by 2030-2039 and 2050-2059 relative to 1970-2000. The results represent ensemble-average projections across outputs driven by three Earth system models (GFDL, IPSL, MPI - see paper A in this Collection): (top panel) projected distribution of current maximum catch potential, (middle row) projected distribution of maximum catch potential under RCP2.6, (bottom row) projected distribution of maximum catch potential under RCP8.5, (left) timeframe is 2030-2039 and (right) timeframe is 2050-2059.

3.2.5 Synthesis of key risks

Overall, key risks of climate impacts on marine species and fisheries were estimated across all species and RCPs with variations among species groups (Figure 11). Vulnerability and risk index were estimated to be generally high for all species, particularly ocean pelagics, groupers and parrotfish. These three species groups were also projected to have the largest decline in habitat suitability index. However, average invasion and local extinction rates were high across all species groups. Declines in maximum catch potential were projected to be high by the 2050s under RCP8.5 across most species groups. Parrotfish and other reef fish stand out as an exception as an insufficient number of species were included in DBEM for these two groups of fishes, thus the results may not be representative for the average responses of these groups.

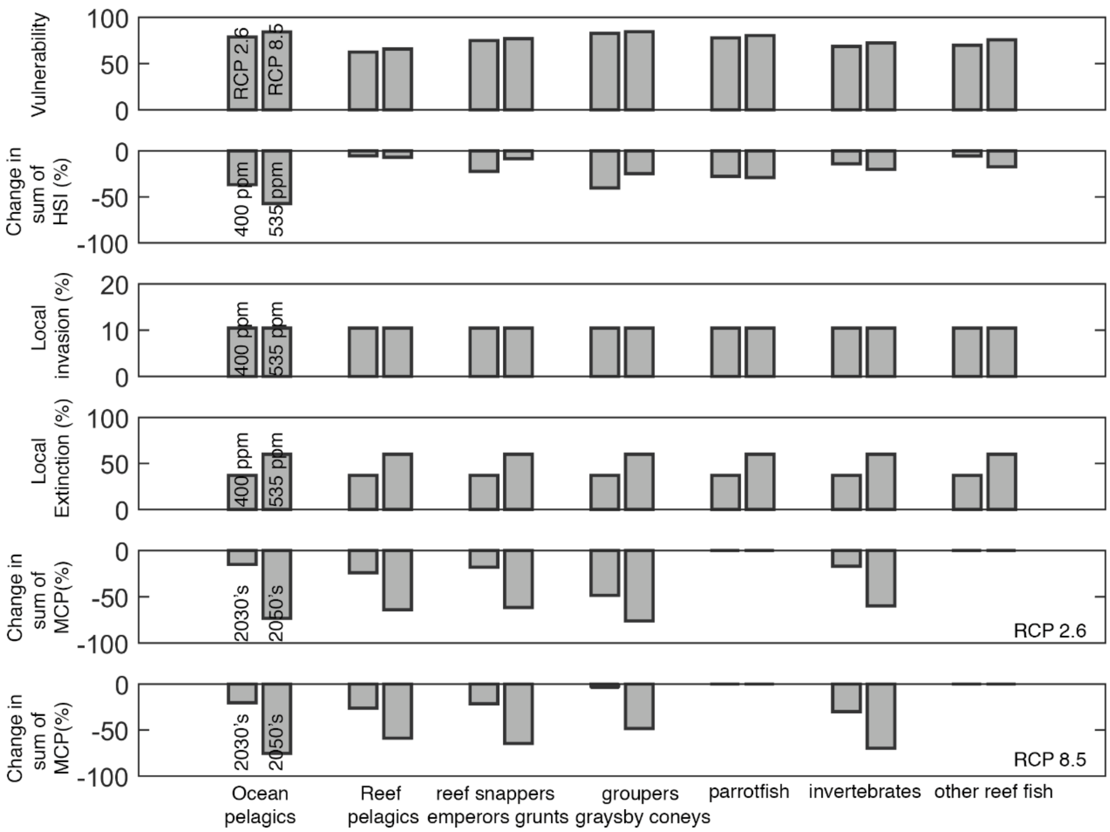


Figure 11. Projected climate risk indicators for Grenada across different groups of marine species. The climate risk indicators include vulnerability index for the species' groups, change in the sum of habitat suitability index (HSI) across species groups, rate of local invasion and local extinction, and changes in maximum catch potential (MCP).

3.3 **Haiti**

3.3.1 Fisheries Catch Time Series and Climate Change Challenges

3.3.1.1 Fisheries

Haiti's fisheries focus mainly on demersal (reef) fish species and a limited quantity of pelagic fish. Fishing takes place just off the continental shelf as well as offshore, particularly during the migratory season (Romain, 2005) using a wide range of different gear types: traps, nets (gill nets, trammel nets, cast nets), spearguns, beach seines and hook and line (pelagic and demersal longlines). As the continental shelf around the island is narrow and easily accessible to fishers, most coastal and demersal stocks have been and remain heavily over-exploited (Mulliken, 1996; Theile, 2001; JICA, 2011). Coastal resources in general are considered in poor condition as a result of overfishing, poorly enforced regulations (Wood, 2010), as well as pollution and severe land erosion resulting from poor land use practices, including deforestation. In 2011, ReefCheck estimated that 85% of coral on the island's reefs was dead (McDonald, 2011). In contrast, technological limitations have thus far maintained low levels of exploitation of offshore pelagic and deep-water demersal fishes (Mateo and Haughton, 2003). Coastal communities are also known to target shrimp, fish and shellfish in coastal mangrove forests (Aube and Caron, 2001).

The fishing sector is primarily artisanal in nature with most catches marketed for local sale and personal consumption (FAO, 1981), except for conch, spiny lobster, octopus and crabs, which are also exported. Haiti has been an important exporter of conch meat and shells, with poor monitoring of activities (Theile, 2001), resulting in the suspension of imports from the United States since 2003 in accordance with CITES recommendations to suspend trade in conch based on the country's failure to implement recommendations under the Review of Significant Trade (CITES, 2012; 2019). The number of total fishers is estimated at more than 50,000 (JICA, 2011), a number that is continuously rising due to human population growth, high levels of poverty and local unemployment conditions (Zacks, 1998). Indeed, Ramdeen *et al*. (2012) found the population of fishers to have increased by a factor of 2.5 from 1990 to 2000, while CPUE registered a 60% decline from 1976 to 2005.

Total reconstructed catches[12] amounted to 990,602 tonnes from 1950 to 2014, registering an increasing trend over time, particularly from 2000 onwards with a slight stabilization in catches between 2010 and 2014 (Figure 12). Thus, catches were lowest in 1950 (6,565 tonnes) and highest in 2008 (26,047 tonnes), with an average of 15,240 tonnes per year. Over the entire time period, the artisanal sector was most important (56.7%), followed by subsistence (38.8%) and industrial fisheries (4.5%). This trend was reflected in both total catches as well as landed value. While the industrial sector remained fairly constant over time, artisanal fisheries registered an important expansion in 1990, with the subsistence sector increasing linearly through time. Discards were estimated to be very low, while unreported catches were extremely high accounting for 0.3% and 57.2% of total reconstructed catches, respectively.

Small-scale fisheries was by far the most common sub-sector in Haiti (97.2%). These fisheries consist of fishers operating from small un-mechanized wooden boats (Zacks, 1998), canoes and pirogues. Mixed fish featured most prominently in catches, followed by wrasses (18.9% Labridae) and spiny lobster (8.4% *Panulirus argus*). Taken together, reef-associated fishes and invertebrates made up 53.1% of total reconstructed catches, with pelagic species only accounting for 13.1%. The dominant species in the latter group included bigeye scad (*Selar crumenophthalmus* 3.9%), dolphinfish (*Coryphaena hippurus* 1.4%), and blue marlin (*Makaira nigricans* 1.4%). Shrimps and prawns accounted for 5.3% of total catches through time, registering an increase in catches in 2004 (for a total of 1,904 tonnes) followed by a sharp decline (110 tonnes, the lowest in the time series).

[12] Details regarding method and data sources for the catch reconstruction effort for Haiti are detailed in Ramdeen et al. (2012) and follow the approach outlined in Section 3.1.1. above.

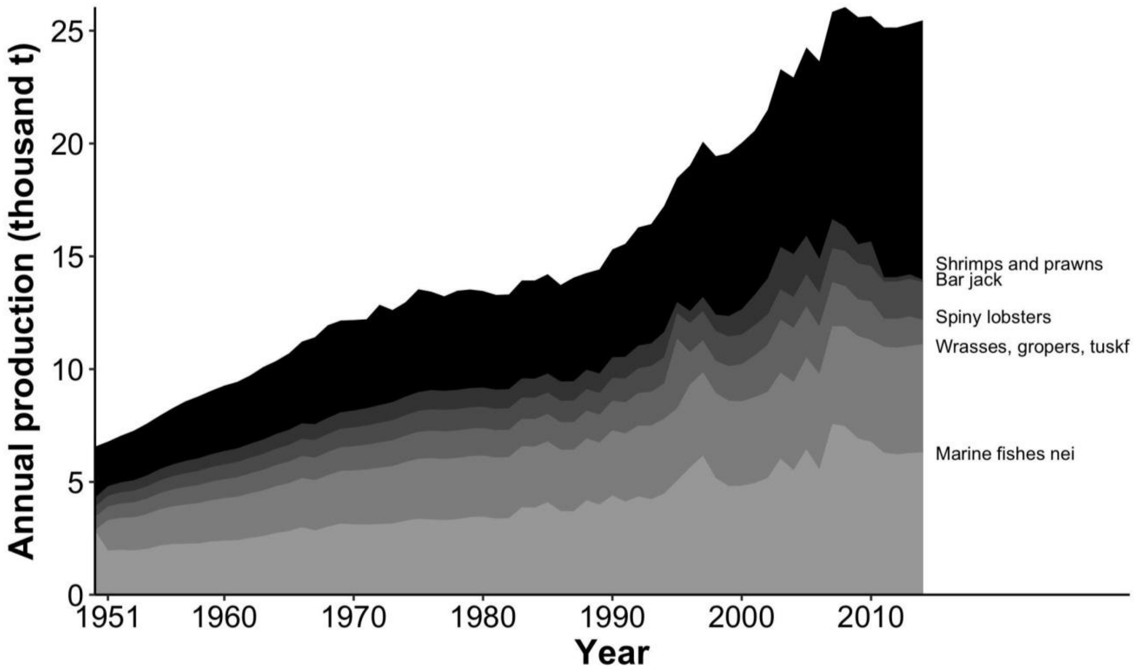


Figure 12. Reconstructed catches from the EEZ of Haiti from 1950 to 2014. Total catches are plotted in black, while key species groups contributing to those catches over time are plotted in different shades of grey. Data source: Sea Around Us (www.seaaroundus.org).

3.3.1.2 *Climate change*

Haiti is considered one of the countries most exposed to environmental hazards, including floods, droughts, hurricanes, earthquakes, and landslides. Combined with Haiti's high sensitivity and particularly low adaptive capacity (in part the result of political turmoil for the last few decades) this makes it one of the most vulnerable countries in the world to climate change (Maplecroft, 2012; Blasiak *et al*., 2017). Indeed, Haiti's vulnerability to climate change is mostly determined by its poor socio-economic status, weak governance structure and capacity and finance challenges that interact with, and exacerbate, the projected biophysical impacts of climate change (Singh and Cohen, 2014). The degraded status of marine resources further significantly undermines the ability of marine ecosystems to recover from present and future environmental hazards. Based on available historic data, weather-related disasters are estimated to have caused damage and losses in Haiti equivalent to an estimated two percent of GDP on average per year from 1975 to 2012 (The WorldBank 2017a). In 2008 alone, over the course of 30 days, four hurricanes – Ike, Fay, Hanna and Gustav – struck Haiti, destroying more than 60% of agricultural crops, with total damages to the island estimated at 15% of GDP (The Worldbank 2017a). Hurricane Matthew, which struck Haiti in 2016, cost the island $US1.9 billion in damages (Wikipedia, 2018), and left 12.9% of Haiti's population in need of humanitarian assistance (OCHA, 2016), making it the worst disaster to affect the country since the 2010 earthquake.

One of the main challenges facing Haiti in adapting to projected changes includes the extremely high levels of poverty combined with severely limited resource and capacity at all levels, essentially making the development, implementation and enforcement of effective measures to ensure the sustainable management of marine resources exceptionally difficult. The same applies to disaster preparedness and early warning systems, where despite significant bilateral and multilateral investments in the country over the last decade, persistent poverty, chronic health deficiencies, political instability and high unemployment have generally undermined development efforts (Herard, 2011).

Increasing atmospheric CO_2 concentration was projected to increase ocean temperature and salinity in the EEZ of Haiti (Figure 13). Based on the projections from the coupled ocean-atmospheric climate model GFDL CM 2.6, sensitivity of sea surface and sea bottom temperature to atmospheric CO_2 concentration in the EEZ was 0.61°C per 100 ppm CO_2 and 0.08°C per 100 ppm CO_2, respectively. Both sea surface and sea bottom salinity were also projected to increase, at rates of 0.144 unit per 100 ppm CO_2 and 0.011 unit per 100 ppm CO_2 although the projected sensitivity for sea bottom salinity was low.

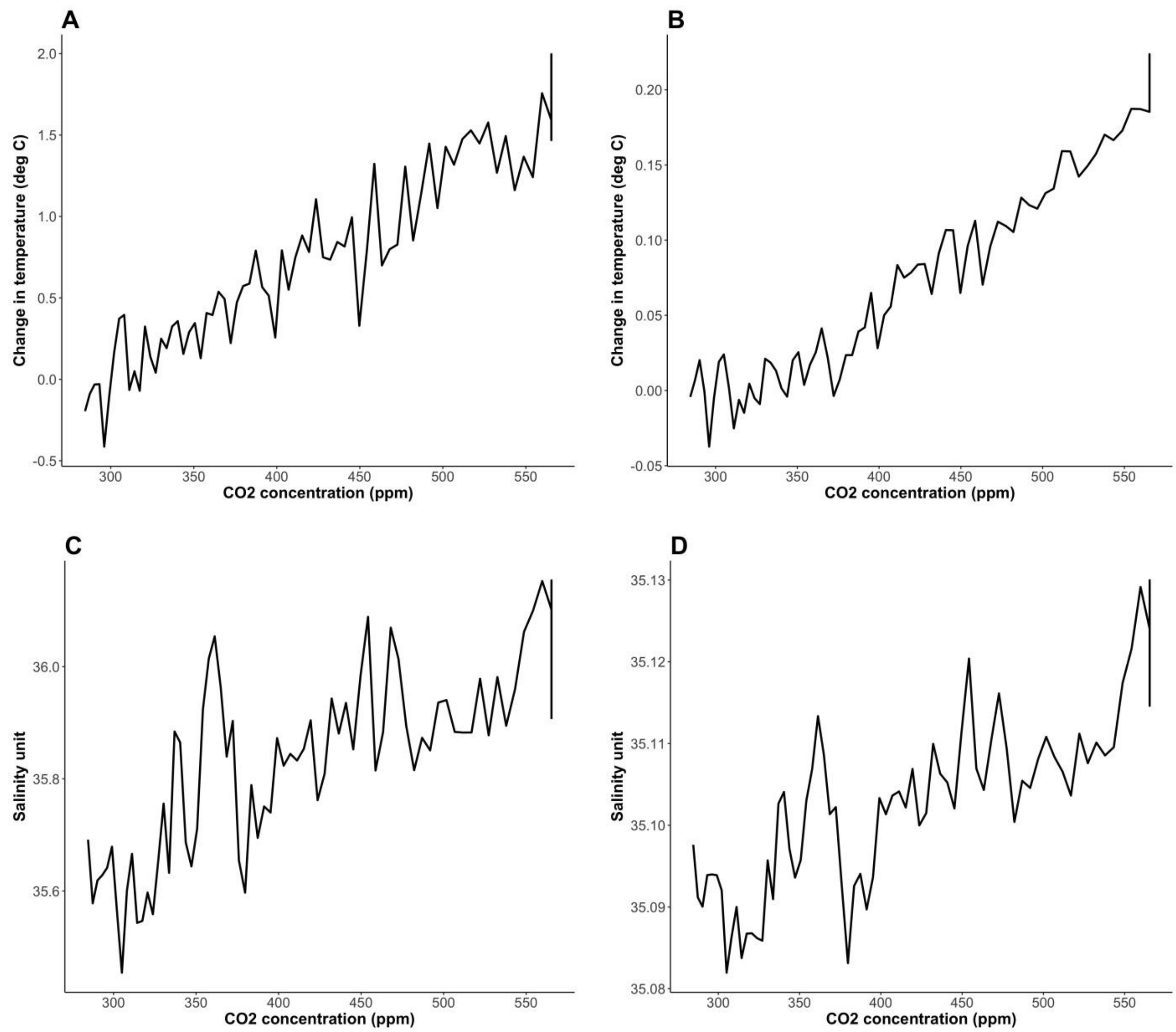


Figure 13. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (°C), (B) sea bottom temperature (°C), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels for the EEZ of Haiti

3.3.2 Vulnerability of exploited species

Vulnerability of selected species occurring in the EEZ of Haiti was evaluated as moderate (Table 3). A total of 82 of the selected study species were reported to occur in the EEZ of Haiti (i.e., in the Changing Ocean Research Unit global marine biodiversity database), with a median climate vulnerability index of 56.5 (25th and 75th quartiles = 39.8 and 70.5, respectively, with 100 = maximum vulnerability). Amongst the 82 species, the ones with the highest vulnerability index were Mutton snapper (*Lutjanus analis*, index =90), jack (*Caranx* spp., index = 88), and gray snapper (*Lutjanus griseus*, index = 88). Those with the lowest vulnerability index were spotted goatfish (*Pseudupeneus maculatus*, index = 19), mackerel scad (*Decapterus macarellus*, index = 24) and sergeant major (*Abudefduf saxatills*, index = 27).

Table 3. Vulnerability and risk of impacts of selected species in Haiti. Vul : vulnerabilities, Risk : risk of impact, Status-quo : current exploitation status, OverF : overfishing scenario, Sust : sustainable fishing scenario.

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Ris: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Ocyurus chrysurus	Yellowtail snapper	80	93	98	86	93	98	86
Epinephelus guttatus	Red hind	81	92	96	85	93	97	85
Lutjanus analis	Mutton snapper	90	92	95	84	92	95	84
Acanthurus bahianus	Ocean surgeon	46	92	95	82	93	96	83
Calamus calamus	Porgy	53	91	94	82	92	95	83
Caranx latus	Horse eye jack	88	91	93	81	91	93	81
Caranx lugubris	Black jack	88	88	93	80	88	93	80
Sparisoma viride	Stoplight parrotfish	71	87	92	76	88	92	78
Epinephelus adscensionis	Rock hind	54	86	91	73	90	94	80
Scarus coeruleus	Blue parrotfish	90	85	91	70	86	91	71
Sparisoma aurofrenatum	Redband parrotfish	35	85	91	73	87	92	76
Mulloidichthys martinicus	Yellow goatfish	29	87	90	70	87	90	70
Haemulon sciurus	Bluestriped grunt	34	82	90	71	85	91	76
Lutjanus apodus	Schoolmaster	67	83	90	73	84	91	74
Tetrapturus pfluegeri	Longbill spearfish	63	82	89	69	85	90	72
Caranx ruber	Bar jack	78	81	89	69	82	89	70
Neoniphon marianus	Longjaw squirrelfish	29	83	89	69	83	89	69
Thunnus obesus	Bigeye tuna	44	81	88	67	84	89	72
Hemiramphus balao	Balao halfbeak	27	84	88	70	84	87	71
Scarus coelestinus	Midnight parrotfish	88	80	88	68	80	88	69
Haemulon plumierii	White grunt	43	77	88	66	77	88	66
Tetrapturus georgii	Roundscale spearfish	61	80	88	68	83	90	71
Rhomboplites aurorubens	Vermillion snapper	74	81	88	60	82	89	65

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Ris: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Hemiramphus brasiliensis	Ballyhoo halfbeak	45	79	87	62	79	87	62
Caranx crysos	Blue runner	46	78	87	65	78	87	65
Sparisoma chrysopterum	Redtail parrotfish	56	79	87	64	81	88	65
Mycteroperca venenosa	Yellowfin grouper	87	78	87	66	78	87	66
Etelis oculatus	Queen snapper	86	79	87	63	78	87	65
Coryphaena hippurus	Common dolphinfish	61	77	86	65	80	88	67
Lutjanus synagris	Lane snapper	73	78	86	61	78	86	61
Thunnus atlanticus	Blackfin tuna	75	78	86	65	78	86	66
Lutjanus griseus	Gray snapper	88	77	86	63	77	86	63
Thunnus thynnus	Atlantic bluefin tuna	38	78	85	63	83	88	67
Istiophorus albicans	Sailfish	39	76	85	62	76	85	62
Scomberomorus cavalla	King mackerel	55	77	85	61	79	86	63
Cephalopholis fulva	Coney	58	76	85	60	79	87	62
Epinephelus striatus	Nassau grouper	77	75	85	60	75	85	60
Haemulon parra	Sailor’s grunt	61	83	85	68	88	90	75
Clepticus parrae	Creole wrasse	46	78	85	62	81	87	64
Scarus taeniopterus	Princess parrotfish	61	81	85	69	84	87	72
Haemulon flavolineatum	French grunt	36	75	85	60	80	88	63
Opisthonema oglinum	Atlantic thread herring	52	76	84	54	76	84	54
Scomberomorus regalis	Cero	57	76	84	62	80	87	66
Caranx hippos	Crevalle jack	60	75	84	55	75	84	55
Lutjanus mahogoni	Mahagony snapper	73	83	84	67	83	84	67
Hirundichthys affinis	Fourwing flyingfish	64	74	84	61	80	88	67
Pseudupeneus maculatus	Spotted goatfish	19	77	84	63	77	84	63
Scarus vetula	Queen parrotfish	87	75	84	61	76	85	63
Kajikia albida	White marlin	56	75	84	62	79	87	65

Scientific name	**Common name**	**Vul**	**Risk: Status quo-2.6**	**Risk: OverF-2.6**	**Ris: Sust-2.6**	**Risk: Status quo-8.5**	**Risk: OverF-8.5**	**Risk: Sust-8.5**
Pterois volitans	Red lionfish	46	74	84	61	76	86	62
Acanthurus chirurgus	Doctorfish	59	81	83	66	83	86	69
Scarus iseri	Striped parrotfish	55	79	83	65	81	85	68
Thunnus albacares	Yellowfin tuna	39	72	82	59	77	85	63
Makaira nigricans	Blue marlin	50	70	82	59	76	86	63
Lachnolaimus maximus	Hogfish	88	69	82	52	69	82	52
Haemulon aurolineatum	Tomtate	31	70	81	47	70	81	47
Holocentrus adscensionis	Squirrelfish	57	67	81	46	67	81	46
Holocentrus rufus	Longspine squirrelfish	42	72	81	51	72	81	51
Myripristis jacobus	Blackbar soldierfish	36	66	81	43	66	81	43
Mycteroperca tigris	Tiger grouper	89	67	81	50	67	81	50
Katsuwonus pelamis	Skipjack tuna	39	72	80	54	77	83	58
Acanthocybium solandri	Wahoo	68	71	80	52	77	84	57
Sparisoma rubripinne	Yellowtail parrotfish	64	66	80	47	69	82	49
Thunnus alalunga	Albacore tuna	39	71	79	50	77	82	54
Decapterus punctatus	Round scad	35	78	79	58	87	89	71
Carangoides bartholomaei	Yellow jack	74	68	78	52	70	81	56
Decapterus macarellus	Mackerel scad	24	69	77	42	69	77	42
Haemulon chrysargyreum	Smallmouth grunt	55	70	76	50	72	79	51
Pristipomoides aquilonaris	Wenchman	38	60	76	46	71	84	58
Sargocentron coruscum	Reef squirrelfish	66	61	75	49	63	77	53
Sargocentron vexillarium	Dusky squirrelfish	54	64	75	43	65	76	44
Panulirus argus	Caribbean spiny lobster	64	61	72	48	64	74	52
Halichoeres radiatus	Puddingwife wrasse	66	61	71	46	63	73	49
Balistes vetula	Queen triggerfish	59	55	70	43	60	75	49

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Ris: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Isostichopus badionotus	Three rowed sea cucumber	69	55	70	41	57	72	43
Haemulon striatum	Striped grunt	28	57	69	41	68	80	52
Abudefduf saxatilis	Sergeant major	27	57	67	43	61	70	47
Thalassoma bifasciatum	Bluehead wrasse	53	55	65	38	58	67	41
Astichopus multifidus	Furry sea cucumber	54	48	61	35	51	64	38
Cephalopholis cruentata	Graysby	34	47	60	33	51	63	37
Acanthurus coeruleus	Blue tang	31	42	58	26	45	61	29
Holothuria (Halodeima) mexicana	Donkey dung sea cucumber	60	38	54	27	42	58	34

Risk of impacts as a result of fishing and climate change were evaluated as moderate to high in the EEZ of Haiti under status quo fishing and both RCP2.6 and RCP8.5 scenarios (Table 3). Across the 82 selected species, the median risk of impact index was 77.0 (25th and 75th quartiles = 69.3 and 81.0, respectively) and 78.0 (25th and 75th quartiles = 70.3 and 83.0, respectively) under RCP2.6 and RCP8.5, respectively, and status quo fishing scenario (i.e., an Ocean Health Index (fisheries) value of 0.32; meaning ~ 32% of fish stocks were considered to be sustainably exploited). Under a sustainable fishing scenario (i.e., an Ocean Health Index (fisheries) value estimated at twice the current value, meaning a high proportion of fish stocks are sustainably exploited), the risk of impact index decreased to 61.5 and 63.0 under RCP2.6 and RCP8.5, respectively. In contrast, under a scenario of further intensification of overfishing, the risk of impact index increased to 84.5 and 86.0 respectively under RCP 2.6 and RCP8.5.

Amongst the 82 selected species, those with the highest risk of impact index included yellowtail snapper (*Ocyurus crysurus*), red hind (*Epinephelus guttatus*) and mutton snapper (*Lutjanus analis*) (Table 3). Those with the lowest risk of impact index included donkey dung sea cucumber (*Holothuria mexicana*), blue tang (*Acanthurus coeruleus*), and graysby (*Cephalopolis cruentata*).

3.3.3 Projected changes in habitat suitability

Changes in ocean conditions under increased atmospheric CO_2 concentrations were projected to result in a decline in the habitat suitability for selected species in the EEZ of Haiti (Figure 14). Overall, the sum of the habitat suitability index across the selected species in the EEZ of Haiti was projected to decrease by 25.2% and 29%, under atmospheric CO_2 concentrations that would be similar to the 2030-2039 and 2050-2059 periods under RCP8.5. Species that were projected to have the largest decline in HSI include the Florida sea cucumber (*Holothuria (Halodeima) floridana*), fourwing flyingfish (*Hirundichthys affinis*) and red hind (*Epinephelus guttatus*) (see online data portal associated with this project for maps of HSI for all individual species).

A high proportion of Haiti’s EEZ was projected to incur high rates of local species gains and losses (Figure 14). The western and northern parts of the EEZ were projected to have particularly higher rates of local species gains with some areas gaining 50% or more new species relative to current species richness.

In contrast, local extinction rates were projected to be high (>50% relative to current species richness) in the northern part of the EEZ.

3.3.4 Projected changes in fisheries catches

Maximum catch potential (MCP) was projected to decrease in the EEZ of Haiti across time periods and scenarios (Figure 15). We projected that catch potential will decline by 5% to 15% and 10% to 30% by 2030-2039 and 2050-2059 relative to the 1970-2000 period, respectively, under RCP2.6. The projected decreases in MCP almost doubled in both time frames under RCP8.5.

3.3.5 Synthesis of key risks

Overall, key risks of climate impacts on marine species and fisheries were estimated across all species and RCPs with variations among species groups (Figure 16). Vulnerability and risk index were estimated to be generally high for all species, particularly ocean pelagics, groupers and parrotfish. Ocean pelagics were also projected to have the largest decline in habitat suitability index followed by groupers, the Caribbean graysby and coney. Local invasion and extinction rates were high across all species groups. Local invasion rates were particularly high for invertebrates and other reef fish, followed by ocean pelagics. Local extinction rates were very high for groupers, parrotfish, the graysby and coney (almost 100% under the high CO_2 concentration condition). Declines in maximum catch potential were projected to be high by the 2050s under RCP8.5 across most species groups. Parrotfish and other reef fish stand out as an exception as an insufficient number of species were included in DBEM for these two groups of fishes, thus the results may not be representative for the average responses of these groups.

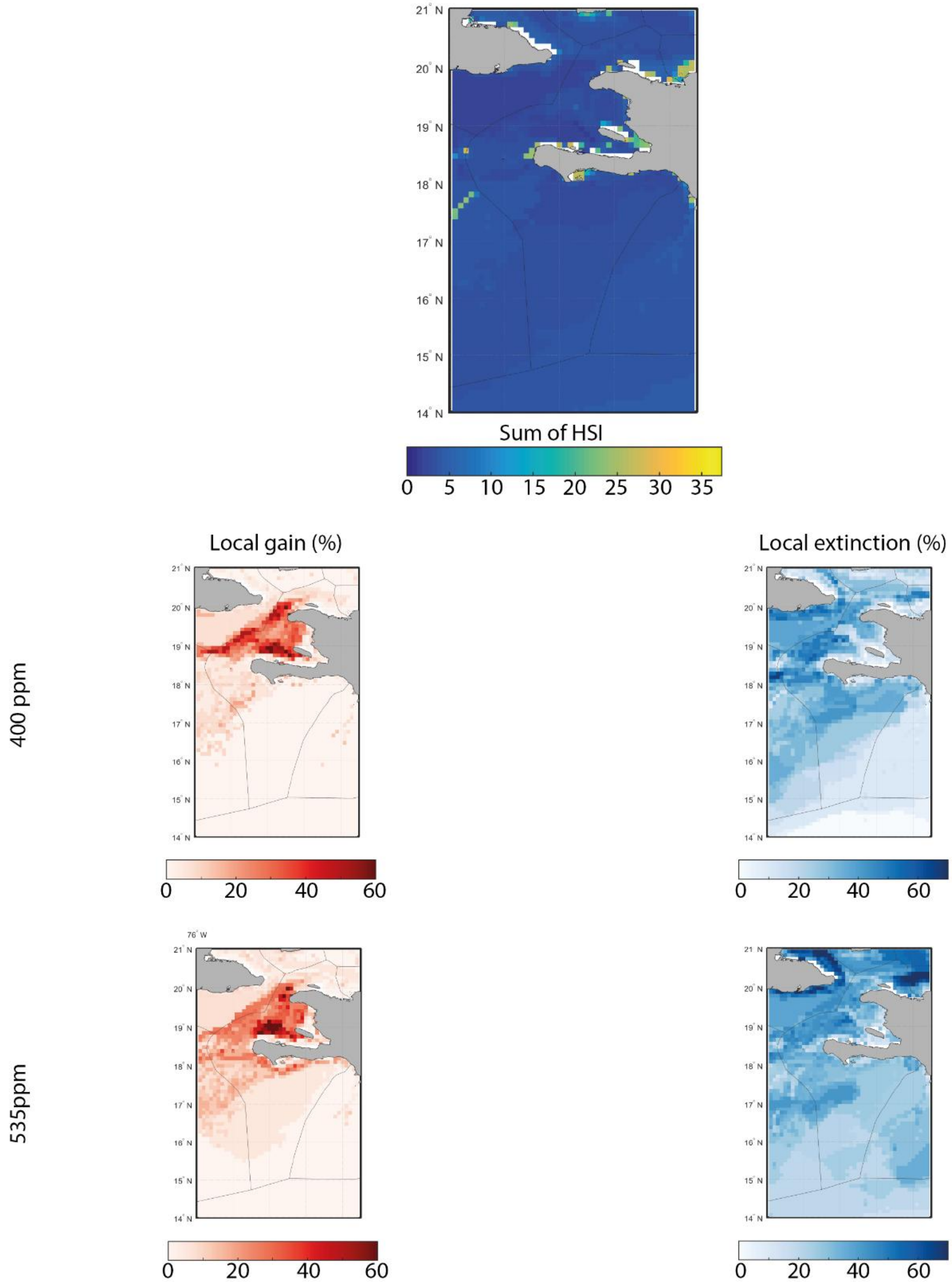


Figure 14. Current habitat suitability index and projected climate risk for marine biodiversity in the EEZ of Haiti. Sum of HSI for the current period (1970 to 2000) across the selected species (top). Climate risk represented as projected change of: percentage of species gained relative to current species richness with atmospheric CO_2 concentration of 400 ppm (upper left) and 535 ppm (lower left), and percentage of species local losses (extinction) relative to current species richness under the 400 ppm (upper right) and 535 ppm (lower right) CO_2 concentration scenarios.

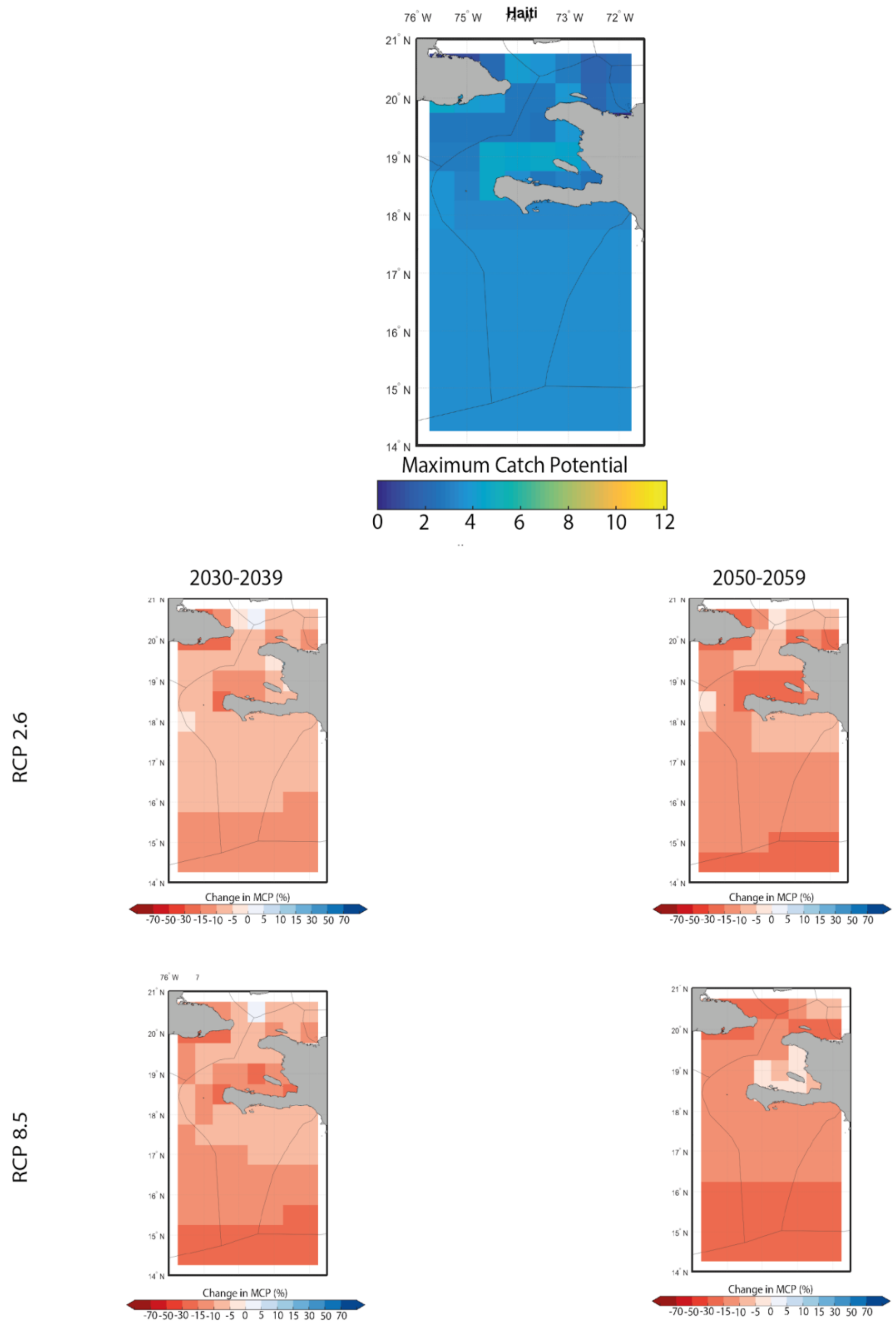


Figure 15. Projected changes in maximum catch potential using the Dynamic Bioclimate Envelope Model (DBEM) under RCP2.6 and RCP8.5 by 2030-2039 and 2050-2059 relative to 1970-2000. The results represent ensemble-average projections across outputs driven by three Earth system models (GFDL, IPSL, MPI - see paper A in this Collection): (top panel) projected distribution of current maximum catch potential, (middle row) projected distribution of maximum catch potential under RCP2.6, (bottom row) projected distribution of maximum catch potential under RCP8.5, (left) timeframe is 2030-2039 and (right) timeframe is 2050-2059.

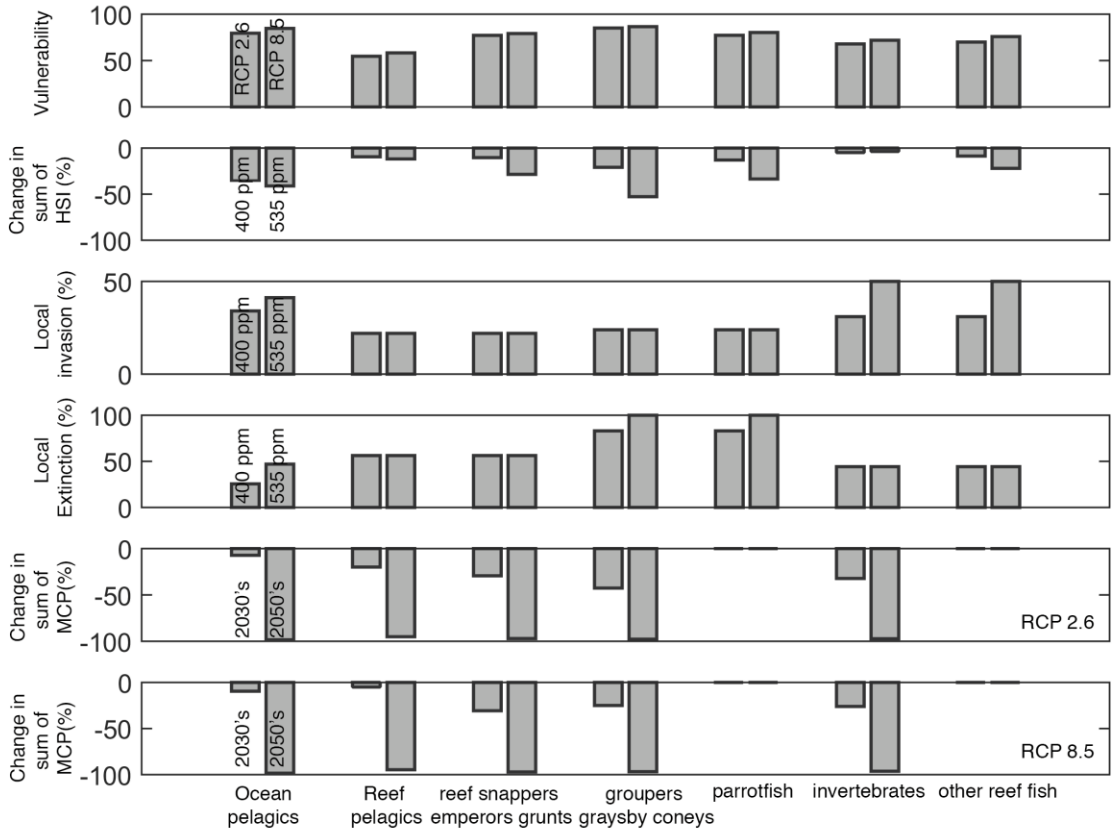


Figure 16. Projected climate risk indicators for Haiti across different groups of marine species. The climate risk indicators include vulnerability index for the species' groups, change in the sum of habitat suitability index (HSI) across species groups, rate of local invasion and local extinction, and changes in maximum catch potential (MCP).

3.4 **Jamaica**

3.4.1 <u>Fisheries catch time series and climate change challenges</u>

3.4.1.1 Fisheries

Fisheries in Jamaica are diverse, complex (Aiken and Kong, 2000) and mostly small-scale. There are at least 23,700 active fishers and at least 6,700 registered fishing vessels (FAO, 2017). Despite fisheries contributing to a large number of people's livelihoods and fish being important to Jamaican culture, marine resources have generally been undervalued by the government and the public, leading to the marginalization of Jamaica's small-scale fishers (Lingard *et al*., 2012). Fishing activities in Jamaica are multi-species and multi-gear and tend to focus on inshore habitats. There is a targeted and high-value fishery (including industrial) for Caribbean spiny lobster (*Panulirus argus*) and queen conch (*Lobatus gigas*), with landings by designated licenses destined mostly for export (Aiken and Kong, 2000).

Total reconstructed catches[13] amounted to 3,155,857 tonnes from 1950 to 2014, registering an increasing trend through to 1978 (62,989 tonnes), and a steady decline to 2014 (29,267 tonnes), with a dramatic peak in 1990 (65,179 tonnes) due to a sharp increase in industrial fishing that year after minimal catches from 1950 onwards (Figure 17). Specifically, this dramatic increase in catches was due to the establishment of the Pedro Bank queen conch fishery (Aiken *et al*., 1999). No industrial reconstructed catches are recorded post 1990. Catches were on average 48,552 tonnes per year. Over the entire time period, the subsistence sector was most important (71.2%), followed by artisanal (26.6%) and industrial fisheries (4.5%). Recreational fisheries accounted for 0.02% of catches. This trend was reflected in both total catches as well as landed value. Artisanal fisheries were initially by far the most important sector in Jamaica, registering a slight decline through 1960, followed by an increase through to 1979, and a dramatic decline until 1994, after which the fishery rose again in importance until 2000 before declining again and levelling off. Subsistence fisheries on the other hand remained relatively stable through to 1987, gaining in importance until 1996, before declining to their lowest point in 2000, increasing again and levelling off to similar catch levels as artisanal take. The increase is likely due to the growing popularity in the use of spearguns (Sary *et al*., 2003; Passley *et al*., 2009). Discards were estimated to be low, while unreported catches were extremely high accounting for 2.6% and 74.1% of total reconstructed catches, respectively. The large proportion of catches landed by subsistence fisheries is the main reason behind the considerable difference between the total reconstructed catch and catches presented by the FAO as they are absent from officially reported data (Lingard *et al*., 2012).

Small-scale fisheries was by far the most common sub-sector in Jamaica (98.4%). Fishing vessels are typically open canoes (95% of all vessels) made out of wood for the smaller-sized ones and fiberglass for those > 18 m (Murray and Aiken, 2006). All larger canoes use large (> 40 hp) outboard engines. Catch data were generally poorly resolved with mixed fishes and finfishes jointly accounting for 28.9% of overall reconstructed catches. Jacks and pompanos (Carangidae) were next followed by a range of reef-associated species (Sphyraenidae 9.9%, Serranidae 9.6%, Lutjanidae 9.6%, Haemulidae 6.1%). Conch (*Lobatus gigas*) and spiny lobster (*Panulirus argus*) made up 6.1% and 0.6% of catches respectively. Queen conch represents a valuable component of commercial fisheries in Jamaica and has been an important foreign exchange earner for the country (Aiken *et al*., 2006). According to the Food and Agriculture Organization, queen conch in Jamaica is currently fully exploited (FAO, 2017). Taken together, of groups identified at least to family level, reef-associated fishes and invertebrates made up 50.4% of total reconstructed catches, with pelagic species accounting for 16%. Requiem sharks accounted for 4.5% of total catches.

[13] Details regarding method and data sources for the catch reconstruction effort for Jamaica are detailed in Lingard et al. (2012) and follow the approach outlined under Section 3.1.1.

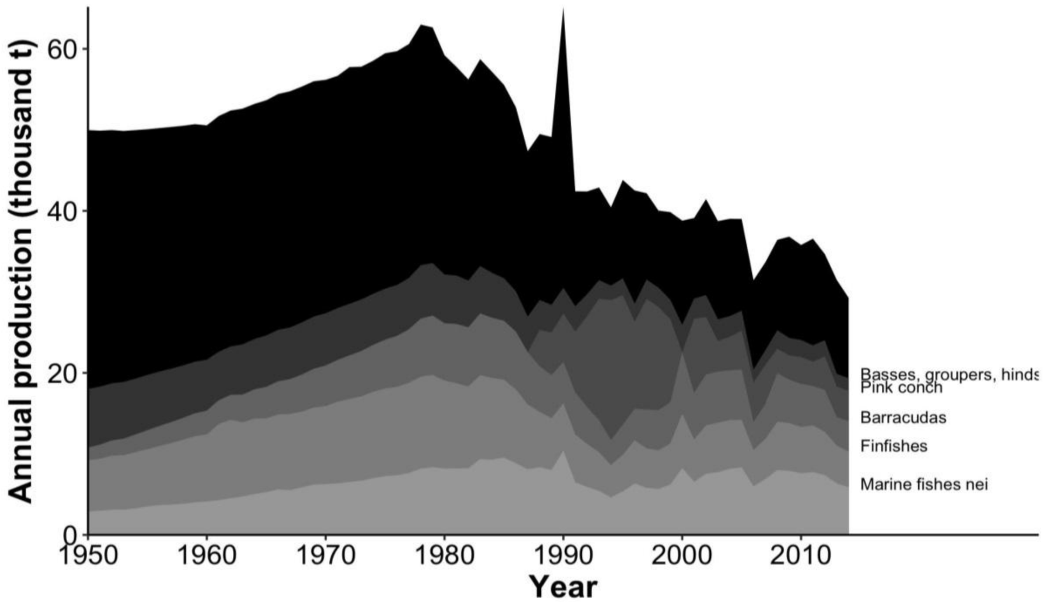


Figure 17. Reconstructed catches from the EEZ of Jamaica from 1950 to 2014. Total catches are plotted in black, while key species groups contributing to those catches over time are plotted in different shades of grey. Data source: Sea Around Us (www.seaaroundus.org).

3.4.1.2 Climate change

Jamaica's marine resources are generally considered severely depleted with cumulative stresses including hurricanes, the die-off of the sea urchin *Diadema antillarum* - an important grazer - high levels of watershed-pollution, poor land practices and coastal development, as well as overfishing of herbivores having led to a dramatic phase shift from once coral-dominated to algae-dominated reefs (Hughes, 1994). While reef health has improved at a number of locations (Idjadi *et al*., 2006) the impacts of mass bleaching events and hurricanes have been evident. In 2005, coral cover suffered severe declines as a result of bleaching due to due to high sea surface temperatures and the effects of hurricane Katrina (Wilkinson and Souter, 2008). In combination, these stressors have reduced the reef ecosystem's capacity to recover from additional perturbations and long-term climate change impacts (Burke and Maidens, 2004).

In a study looking at the vulnerability of country's fisheries to climate change, Jamaica ranked second behind Haiti, mostly because of an aggregate low adaptive capacity compared to the other countries considered here (Blasiak *et al*. 2017). Large economic challenges, including high levels of debt (Hurley *et al*., 2010) and limited institutional and human capacity further limit the country's capacity to implement adaptation programs. In general, fishers struggle to recover their costs. Thus, adaptation mechanisms that would seek to reduce fishing pressure - to provide an opportunity for reef resources to recover from overexploitation - without extending alternative livelihood options to fishers would further contribute to economic hardships for those communities (Lingard *et al*. 2012).

In response to evidence-based concerns, and in an effort to minimize climate change impact on and support fisheries dependent livelihoods, Jamaica has set aside $22.8million to plan and execute a *Fisheries Ecosystem Adaptation Strategies and Technologies project*. The initiative seeks to "enhance marine protected areas (MPAs) ecosystem services via reduction of human-induced stressors and increased sustainable resource use; apply climate adaptation measures to minimize impacts on MPA ecosystems from land-based sources of pollution; and minimize climate change impact on fishing livelihoods" (Patterson, 2018).

Increasing atmospheric CO_2 concentration was projected to increase ocean temperature and salinity in the EEZ of Jamaica (Figure 18). Based on the projections from the coupled ocean-atmospheric climate model GFDL CM 2.6, sensitivity of both sea surface and sea bottom temperature to atmospheric CO_2 concentration in the EEZ was 0.63°C per 100 ppm CO_2 and 0.11°C per 100 ppm CO_2, respectively. Both sea surface and sea bottom salinity were also projected to increase, at rates of 0.136 unit per 100 ppm CO_2 and 0.014 unit per 100 ppm CO_2 although the projected sensitivity for sea bottom salinity was low.

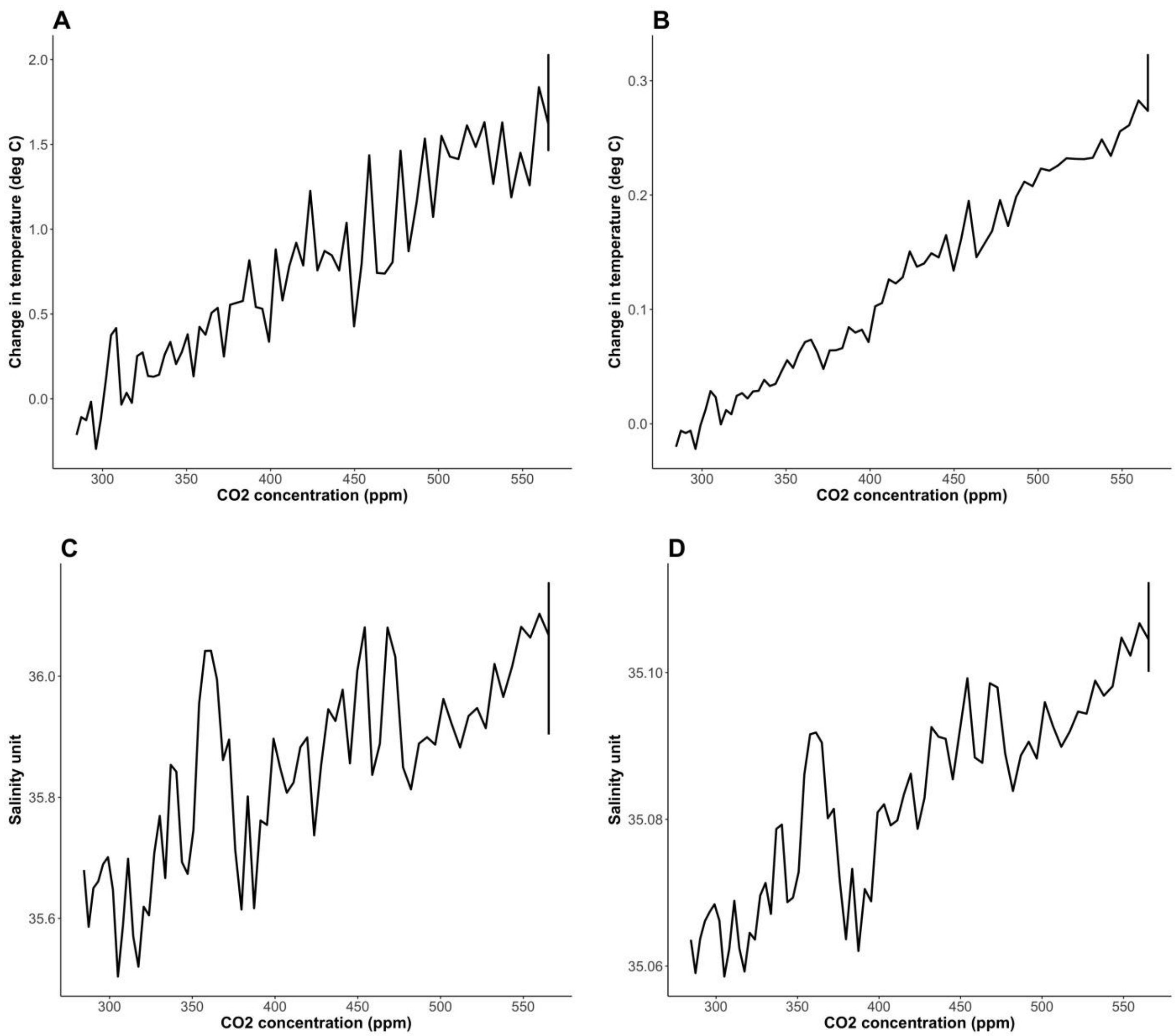


Figure 18. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (°C), (B) sea bottom temperature (°C), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels for the EEZ of Jamaica

3.4.2 Vulnerability of exploited species

Vulnerability of selected species occurring in Jamaica was evaluated as moderate (Table 4). A total of 78 of the selected study species were reported to occur in the EEZ of Jamaica (i.e., in the Changing Ocean Research Unit global marine biodiversity database), with a median climate vulnerability index of 57.5 (25th and 75th quartiles = 44.3 and 70.5, respectively, with 100 = maximum vulnerability). Amongst the 78 species, the ones with the highest vulnerability index were cubera snapper (*Lutjanus cyanopterus*, index =93), mutton snapper (*Lutjanus analis*, index = 90), dog snapper (*Lutjanus jocu*, index = 90) and blue parrotfish (*Scarus coeruleus*, index = 90). Those with the lowest vulnerability index were spotted goatfish (*Pseudupeneus maculatus*, index = 19), balao halfbeak (*Hemiramphus balao*, index = 27) and sergeant major (*Abudefduf saxatills*, index = 27).

Table 4. Vulnerability and risk of impacts of the fisheries-important species in Jamaica. Vul :vulnerabilities, Risk : risk of impact, Status-quo : current exploitation status, OverF : overfishing scenario, Sust : sustainable fishing scenario.

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Ris: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Ocyurus chrysurus	Yellowtail snapper	80	98	98	91	98	98	91
Epinephelus guttatus	Red hind	81	97	97	90	97	97	90
Lutjanus cyanopterus	Cubera snapper	93	93	97	91	93	97	91
Lutjanus analis	Mutton snapper	90	95	97	91	95	97	91
Calamus calamus	Porgy	53	94	97	88	94	97	88
Acanthurus bahianus	Ocean surgeon	46	96	97	89	96	97	89
Haemulon album	White margate	60	92	95	85	92	96	87
Lutjanus jocu	Dog snapper	90	94	94	89	94	94	89
Haemulon sciurus	Bluestriped grunt	34	90	93	85	90	93	85
Lutjanus apodus	Schoolmaster	67	89	93	84	89	93	84
Sparisoma viride	Stoplight parrotfish	71	91	93	87	91	93	87
Sparisoma aurofrenatum	Redband parrotfish	35	90	93	85	90	93	85
Lutjanus mahogoni	Mahagony snapper	73	90	92	86	92	95	89
Caranx ruber	Bar jack	78	89	91	77	89	91	77
Scarus coeruleus	Blue parrotfish	90	90	91	83	90	91	83
Neoniphon marianus	Longjaw squirrelfish	29	87	91	82	87	91	82
Tetrapturus pfluegeri	Longbill spearfish	63	86	90	77	87	90	79
Acanthurus chirurgus	Doctorfish	59	85	90	82	86	91	83
Scarus taeniopterus	Princess parrotfish	61	88	90	83	89	91	83
Scarus iseri	Striped parrotfish	55	84	90	81	85	90	82
Mycteroperca venenosa	Yellowfin grouper	87	85	90	73	85	90	73
Thunnus obesus	Bigeye tuna	44	84	89	73	86	90	77

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Ris: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Caranx crysos	Blue runner	46	86	89	77	86	89	77
Sphyraena barracuda	Great barracuda	49	86	89	76	86	89	76
Scarus coelestinus	Midnight parrotfish	88	88	89	78	88	89	78
Sparisoma chrysopterum	Redtail parrotfish	56	87	89	75	87	89	75
Haemulon plumierii	White grunt	43	86	89	77	86	89	77
Haemulon flavolineatum	French grunt	36	87	89	75	87	89	75
Tetrapturus georgii	Roundscale spearfish	61	86	89	77	88	90	78
Hemiramphus brasiliensis	Ballyhoo halfbeak	45	86	88	74	86	88	74
Cephalopholis fulva	Coney	58	86	88	74	86	88	74
Lutjanus griseus	Gray snapper	88	85	88	73	85	88	73
Lutjanus vivanus	Silk snapper	88	80	88	64	80	88	64
Pterois volitans	Red lionfish	46	84	88	72	84	88	72
Thunnus thynnus	Atlantic bluefin tuna	38	84	87	70	85	88	72
Scomberomorus cavalla	King mackerel	55	86	87	73	86	87	73
Scomberomorus regalis	Cero	57	84	87	73	85	89	74
Lutjanus synagris	Lane snapper	73	85	87	73	85	87	73
Thunnus atlanticus	Blackfin tuna	75	82	87	69	82	87	70
Epinephelus striatus	Nassau grouper	77	84	87	70	84	87	70
Clepticus parrae	Creole wrasse	46	86	87	75	86	87	75
Pseudupeneus maculatus	Spotted goatfish	19	82	87	77	82	87	77
Scarus vetula	Queen parrotfish	87	82	87	70	83	87	71
Coryphaena hippurus	Common dolphinfish	61	82	86	72	85	88	74
Makaira nigricans	Blue marlin	50	78	85	66	81	87	69
Opisthonema oglinum	Atlantic thread herring	52	83	85	69	83	85	69
Haemulon parra	Sailor’s grunt	61	79	85	76	84	86	82

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Ris: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Haemulon chrysargyreum	Smallmouth grunt	55	84	85	74	88	88	78
Lachnolaimus maximus	Hogfish	88	79	85	59	79	85	59
Kajikia albida	White marlin	56	81	85	69	84	87	72
Caranx hippos	Crevalle jack	60	81	84	66	83	86	69
Sparisoma rubripinne	Yellowtail parrotfish	64	79	84	59	79	84	59
Holocentrus adscensionis	Squirrelfish	57	79	84	59	79	84	59
Thunnus albacares	Yellowfin tuna	39	78	83	65	81	86	68
Hemiramphus balao	Balao halfbeak	27	83	83	72	82	82	72
Myripristis jacobus	Blackbar soldierfish	36	79	83	58	79	83	58
Actinopyga agassizii	Five toothed sea cucumber	64	75	83	50	75	83	50
Apsilus dentatus	Black snapper	82	75	83	50	75	83	50
Acanthocybium solandri	Wahoo	68	77	82	60	81	85	64
Haemulon aurolineatum	Tomtate	31	81	82	64	81	82	64
Holocentrus rufus	Longspine squirrelfish	42	82	82	67	82	82	67
Katsuwonus pelamis	Skipjack tuna	39	78	81	63	81	83	66
Panulirus argus	Caribbean spiny lobster	64	73	80	60	74	81	61
Thunnus alalunga	Albacore tuna	39	76	79	58	80	83	62
Sargocentron vexillarium	Dusky squirrelfish	54	76	79	63	80	83	68
Halichoeres radiatus	Puddingwife wrasse	66	73	78	59	74	79	60
Haemulon carbonarium	Caesar grunt	63	73	76	58	75	77	60
Isostichopus badionotus	Three rowed sea cucumber	69	70	76	53	71	77	54
Abudefduf saxatilis	Sergeant major	27	71	75	58	72	76	60
Thalassoma bifasciatum	Bluehead wrasse	53	67	73	53	68	73	55
Carangoides bartholomaei	Yellow jack	74	69	73	54	77	79	63
Astichopus multifidus	Furry sea cucumber	54	64	73	48	65	73	48

Scientific name	**Common name**	**Vul**	**Risk: Status quo-2.6**	**Risk: OverF-2.6**	**Ris: Sust-2.6**	**Risk: Status quo-8.5**	**Risk: OverF-8.5**	**Risk: Sust-8.5**
Balistes vetula	Queen triggerfish	59	68	72	53	77	80	63
Sargocentron coruscum	Reef squirrelfish	66	68	72	54	79	82	64
Cephalopholis cruentata	Graysby	34	64	70	50	70	74	55
Pristipomoides aquilonaris	Wenchman	38	65	70	49	64	68	50
Acanthurus coeruleus	Blue tang	31	61	69	42	62	70	44
Priacanthus arenatus	Atlantic bigeye	36	48	61	33	48	60	33

Risk of impacts as a result of fishing and climate change were evaluated as moderate to high in the EEZ of Jamaica under status quo fishing and both RCP2.6 and RCP8.5 scenarios (Table 4). Across the 78 selected species that occur in the EEZ of Jamaica, the median risk of impact index was 84.0 (25th and 75th quartiles = 78.0 and 86.8, respectively) and 87.0 (25th and 75th quartiles = 83.0 and 90.0, respectively) under RCP2.6 and RCP8.5, respectively, and status quo fishing scenario (i.e., an Ocean Health Index (fisheries) value of 0.20; meaning ~ 20% of fish stocks were considered to be sustainably exploited). Under a sustainable fishing scenario (i.e., the Ocean Health Index (fisheries) is estimated at twice the current value, meaning a high proportion of fish stocks are sustainably exploited), the risk of impact index declined to 72.5 and 73.0 under RCP2.6 and RCP8.5, respectively. In contrast, under a scenario of increased overfishing, the risk of impact index increased to 87.0, respectively under both RCP 2.6 and RCP8.5.

Amongst the 78 selected species, those with the highest risk of impact index included yellowtail snapper (*Ocyurus crysurus*), red hind (*Epinephelus guttatus*) and mutton snapper (*Lutjanus analis*) (Table 4). Those with the lowest risk of impact index included the wenchman (*Pristipomoides aquilonaris*), blue tang (*Acanthurus coeruleus*), and Atlantic bigeye (*Priacanthus arenatus*).

3.4.3 Projected changes in habitat suitability

Changes in ocean conditions under increased atmospheric CO_2 concentrations were projected to result in a decline in the habitat suitability for selected species in the EEZ of Jamaica (Figure 19). Overall, the sum of the habitat suitability index across the selected species in the EEZ of Jamaica was projected to decline by 17.9% and 29.4%, under atmospheric CO_2 concentrations that would be similar to the 2030-2039 and 2050-2059 periods under RCP8.5. Species that were projected to have the largest decrease in this included the Florida sea cucumber (*Holothuria (Halodeima) floridana*), the donkey dung sea cucumber (*Holothuria (Halodeima) Mexicana*) and the white margate (*Haemulon album*) (see online data portal associated with this project for maps of HSI for individual species).

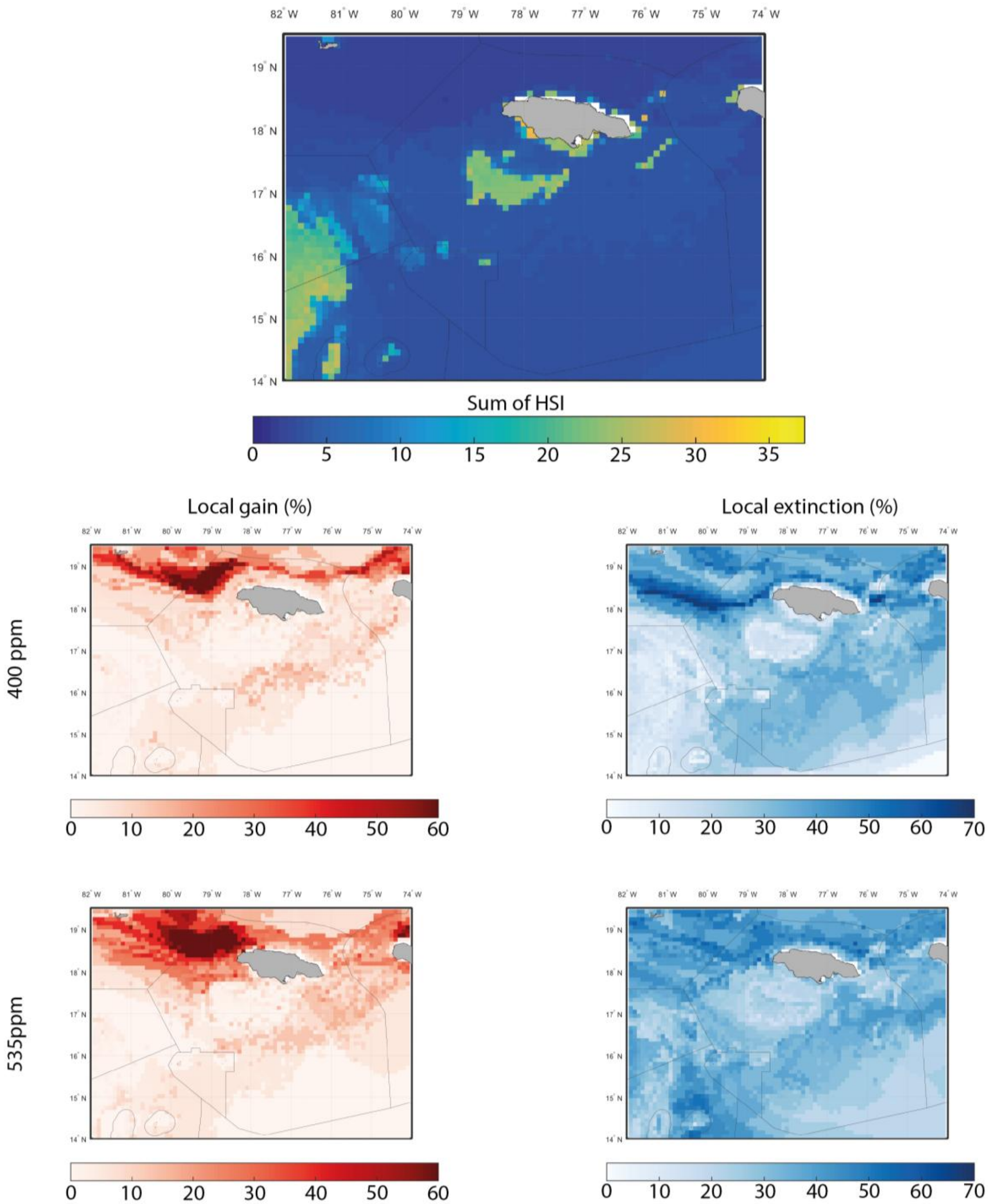


Figure 19. Current habitat suitability index and projected climate risk for marine biodiversity in the EEZ of Jamaica. Sum of HSI for the current period (1970 to 2000) across the selected species (top). Climate risk represented as projected change of: percentage of species gained relative to current species richness with atmospheric CO_2 concentration of 400 ppm (upper left) and 535 ppm (lower left), and percentage of species local losses (extinction) relative to current species richness under the 400 ppm (upper right) and 535 ppm (lower right) CO_2 concentration scenarios.

A large proportion of Jamaica's EEZ was projected to have high rates of local species gains and losses (Figure 20). The north-western parts of the EEZ were projected to have particularly higher rates of local species gains with some areas gaining 50% or more new species relative to current species richness. In contrast, local extinction rates were projected to be high (>50% relative to current species richness) in the northern part of the EEZ. The Pedro Bank (south of the Jamaican main island) appears as a hot spot of diversity owing to its favourable environmental conditions and habitat for benthic and demersal species. It is recognized as a biologically and economically-significant area and considered one of Jamaica's main commercial and artisanal fishing grounds, particularly for queen conch. Projections of future changes in diversity highlight that species inhabiting Pedro Bank may see relatively lower impacts in terms of shifting species composition and local extinction compared to the overall EEZ. An extensive participatory marine spatial planning effort led by TNC was accepted by the National Environment and Planning Agency and is under consideration by the Government (Baldwin, 2015). The fact that climate change impacts may be lower in this area of the EEZ may help further support efforts toward the successful implementation of this initiative.

3.4.4 Projected changes in fisheries catches

Maximum catch potential (MCP) was projected to decrease in the EEZ of Jamaica across time frames and scenarios (Figure 20). We projected that catch potential will decline by 5% to 15% and 10% to 30% by 2030-2039 and 2050-2059 relative to the 1970-2000 period, respectively, under RCP2.6. The projected decline in MCP almost doubled in both time frames under RCP8.5.

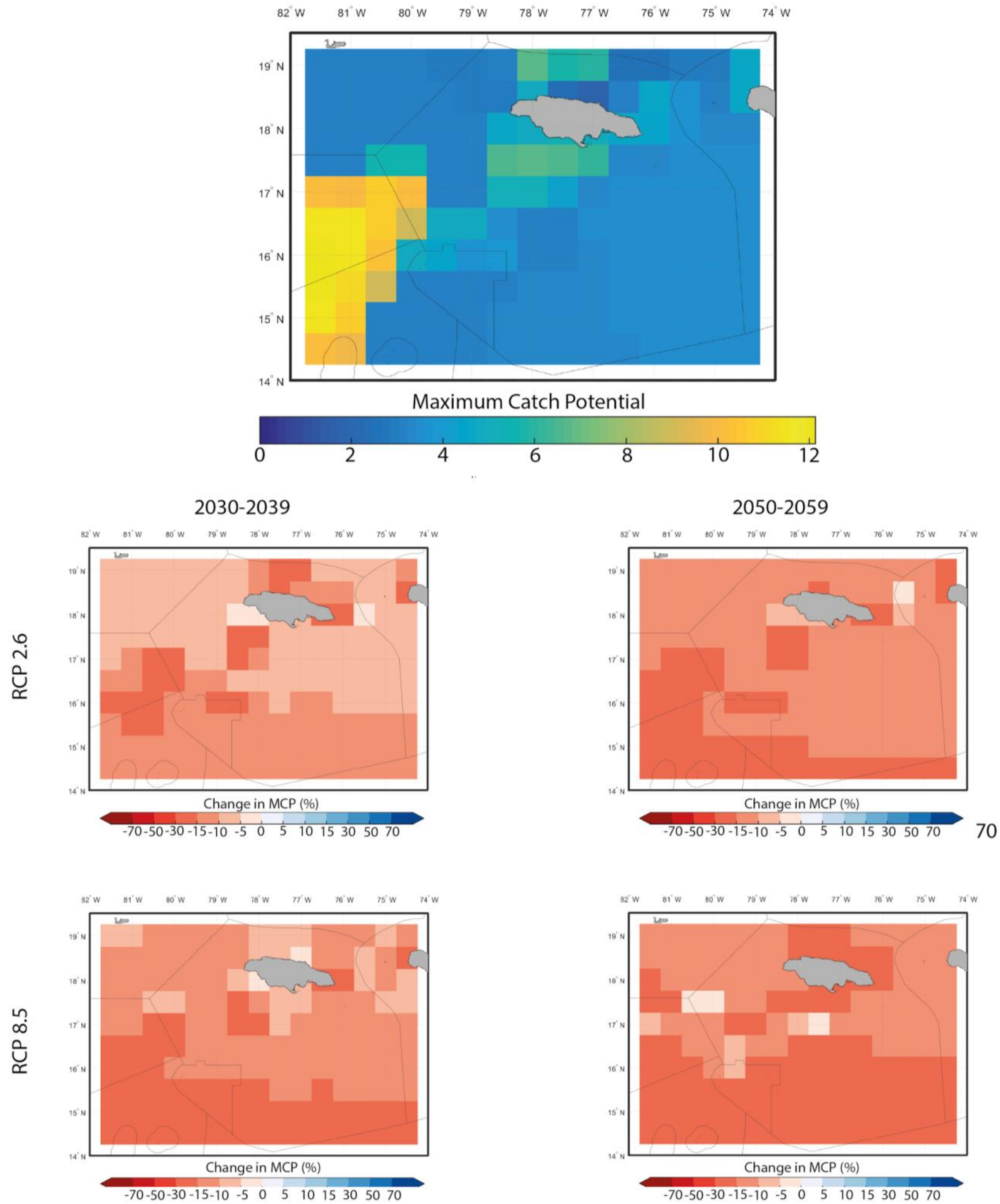


Figure 20. Projected changes in maximum catch potential using the Dynamic Bioclimate Envelope Model (DBEM) under RCP2.6 and RCP8.5 by 2030-2039 and 2050-2059 relative to 1970-2000. The results represent ensemble-average projections across outputs driven by three Earth system models (GFDL, IPSL, MPI - see paper A in this Collection): (top panel) projected distribution of current maximum catch potential, (middle row) projected distribution of maximum catch potential under RCP2.6, (bottom row) projected distribution of maximum catch potential under RCP8.5, (left) timeframe is 2030-2039 and (right) timeframe is 2050-2059.

3.4.5 Synthesis of key risks

Overall, key risks of climate impacts on marine species and fisheries were estimated across all species and RCPs with variations among species groups (Figure 21). Vulnerability and risk index were estimated to be generally high for all species, particularly ocean pelagics, groupers and parrotfish. Groupers, the Caribbean graysby and coney, and ocean pelagics were also projected to have the largest decline in habitat suitability index. Invasion and local extinction rates were high across all species groups. Invasion rates were particularly high for invertebrates and other reef fish, followed by ocean pelagics. Local extinction rates were very high for groupers, parrotfish, the graysby, and coney (almost 100% under the high CO_2 concentration condition). Declines in maximum catch potential were projected to be high by the 2050s under RCP8.5 across most species groups. Parrotfish and other reef fish stand out as an exception as an insufficient number of species were included in DBEM for these two groups of fishes, thus the results may not be representative for the average responses of these groups.

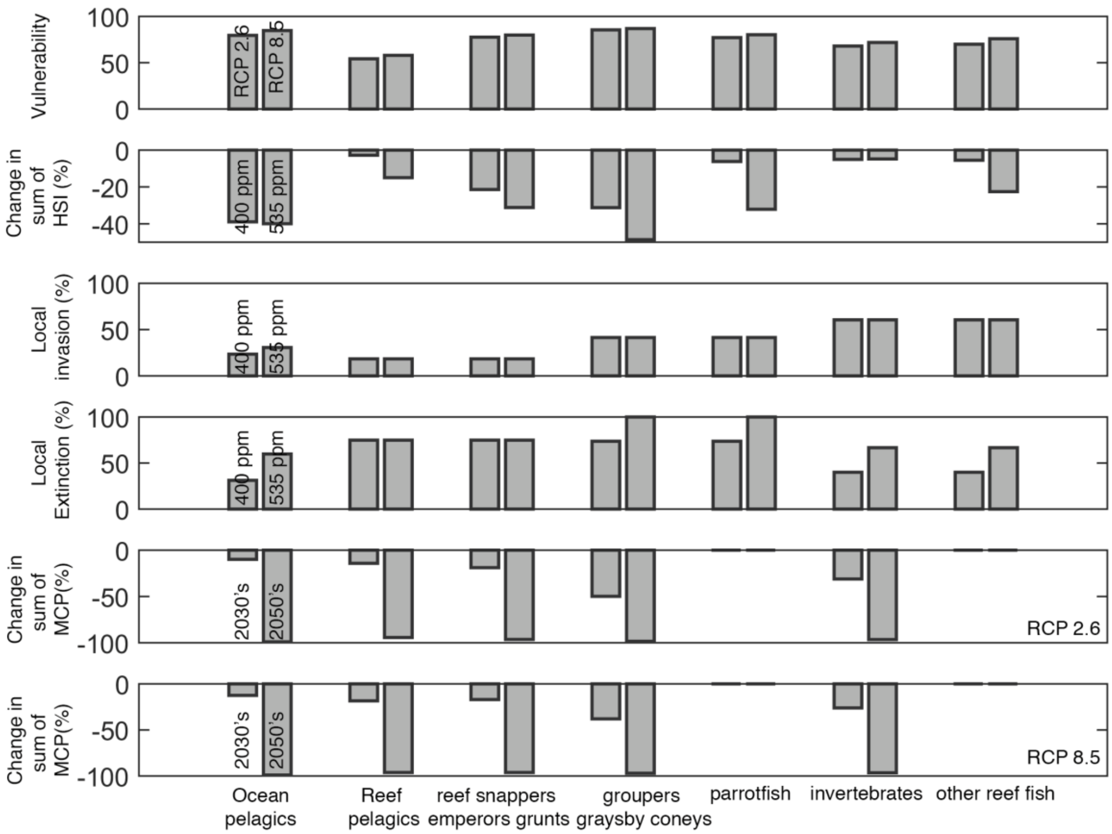


Figure 21. Projected climate risk indicators for Jamaica across different groups of marine species. The climate risk indicators include vulnerability index for species groups, change in the sum of habitat suitability index (HSI) across species groups, rate of local invasion and local extinction, and changes in maximum catch potential (MCP).

3.5 **Saint Lucia**

3.5.1 Fisheries catch times series and climate change challenges

3.5.1.1 Fisheries

Fisheries in Saint Lucia have undergone a lengthy history of development and are considered diverse, targeting offshore pelagic species with gillnets, handlines, troll lines and longlines; coastal pelagic species using beach seines and gillnets, and inshore species with traps and handlines, or via diving in the case of lobster and conch resources (Mohammed and Lindop, 2015a). As of December 31, 2018, the fishing fleet consists of 891 registered vessels - mostly fibreglass pirogues - operated by 3,282 registered fishers (both full and part time) (A. Joseph, personal communication). While the sector has undergone increased commercialization through time, it is generally still considered artisanal in nature (Murray, 2010).

Saint Lucia has been engaged in the protection and sustainable use of coastal marine resources for several decades (UNEP/IUCN, 1988) and the island's experiences and lessons learned have been widely published as a case study in integrated coastal zone management (Goodridge *et al*., 1997; Sanderson and Koester, 2000; Christie *et al*., 2007; McConney and Pena, 2012). In addition, a number of fisheries regulations have been implemented to support the sustainable management of marine resources, including a limited entry system in the conch and sea urchin fishery, the ban of trammel nets for the capture of lobsters, a buy-back scheme for bottom gillnets and the replacement of small meshed pots with larger meshed ones (George, 1999 cited in Mohammed and Lindop, 2015a).

Total reconstructed catches[14] amounted to 103,258 tonnes from 1950 to 2014, registering an increasing trend through to 1978 (2,775 tonnes), an overall decline to 1987 (890 tonnes), and a continuous increase through to 2002, followed by a series of rises and falls (Figure 22). The marked trough in catches in the early 1980s was the result, in part, of the considerable destruction of fishing vessels and equipment due to hurricane Allen (Mohammed and Lindop, 2015a). Low catches toward the end of the decade are less easily explained (Mohammed and Lindop, 2015a). Catches were on average 1,589 tonnes per year. Over the entire time period, the artisanal sector was most important (47.2%), followed by industrial (28.4%) and subsistence fisheries (24.1%). However, each sector's relative contribution to overall catches has changed over time, with industrial and artisanal fisheries' gaining in importance and subsistence fisheries' declining. Recreational fisheries accounted for 0.3% of catches. This trend was reflected in both total catches as well as landed value. Artisanal fisheries registered an increasing trend through to 1981 (840 tonnes), followed by a decline through to 1987 (320 tonnes), with a subsequent dramatic rise through to 2001(1,603 tonnes), before declining and levelling off around 1,000 tonnes. In general, industrial fisheries followed the trend of overall catches through time, with a dramatic peak in catches in 1978 (1,554 tonnes) and strong subsequent decline in 2013. Subsistence fisheries on the other hand remained relatively stable with a slight decline across the time series considered. Discards and unreported catches were relatively low accounting for 1.3% and 10.5% of total reconstructed catches, respectively.

Small-scale fisheries were the most common sub-sector in Saint Lucia (74.1%), followed by longlines (10.6%). Mackerels, tunas and bonitos (Scombridae) accounted for the largest proportion of total catches (23.3%), followed by mixed marine fishes (21.5%), common dolphinfish (*Coryphaena hippurus* 14.9%) and jacks and pompanos (13.43% Carangidae). These groups dominated artisanal catches as well as industrial catches, with Carangidae and reef-associated species such as snappers (Lutjanidae) groupers (Serranidae), triggerfish (Balistidae) being important in subsistence catches. In aggregate, pelagic groups contributed 55.8% to overall reconstructed catches with large pelagics accounting for 41.2% of this total. Taken together, reef-associated fishes and invertebrates made up 19.7% of total reconstructed catches.

[14] Details regarding method and data sources for the catch reconstruction effort for Saint Lucia are detailed in Mohammed and Lindop (2015a) and follow the approach outlined in Section 3.1.1. above.

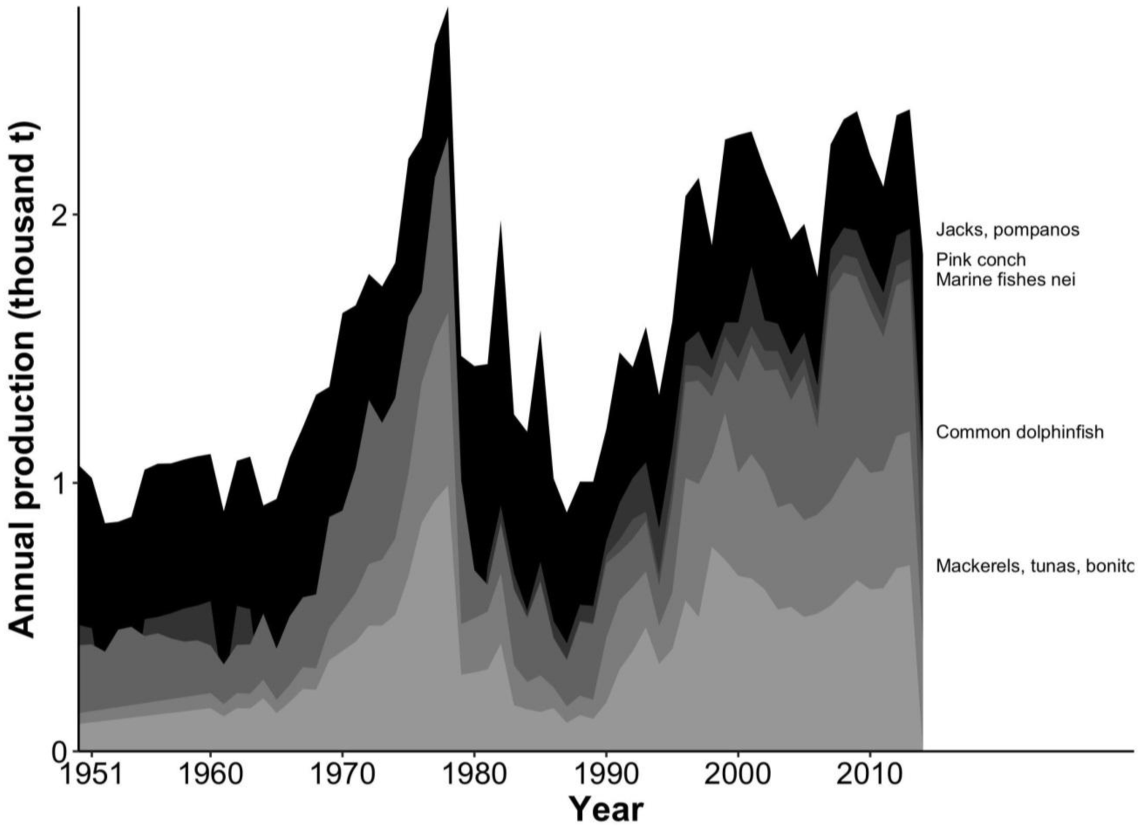


Figure 22. Reconstructed catches from the EEZ of St Lucia from 1950 to 2014. Total catches are plotted in black, while key species groups contributing to those catches over time are plotted in different shades of grey. Data source: Sea Around Us (www.seaaroundus.org).

3.5.1.2 *Climate change*

Like other islands in the region, Saint Lucia is exposed to severe storms and has difficulty in re-activating development processes following such events. In 2010, Hurricane Tomas caused USD336 million in damages - including to fishing vessel, gear and coastal infrastructure -, and cost the island the equivalent of 43.4% of its GDP. In 2013, an unseasonal low-pressure system associated with catastrophic rainfall caused USD89.2 million in damages (Government of Saint Lucia, 2018). Heightened sedimentation from these events threatens the health of coastal ecosystems and the services coastal communities depend on for their livelihoods, food security, cultural identity and income. These events highlight the dramatic impact extreme weather events can have and the need to adapt to projected changes in the future. Nevertheless, despite heightened exposure (and sensitivity) to climate change, in the study by Blasiak *et al*. (2017), fisheries in Saint Lucia emerged as the least vulnerable of the six countries considered here mainly because of the island's higher adaptive capacity when compared to the other nations (based on the variables considered).

Saint Lucia's current fisheries legislation is dated and will need to be reformed in order to be better equipped to respond to future challenges. Hence aligning current regulations with more recent international fisheries agreements would support implementation of existing mechanisms and the adaptation of governance mechanisms to address climate change, including the need to engage with other countries in the region in regards to shifting stocks (George *et al*., 2015). It would also assist in supporting enforcement and addressing conflicts within a given fisheries sector and across economic sectors (e.g., tourism) (George *et al*., 2015), which are only likely to be exacerbated given projected changes (Spijkers *et al*., 2018). Saint Lucia has developed and adopted a climate change adaptation plan which it defined as a ten (10)-year process (2018-2028) and consisting of priority cross-sectoral and sectoral adaptation measures for eight key sectors/areas, including fisheries (Government of Saint Lucia, 2018).

Increasing atmospheric CO_2 concentration was projected to increase ocean temperature and salinity in the EEZ of Saint Lucia (Figure 23). Based on the projections from the coupled ocean-atmospheric climate model GFDL CM 2.6, sensitivity of sea surface and sea bottom temperature to atmospheric CO_2 concentration in the EEZ was 0.61^{o}C per 100 ppm CO_2 and 0.063^{o}C per 100 ppm CO_2, respectively. Sea surface salinity was also projected to increase, at rates of 0.109 unit per 100 ppm CO_2. However, no clear trend was projected for sea bottom salinity.

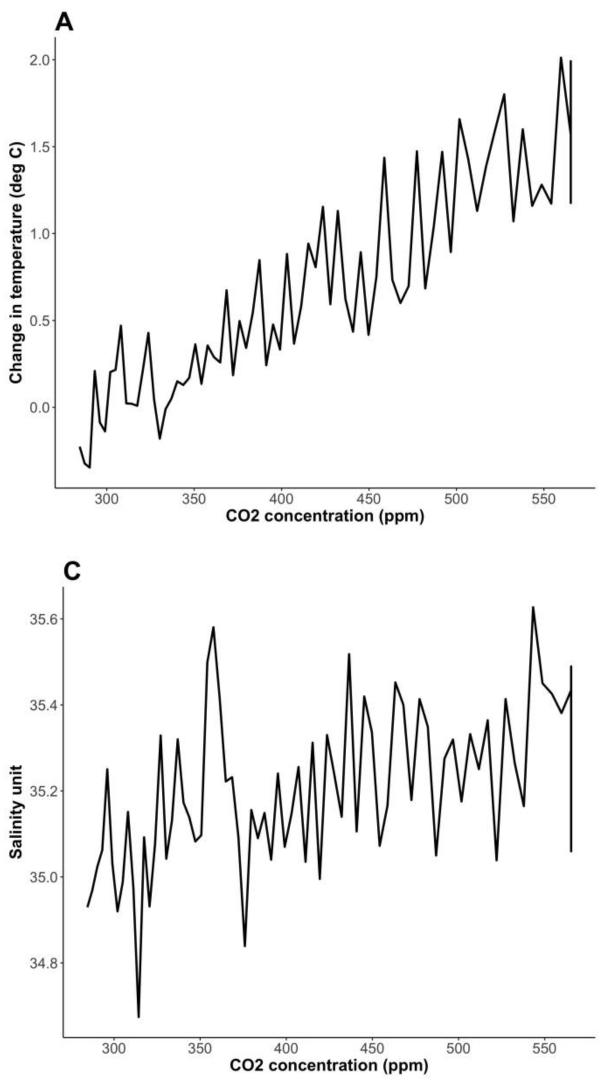


Figure 23. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (^{o}C), (B) sea bottom temperature (^{o}C), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels for the EEZ of St Lucia.

3.5.2 <u>Vulnerability of exploited species</u>

Vulnerability of selected species occurring in the Saint Lucia EEZ was evaluated as moderate (Table 5). A total of 72 of the selected study species were reported to occur in the EEZ of Saint Lucia (i.e., in the Changing Ocean Research Unit global marine biodiversity database), with a median climate vulnerability index of 57.0 (25th and 75th quartiles = 43.5 and 66.0, respectively, with 100 = maximum vulnerability). Amongst the 72 species, dog snapper (*Lutjanus jocu*, index =90), mutton snapper (*Lutjanus analis*, index = 90), and blue parrotfish (*Scarus coeruleus*, index = 90) registered the highest vulnerabilities. Spotted goatfish (*Pseudupeneus maculatus*, index = 19), sergeant major (*Abudefduf saxatills*, index = 27) and mackerel scad (*Decapterus macarellus*, index = 24) on the other hand had the lowest vulnerabilities.

Table 5. Vulnerability and risk of impacts of selected species in Saint Lucia. Vul : vulnerabilities, Risk : risk of impact, Status-quo : current exploitation status, OverF : overfishing scenario, Sust : sustainable fishing scenario.

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Epinephelus guttatus	Red hind	81	92	95	83	93	97	85
Sphyraena picudilla	Southern sennet	66	91	95	86	97	100	87
Lutjanus analis	Mutton snapper	90	92	95	85	92	95	84
Lutjanus jocu	Dog snapper	90	90	94	80	90	94	80
Caranx latus	Horse eye jack	88	90	94	81	91	93	81
Lutjanus mahogoni	Mahagony snapper	73	90	92	79	92	95	84
Scarus coeruleus	Blue parrotfish	90	85	91	67	85	91	67
Acanthurus bahianus	Ocean surgeon	46	89	91	76	93	96	83
Haemulon parra	Sailor's grunt	61	88	90	76	92	95	85
Calamus calamus	Porgy	53	87	90	74	90	94	83
Sparisoma viride	Stoplight parrotfish	71	83	90	67	87	92	74
Lutjanus buccanella	Blackfin snapper	87	82	89	67	82	89	69
Epinephelus adscensionis	Rock hind	54	85	89	70	90	94	80
Scarus coelestinus	Midnight parrotfish	88	80	89	66	80	89	65
Haemulon melanurum	Cottonwick grunt	59	82	89	65	87	92	76
Hemiramphus balao	Balao halfbeak	27	87	88	76	93	97	82
Tetrapturus pfluegeri	Longbill spearfish	63	78	87	59	83	89	67
Scarus taeniopterus	Princess parrotfish	61	84	87	71	86	91	76
Sparisoma aurofrenatum	Redband parrotfish	35	80	87	62	86	91	74

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Sargocentron vexillarium	Dusky squirrelfish	54	81	87	56	85	90	71
Thunnus obesus	Bigeye tuna	44	77	86	59	83	89	72
Mulloidichthys martinicus	Yellow goatfish	29	81	86	57	87	90	70
Lutjanus griseus	Gray snapper	88	79	86	62	78	86	63
Acanthurus chirurgus	Doctorfish	59	83	86	68	85	89	73
Tetrapturus georgii	Roundscale spearfish	61	75	86	65	82	90	71
Neoniphon marianus	Longjaw squirrelfish	29	76	86	57	83	89	69
Thunnus atlanticus	Blackfin tuna	75	75	85	58	75	85	60
Haemulon chrysargyreum	Smallmouth grunt	55	80	85	59	84	88	67
Scarus iseri	Striped parrotfish	55	82	85	66	84	88	72
Hirundichthys affinis	Fourwinf flyingfish	64	73	84	60	79	88	65
Scarus vetula	Queen parrotfish	87	73	84	59	73	85	61
Thunnus thynnus	Atlantic bluefin tuna	38	76	83	61	83	88	66
Coryphaena hippurus	Common dolphinfish	61	70	82	59	79	88	67
Pseudupeneus maculatus	Spotted goatfish	19	71	82	49	77	84	65
Mycteroperca interstitialis	Yellowmouth grouper	88	68	82	50	68	82	50
Caranx crysos	Blue runner	46	69	81	53	78	87	66
Sparisoma chrysopterum	Redtail parrotfish	56	68	81	56	77	88	62
Haemulon plumierii	White grunt	43	67	81	57	78	88	68
Sargocentron coruscum	Reef squirrelfish	66	68	81	56	76	86	65
Hemiramphus brasiliensis	Ballyhoo halfbeak	45	70	80	55	79	87	62
Sphyraena barracuda	Great barracuda	49	69	80	54	79	87	65
Lutjanus synagris	Lane snapper	73	70	80	55	79	86	62
Lachnolaimus maximus	Hogfish	88	63	80	50	63	80	50
Scomberomorus regalis	Cero	57	67	79	50	78	87	61

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Selar crumenophthalmus	Bigeye scad	58	67	79	56	77	86	63
Cephalopholis fulva	Coney	58	68	79	51	79	87	63
Kajikia albida	White marlin	56	66	79	51	77	86	60
Makaira nigricans	Blue marlin	50	64	78	52	74	85	60
Clepticus parrae	Creole wrasse	46	67	78	52	77	86	60
Haemulon flavolineatum	French grunt	36	67	78	53	81	89	63
Scomberomorus cavalla	King mackerel	55	64	77	47	76	86	58
Thunnus albacares	Yellowfin tuna	39	63	76	47	75	85	58
Opisthonema oglinum	Atlantic thread herring	52	65	76	44	77	84	55
Caranx hippos	Crevalle jack	60	64	76	44	76	85	56
Acanthocybium solandri	Wahoo	68	63	76	45	73	84	52
Balistes vetula	Queen triggerfish	59	62	76	50	67	79	55
Thunnus alalunga	Albacore tuna	39	68	75	46	77	82	54
Sparisoma rubripinne	Yellowtail parrotfish	64	55	75	42	63	80	47
Panulirus argus	Caribbean spiny lobster	64	61	74	46	67	79	55
Katsuwonus pelamis	Skipjack tuna	39	61	73	40	74	83	52
Halichoeres radiatus	Puddingwife wrasse	66	60	73	44	66	78	49
Holocentrus adscensionis	Squirrelfish	57	54	71	39	68	82	46
Holocentrus rufus	Longspine squirrelfish	42	59	71	38	73	81	51
Isostichopus badionotus	Three rowed sea cucumber	69	54	71	40	59	75	43
Haemulon aurolineatum	Tomtate	31	55	70	33	71	81	47
Abudefduf saxatilis	Sergeant major	27	57	69	42	66	77	49
Myripristis jacobus	Blackbar soldierfish	36	50	69	30	67	82	43
Thalassoma bifasciatum	Bluehead wrasse	53	53	68	36	62	73	42
Decapterus macarellus	Mackerel scad	24	54	66	30	70	77	42

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Cephalopholis cruentata	Graysby	34	46	59	32	46	58	35
Acanthurus coeruleus	Blue tang	31	40	59	23	51	68	34

Risk of impacts as a result of fishing and climate change were evaluated as moderate to high in the EEZ of Saint Lucia under the status quo fishing and both RCP2.6 and RCP8.5 scenarios (Table 5). Across the 72 selected species that occur in the EEZ of Saint Lucia, the median risk of impact index was 70.0 (25th and 75th quartiles = 63.5 and 81.5, respectively) and78.0 (25th and 75th quartiles = 73.5 and 85.0, respectively) under RCP2.6 and RCP8.5, respectively, with status quo fishing scenario (i.e., an Ocean Health Index (fisheries) value of 0.31; meaning ~ 31% of fish stocks were considered to be sustainably exploited). Under a sustainable fishing scenario (i.e., the Ocean Health Index (fisheries) value is estimated at twice the current value, meaning a high proportion of fish stocks are sustainably exploited), the risk of impact index decreased to 56.0 and 63.0 under RCP2.6 and RCP8.5, respectively. In contrast, under a scenario of continued overfishing, the risk of impact index increased to 81.0 and 87.0, respectively under both RCP 2.6 and RCP8.5.

Amongst the 72 selected species, those with the highest risk of impact index included red hind (*Epinephelus guttatus*), southern sennet (*Sphyraaena picudilla*) and mutton snapper (*Lutjanus analis*) (Table 5). Those with the lowest risk of impact index included mackerel scad (*Decapterus macarellus*), graysby (*Cephalopholis cruentata*), and blue tang (*Acanthurus coeruleus*).

3.5.3 Projected changes in habitat suitability

Changes in ocean conditions under increased atmospheric CO_2 concentration were projected to result in a decrease in the habitat suitability for selected species in the EEZ of Saint Lucia (Figure 24). Overall, the sum of the habitat suitability indices across the selected species in the EEZ of Saint Lucia was projected to decrease by 25.6% and 39.2%, under atmospheric CO_2 concentrations that would be similar to the 2030-2039 and 2050-2059 periods under RCP8.5. Species that were projected to have the largest declines in HSI include donkey dung sea cucumber (*Holothuria (Halodeima) Mexicana*), the Florida sea cucumber (*Holothuria (Halodeima) floridana*) and the vermilion snapper (*Rhomboplites aurorubens*) (see online data portal associated with this project for maps of HSI for all individual species).

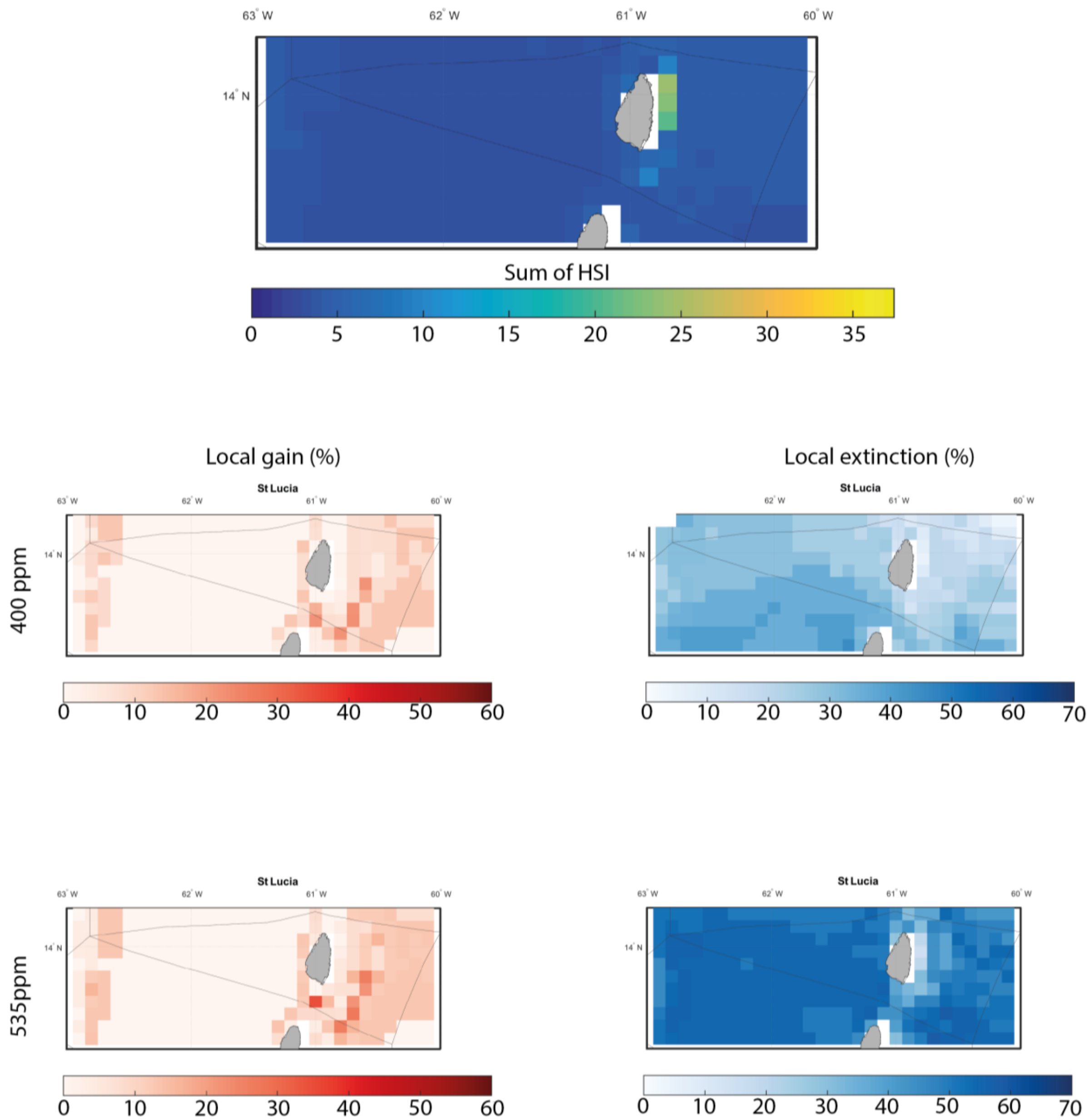


Figure 24. Current habitat suitability index and projected climate risk for marine biodiversity in the EEZ of Saint Lucia. Sum of HSI for the current period (1970 to 2000) across the selected species (top). Climate risk represented as projected change of: percentage of species gained relative to current species richness with atmospheric CO_2 concentration of 400 ppm (upper left) and 535 ppm (lower left), and percentage of species local losses (extinction) relative to current species richness under the 400 ppm (upper right) and 535 ppm (lower right) CO_2 concentration scenarios.

A substantial proportion of the Saint Lucia EEZ was projected to undergo a high rate of local species gains and losses (Figure 24). The eastern parts of the EEZ were projected to experience particularly higher rates of local species gains with some areas gaining 50% or above new species relative to current species richness. In contrast, local extinction rates were projected to be high (>50% relative to current species richness) in the western part of the EEZ.

3.5.4 Projected changes in fisheries catches

Maximum catch potential (MCP) was projected to decline in the EEZ of St. Lucia across time frames and scenarios (Figure 25). We projected that catch potential will decline by 5% to 15% and 10% to 30% by 2030-2039 and 2050-2059 relative to the 1970-2000 period, respectively, under RCP2.6. The projected declines in MCP almost doubled in both time frames under RCP8.5.

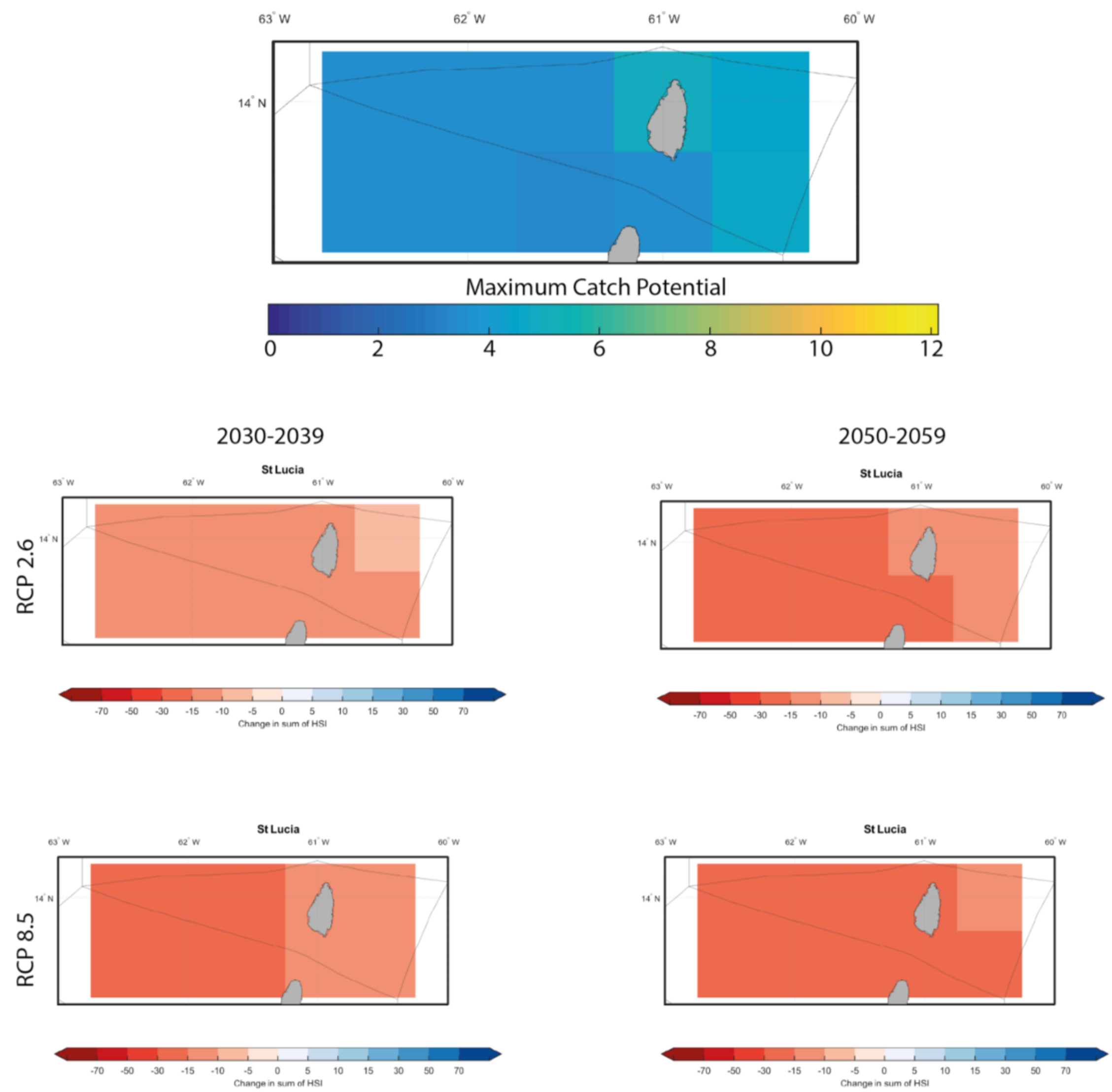


Figure 25. Projected changes in maximum catch potential in the EEZ of Saint Lucia using the Dynamic Bioclimate Envelope Model (DBEM) under RCP2.6 and RCP8.5 by 2030-2039 and 2050-2059 relative to 1970-2000. The results represent ensemble-average across outputs driven by three Earth system models (see paper A in this Collection): (top) projected distribution of current maximum catch potential, (middle row) RCP2.6, (bottom row) RCP8.5, (left) timeframe is 2030-2039 and (right) timeframe is 2050-2059.

3.5.5 Synthesis of key risks

Overall, key risks of climate impacts on marine species and fisheries were estimated across all species and RCPs with variations among species groups (Figure 26). Vulnerability and risk index were estimated to be generally high for all species, particularly ocean pelagics, groupers and parrotfish. Groupers, the Caribbean graysby and coney, and ocean pelagics were also projected to have the largest decline in habitat suitability index. Local invasion and extinction rates were high across all species groups. Invasion rate was particularly high for invertebrates and other reef fish. Local extinction rate was very high for reef pelagics, reef snappers, emperors, grunts, groupers, parrotfish, the graysby and coney (almost 100% under the high CO_2 concentration condition). Declines in maximum catch potential were projected to be high by the 2050s under RCP8.5 across most species groups. Parrotfish and other reef fish stand out as an exception as an insufficient number of species were included in DBEM for these two groups of fishes, thus the results may not be representative for the average responses of these groups.

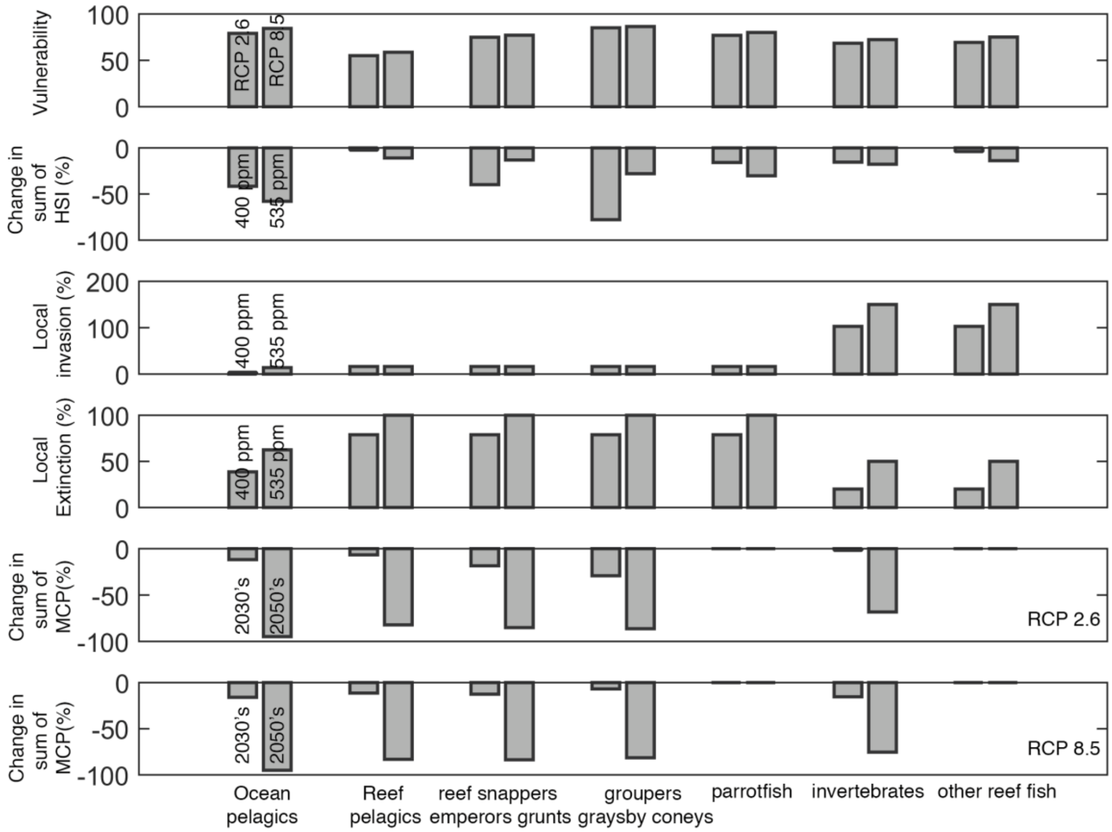


Figure 26. Projected climate risk indicators for Saint Lucia across different groups of marine species. The climate risk indicators include vulnerability index for the species groups, change in the sum of habitat suitability index (HSI) across species groups, rate of local invasion and local extinction, and changes in maximum catch potential (MCP).

3.6 Saint Vincent and the Grenadines (SVG)

3.6.1 Fisheries catch time series and climate change challenges

3.6.1.1 Fisheries

The fisheries of Saint Vincent and the Grenadines (SVG) are composed of an artisanal and subsistence sector, with an industrial sector only developing in the 1990s with the introduction of a multi-gear fleet (Mohammed and Lindop, 2015b). Inshore fisheries target reef-associated fish species using handlines, bottom-set longlines, fish pots, spear guns and trammel nets, while lobsters (*Panulirus argus*), urchins (*Tripneustes ventricosus*) and conch (*Lobatus gigas*) are caught by divers. The coastal small pelagic fishery uses cast nets and beach seines, and large pelagics such as tuna and marlin are caught offshore using troll and surface longlines. A small whaling industry still persists, targeting mainly short-finned pilot whales (*Globicephala macrorhynchus*) and humpback whales (*Megaptera novaeangliae*). Between 1981 and 2012 records indicate that 32 humpbacks were killed, while fishermen of Barrouallie indicate harpooning between 200 and 300 pilot whales and dolphins per year (de Verteuil, 2017). While part of the same country, there is a clear distinction in the dominant fisheries between St Vincent and the Grenadines, with the former mainly targeting pelagic species and the latter more reef-associated species, including conch and lobster.

Total reconstructed catches amounted to 131,948 tonnes from 1950 to 2014, with an average of 2,029 tonnes per year. St. Vincent contributed most of the catch for the country (Mohammed and Lindop, 2015b). Catches followed an overall increasing trend over the entire the time period, mainly as a result of the island's government support to increase local fish catches and employment in the fishing industry, yielding concomitant increases in landings primarily in the St. Vincent inshore fishery (Mohammed and Lindop, 2015b). Catches initially peaked in 1982 (3,439 tonnes). Catches subsequently declined, levelling out through the 1980s and 1990s, with periodic spikes every few years, before declining in 1995 (1,523 tonnes). This decline was likely associated with impact of Hurricane Allen, high costs of engines and scarcity of spare parts, as well as sharp increases in fuel prices and the lack of a proportional increase in fish price (Matthes, 1984 cited in Mohammed and Lindop, 2015b). Overall, catches then increased to the end of the time period, but with significant fluctuations, before abruptly declining in 2014 (1,580 tonnes) (Figure 27). The increases in catches throughout the 2000s were a result of improvements and the establishment of facilities through a variety of official development initiatives as well as the increased targeting of offshore species. Low catches toward the end of the time series are less easily explained.

Over the entire time period, the artisanal and industrial sectors dominated catches (39.4% and 39.2% respectively), followed by the subsistence fleet (21.3%). This trend was reflected in both total catches as well as landed value. The artisanal and industrial sector followed similar trends through time, except in 1995 when artisanal catches peaked while those from the industrial sector abruptly declined (industrial catches peaked in 2003). Catches from subsistence fisheries stayed relatively constant through time. Discards and unreported catches accounted for 6.2% and 10.5% of 32.2% of total reconstructed catches, respectively.

Small-scale fisheries was the most common subsector in SVG (73.5%), followed by longlines (14.6%). Mackerel scad (*Decapterus macarellus*) accounted for the largest proportion of total catches (13.4%), followed by mixed marine fishes (12.3%), bigeye scad (*Selar crumenophthalmus* 8.6%), yellowfin tuna (*Thunnus albacares* 7.1%), red hind (6.3% Carangidae), spiny lobster (*Panulirus argus* 4.7%) and coney (*Cephalopholis fulva* 3.8%). Industrial fleets mostly landed a wide range of unidentified species and yellowfin tuna (18.8% and 18% respectively). The artisanal and subsistence sector mostly targeted mackerel scad and bigeye scad (19.9% and 13% and 26.3% and 16.1% respectively). In aggregate, pelagic groups contributed 46.7% to overall reconstructed catches with large pelagics accounting for 23.4% of this total. Taken together, reef associated fishes and invertebrates made up 29.9% of total reconstructed catches. A proportion of the catch of conch and lobster are traded illegally with Martinique and sold to Saint Lucia, however no detailed data currently exist for these. Similarly, catches by foreign vessels within SVG's EEZ are not available. Therefore, the reconstructed catches represent an underestimate of realized catches (Mohammed and Lindop, 2015b).

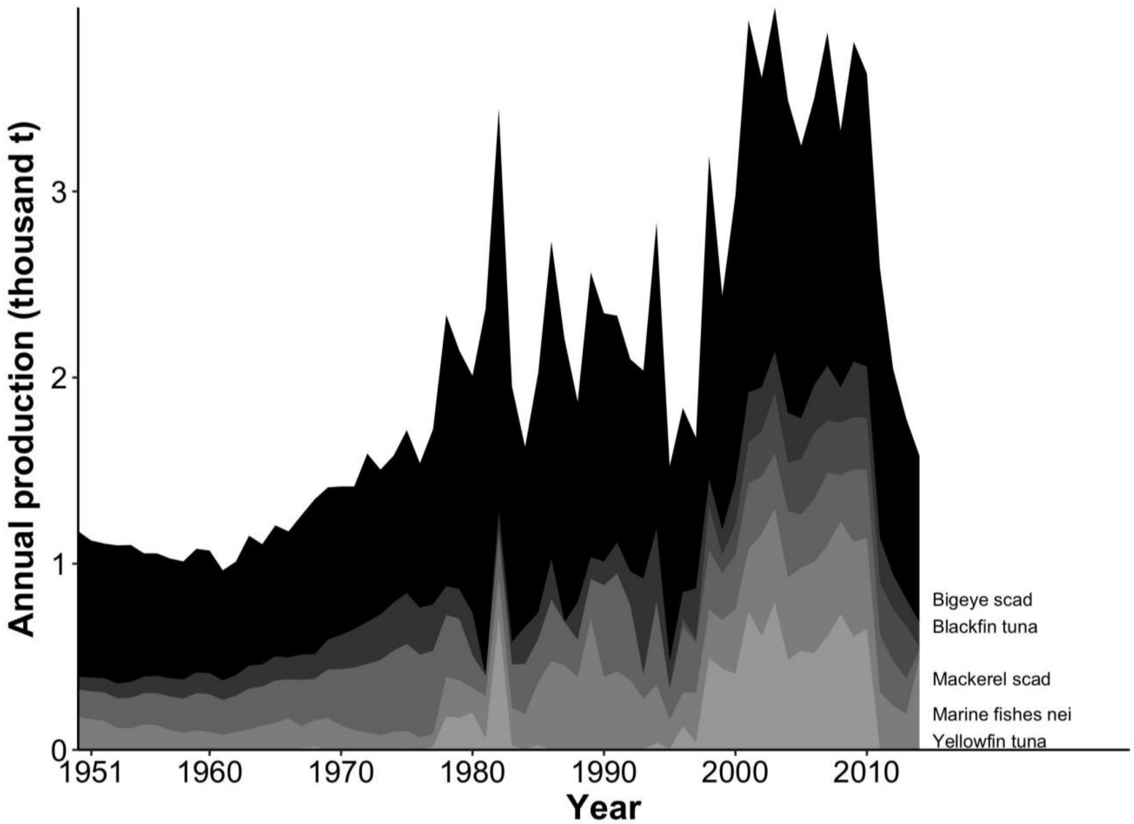


Figure 27. Reconstructed catches from the EEZ of Saint Vincent and the Grenadines from 1950 to 2014. Total catches are plotted in black, while key species groups contributing to those catches over time are plotted in different shades of grey. . Data source: Sea Around Us (www.seaaroundus.org).

3.6.1.2 Climate change

According to UNDP[15], St. Vincent and the Grenadines completed its First National Communication in 2000, which was "prepared in conjunction with the regional program for the Caribbean: Planning for Adaptation to Global Climate Change (CPACC)." As part of this initiative, a climate-monitoring station was established off the southwest coast of St. Vincent to compile a historical record of environmental change. The country also participated in a series of regional efforts to establish database and information systems, inventory coastal resources and uses, and formulate a policy framework for integrated coastal and marine management. Pilot studies were done on coral-reef monitoring for climate change, coastal vulnerability and risk assessment, economic valuation of coastal and marine resources, and formulation of economic/regulatory proposals."

Climate change is likely to exacerbate existing stressors such as deforestation, poor land-use practices - both resulting in increased sedimentation and smothering of coastal habitats such as coral reefs - coastal pollution and overexploitation of marine resources (CaribSave, 2012).

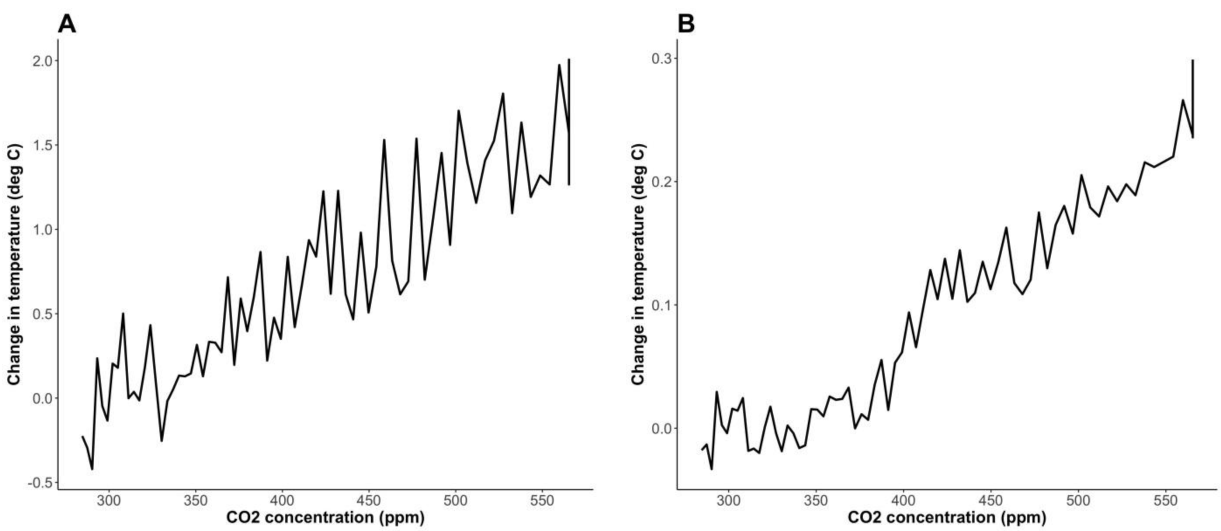
Although agriculture is the most important sector in St Vincent, the topography of the Grenadines limits involvement in this sector, with fisheries contributing substantially to livelihoods, local food security, and

[15] https://adaptation-undp.org/explore/caribbean/saint-vincent-and-grenadines

income. However, the agriculture sector is highly vulnerable to climate change impacts, notably rainfall patterns, as demonstrated by damages recorded after Hurricane Tomas and severe downpours causing flooding the following year (CaribSave, 2012). It is likely that as a result of such impacts, people would shift activities to increase the exploitation of coastal resources. Given the importance of pelagic fisheries in SVG, safety at sea may be jeopardized by projected increases in the intensity of storms, in turn limiting the ability of fishers to exploit offshore resources, and likely increasing pressure on inshore stocks. Coastal infrastructure, including that used by fishing fleets, and the vessels and gear themselves are at increased risk of being exposed to projected increases in sea level rise and intensity of severe weather events under climate change.

The country's good compliance record with existing regulatory mechanisms, such as the lobster fishery, underscores its relative high capacity at adapting to projected changes in the future (Blasiak *et al*., 2017). Under the 'Caribbean Challenge Initiative' St. Vincent and the Grenadines has committed to protecting 20% of its marine habitats by 2020.

Increasing atmospheric CO_2 concentration was projected to increase ocean temperature and salinity in the EEZ of SVG (Figure 28). Based on the projections from the coupled ocean-atmospheric climate model GFDL CM 2.6, sensitivity of sea surface and sea bottom temperature to atmospheric CO_2 concentration in the EEZ was 0.63 ^oC per 100 ppm CO_2 and 0.10 ^oC per 100 ppm CO_2, respectively. Sea surface salinity were also projected to increase, at rates of 0.115 unit per 100 ppm CO_2. However, sea bottom salinity was projected to increase only slightly, at a rate of 0.005 unit per 100 ppm CO_2.



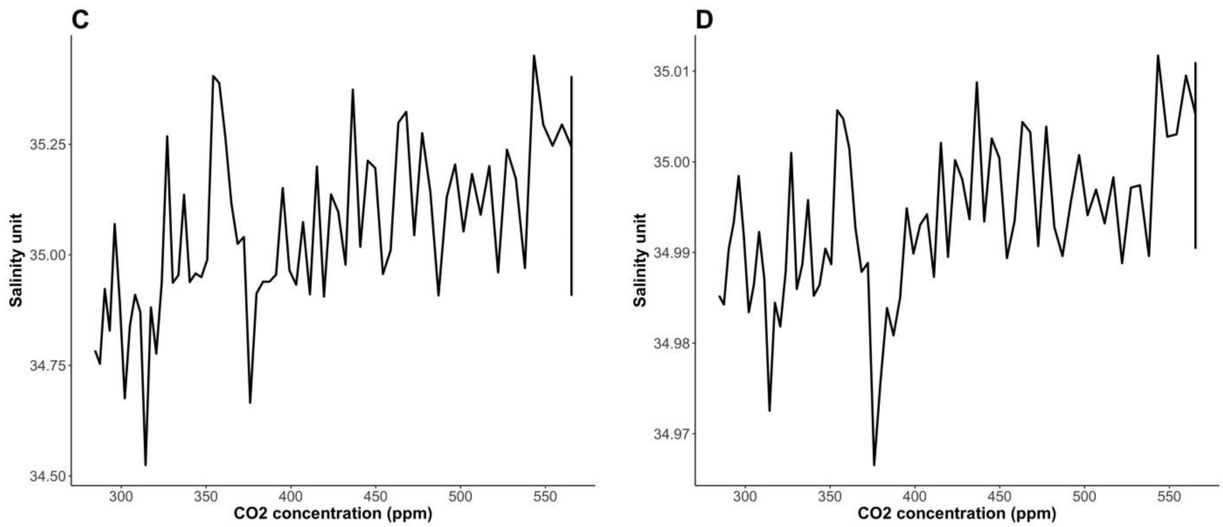


Figure 28. Projected ocean variables from GFDL CM2.6 for the Caribbean Sea region. Changes in (A) sea surface temperature (^oC), (B) sea bottom temperature (^oC), (C) sea surface salinity (‰), and (D) sea bottom salinity (‰) relative to pre-industrial levels for the EEZ of SVG

3.6.2 Vulnerability of exploited species

Vulnerability of selected species occurring in the SVG EEZ was evaluated to be moderate (Table 6). A total of 60 species of the selected study species were reported to occur in the EEZ of SVG (i.e., in the Changing Ocean Research Unit global marine biodiversity database), with a median climate vulnerability index of 55.5 (25th and 75th quartiles = 41.3 and 64.0, respectively, with 100 = maximum vulnerability). Amongst the 60 species, the ones with the highest vulnerability index were blue parrotfish (*Scarus coeruleus*, index =90), midnight parrotfish (*Scarus coeruleus*, index = 88), and hogfish (*Lachnolaimus maximus*, index = 88). Those with the lowest vulnerability index were spotted goatfish (*Pseudupeneus maculatus*, index = 19), sergeant major (*Abudefduf saxatills*, index = 27) and blue tang (*Acanthurus coeruleus*, index = 31).

Table 6. Vulnerability and risk of impacts of selected species in SVG. Vul : vulnerabilities, Risk : risk of impact, Status-quo : current exploitation status, OverF : overfishing scenario, Sust: sustainable fishing scenario.

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Ocyurus chrysurus	Yellowtail snapper	80	89	95	81	90	98	86
Epinephelus guttatus	Red hind	81	89	95	82	90	97	85
Acanthurus bahianus	Ocean surgeon	46	86	91	76	89	96	83
Scarus coeruleus	Blue parrotfish	90	83	90	63	83	90	63
Calamus calamus	Porgy	53	86	90	74	89	94	83
Sparisoma viride	Stoplight parrotfish	71	83	90	65	87	91	73
Epinephelus adscensionis	Rock hind	54	84	89	67	87	92	79

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Scarus coelestinus	Midnight parrotfish	88	79	88	63	78	88	63
Mulloidichthys martinicus	Yellow goatfish	29	75	87	57	84	91	69
Sparisoma aurofrenatum	Redband parrotfish	35	79	87	63	85	90	75
Thunnus obesus	Bigeye tuna	44	76	86	56	83	88	67
Tetrapturus pfluegeri	Longbill spearfish	63	78	86	57	83	89	64
Haemulon sciurus	Bluestriped grunt	34	79	86	57	85	89	72
Scarus taeniopterus	Princess parrotfish	61	82	86	69	84	89	73
Tetrapturus georgii	Roundscale spearfish	61	76	86	64	82	90	69
Thunnus thynnus	Atlantic bluefin tuna	38	77	84	62	83	88	66
Thunnus atlanticus	Blackfin tuna	75	74	84	56	74	85	58
Lutjanus mahogoni	Mahagony snapper	73	82	84	65	81	84	65
Hirundichthys affinis	Fourwinf flyingfish	64	72	84	60	78	88	65
Acanthurus chirurgus	Doctorfish	59	81	83	63	83	86	68
Coryphaena hippurus	Common dolphinfish	61	69	82	54	79	87	64
Scarus vetula	Queen parrotfish	87	69	82	56	69	82	57
Scarus iseri	Striped parrotfish	55	80	82	60	82	85	66
Caranx crysos	Blue runner	46	66	80	45	77	86	60
Pseudupeneus maculatus	Spotted goatfish	19	65	80	36	77	81	55
Sparisoma chrysopterum	Redtail parrotfish	56	66	80	55	75	87	60
Haemulon plumierii	White grunt	43	66	80	48	77	86	61
Istiophorus albicans	Sailfish	39	70	79	53	82	86	67
Hemiramphus brasiliensis	Ballyhoo halfbeak	45	64	79	52	73	86	59
Scomberomorus regalis	Cero	57	65	79	48	77	86	60
Lachnolaimus maximus	Hogfish	88	59	79	50	59	79	50
Kajikia albida	White marlin	56	66	79	49	77	86	59

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Makaira nigricans	Blue marlin	50	64	78	50	74	84	58
Haemulon chrysargyreum	Smallmouth grunt	55	66	78	49	65	78	49
Clepticus parrae	Creole wrasse	46	64	78	51	75	86	58
Scomberomorus cavalla	King mackerel	55	63	77	46	75	86	56
Selar crumenophthalmus	Bigeye scad	58	63	77	45	72	84	53
Elagatis bipinnulata	Rainbow runner	72	58	77	43	68	83	51
Thunnus alalunga	Albacore tuna	39	69	76	47	77	82	54
Cephalopholis fulva	Coney	58	59	76	43	73	85	55
Acanthocybium solandri	Wahoo	68	61	76	44	71	84	51
Thunnus albacares	Yellowfin tuna	39	62	75	45	74	84	56
Haemulon carbonarium	Caesar grunt	63	59	74	37	58	74	37
Sparisoma rubripinne	Yellowtail parrotfish	64	52	74	43	59	79	48
Haemulon flavolineatum	French grunt	36	60	74	50	73	87	61
Katsuwonus pelamis	Skipjack tuna	39	59	73	39	72	83	49
Sargocentron vexillarium	Dusky squirrelfish	54	58	73	34	58	73	35
Halichoeres radiatus	Puddingwife wrasse	66	55	71	39	60	74	43
Panulirus argus	Caribbean spiny lobster	64	56	70	40	62	75	47
Holocentrus rufus	Longspine squirrelfish	42	52	70	32	67	82	45
Balistes vetula	Queen triggerfish	59	54	68	34	54	68	34
Holocentrus adscensionis	Squirrelfish	57	44	68	38	57	78	45
Isostichopus badionotus	Three rowed sea cucumber	69	50	68	38	53	71	40
Sargocentron coruscum	Reef squirrelfish	66	55	68	36	54	67	37
Abudefduf saxatilis	Sergeant major	27	53	66	38	60	72	45
Thalassoma bifasciatum	Bluehead wrasse	53	48	64	33	55	69	37

Scientific name	Common name	Vul	Risk: Status quo-2.6	Risk: OverF-2.6	Risk: Sust-2.6	Risk: Status quo-8.5	Risk: OverF-8.5	Risk: Sust-8.5
Decapterus macarellus	Mackerel scad	24	43	64	20	60	78	33
Myripristis jacobus	Blackbar soldierfish	36	39	64	29	56	79	42
Cephalopholis cruentata	Graysby	34	41	55	23	41	55	25
Acanthurus coeruleus	Blue tang	31	35	54	22	44	62	30

Risk of impacts as a result of fishing and climate change were evaluated as moderate to high in the EEZ of SVG under the status quo fishing and both RCP2.6 and RCP8.5 scenarios (Table 6). Across the 60 selected species that occur in the EEZ of SVG, the median risk of impact index was 66.5 (25th and 75th quartiles = 58.0 and 77.3, respectively) and 75.0 (25th and 75th quartiles =61.5 and 82.3, respectively) under RCP2.6 and RCP8.5, respectively, with status quo fishing scenario (i.e., an Ocean Health Index (fisheries) value of 0.41; meaning ~ 41% of fish stocks were considered to be sustainably exploited). Under a sustainable fishing scenario (i.e., the Ocean Health Index (fisheries) is estimated at twice the current value, meaning a high proportion of fish stocks are sustainably exploited), the risk of impact index decreased to 49.5 and 58.0 under RCP2.6 and RCP8.5, respectively. In contrast, under a scenario of continued overfishing, the risk of impact index increased to 79.0 and 85, respectively under RCP 2.6 and RCP8.5. Amongst the 60 selected species, those with the highest risk of impact index included yellowtail snapper (*Ocyurus crysurus*), red hind (*Epinephelus guttatus*) and ocean surgeon (*Acanthurus bahianus*) (Table 6).

3.6.3 Projected changes in habitat suitability

Changes in ocean conditions under increased atmospheric CO_2 concentration were projected to result in a decline in the habitat suitability for selected species in the EEZ of SVG (Figure 29). Overall, the sum of habitat suitability index across the selected species in the EEZ of SVG was projected to decline by 31.4% and 46.6%, under atmospheric CO_2 concentrations that would be similar to the 2030-2039 and 2050-2059 periods under RCP8.5. Species that were projected to have the largest decrease in HSI include donkey dung sea cucumber (*Holothuria (Halodeima) mexicana*), Atlantic bluefin tuna (*Thunnus* thynnus) and Atlantic sailfish (*Istiophorus albicans*) (see online data portal associated with this project for maps of HSI for all individual species).

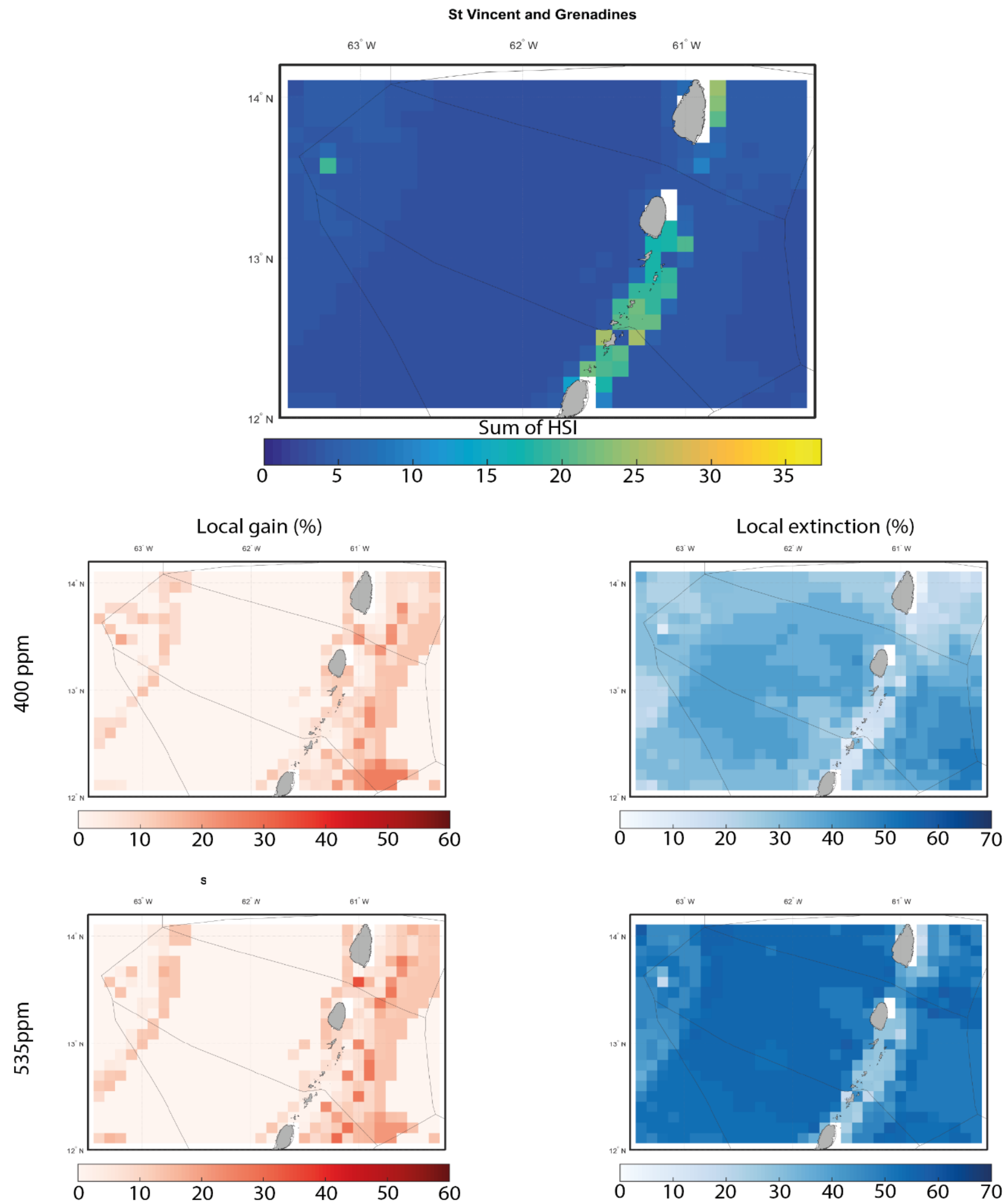


Figure 29. Current habitat suitability index and projected climate risk for marine biodiversity in the EEZ of SVG. Sum of HSI for the current period (1970 to 2000) across the selected species (top). Climate risk represented as projected change of: percentage of species gained relative to current species richness with atmospheric CO_2 concentration of 400 ppm (upper left) and 535 ppm (lower left), and percentage of species local losses (extinction) relative to current species richness under the 400 ppm (upper right) and 535 ppm (lower right) CO_2 concentration scenarios.

A substantial proportion of SVG's EEZ was projected to have high rates of local species gains and losses (Figure 29). The eastern parts of the EEZ were projected to have particularly higher rates of local species gains with some areas gaining 50% or above new species relative to current species richness. In contrast, local extinction rates were projected to be high (>50% relative to current species richness) in the western part of the EEZ.

3.6.4 Projected changes in fisheries catches

Maximum catch potential (MCP) was projected to decline in the EEZ of SVG across time periods and scenarios (Figure 30). We projected that catch potential will decline by 5% to 15% and 10% to 30% by 2030-2039 and 2050-2059 relative to the 1970-2000 period, respectively, under RCP2.6. The projected declines in MCP almost doubled in both time periods under RCP8.5.

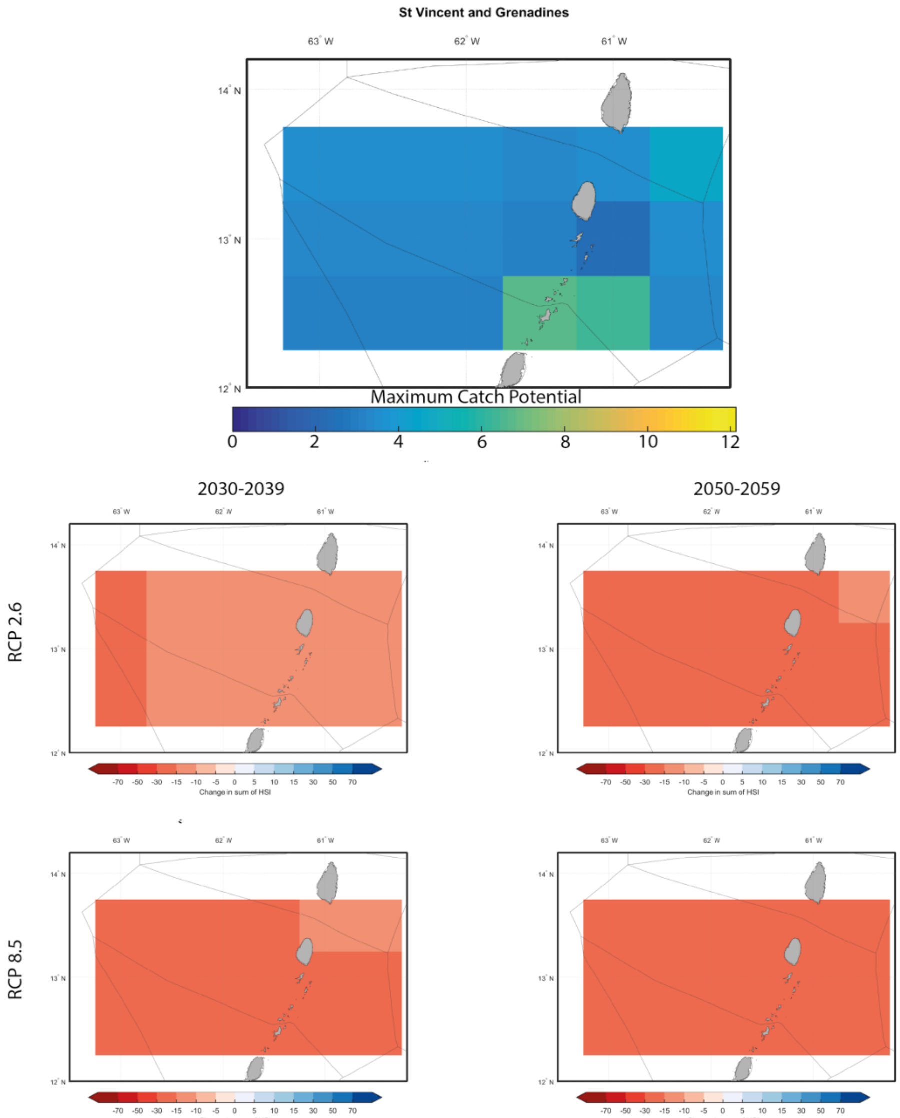


Figure 30. Projected changes in maximum catch potential using the Dynamic Bioclimate Envelope Model (DBEM) under RCP2.6 and RCP8.5 by 2030-2039 and 2050-2059 relative to 1970-2000. The results represent ensemble-average projections across outputs driven by three Earth system models (GFDL, IPSL, MPI - see report (Part A)): (top panel) projected distribution of current maximum catch potential, (middle row) projected distribution of maximum catch potential under RCP2.6, (bottom row) projected distribution of maximum catch potential under RCP8.5, (left) timeframe is 2030-2039 and (right) timeframe is 2050-2059.

3.6.5 Synthesis of key risks

Overall, key risks of climate impacts on marine species and fisheries were estimated across all species and RCPs with variations among species groups (Figure 31). Vulnerability and risk index were estimated to be generally high for all species, particularly ocean pelagics, groupers and parrotfish. Groupers, the Caribbean graysby and coney, and ocean pelagics were also projected to have the largest declines in habitat suitability index. Invasion and local extinction rates were high across all species groups. Invasion rates were particularly high for invertebrates and other reef fish. Local extinction rates were very high for reef pelagics, reef snappers, emperors, grunts, groupers, parrotfish, the graysby and coney (almost 100% under the high CO_2 concentration condition). Declines in maximum catch potential were projected to be high by the 2050s under RCP8.5 across most species groups. Parrotfish and other reef fish stand out as an exception. An insufficient number of species were included in DBEM for these two groups of fishes, thus the results may not be representative for the average responses of these groups.

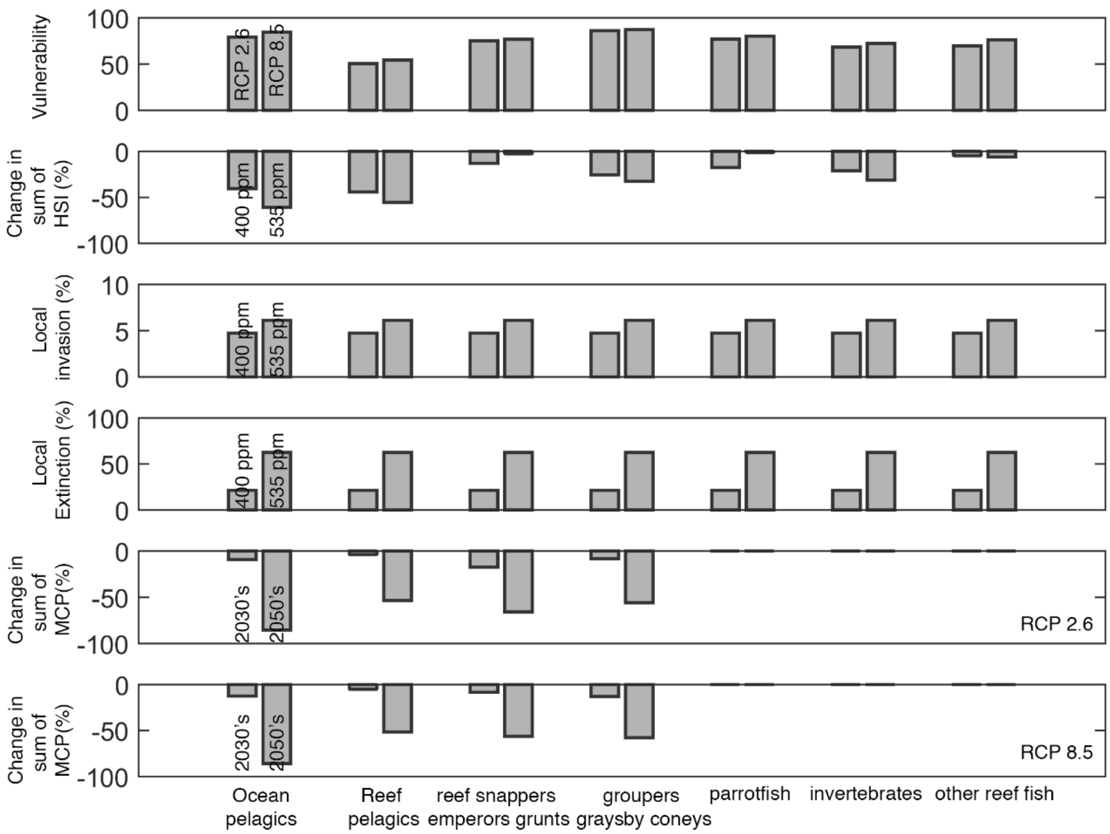


Figure 31. Projected climate risk indicators for SVG across different groups of marine species. The climate risk indicators include vulnerability index across species groups, change in the sum of habitat suitability index (HSI) across species groups, rate of local invasion and local extinction, and changes in maximum catch potential (MCP).

4 DISCUSSION

4.1 Risk and impacts of climate change

Overall, climate change is projected to have similarly high risk and projected impacts on marine biodiversity and fisheries in the case study countries. These result from their similar levels of increase in risk and impact indicators with higher atmospheric CO_2 concentration. The magnitude of risks and impacts is generally above the average of the Caribbean region overall (see paper A in this Collection). The similarity in risks and impacts among the six countries are expected given their close proximity and relatively small EEZ area. Thus, any major differences in climate risks at the country level would depend on the sensitivity and adaptive capacity of the social-economic system.

Spatial variations in climate risks and projected impacts in each case study country are mainly driven by the biogeography of selected species. Pelagic species (oceanic and reef) are generally exposed to particularly large changes in ocean conditions. Moreover, many species with high climate vulnerability have limited geographic range, rendering them highly sensitive to climate impacts. These small-ranged species are mostly demersal fishes that contribute to the high values of the risk indicators.

The projected large declines in maximum catch potential and high level of species turnover (local invasion and extinction) suggest that fisheries in these case study countries are expected to be exposed to large uncertainties around the future abundance of their fisheries resources. Such high risks to fisheries apply to resources that are targeted by larger scale pelagic fisheries as well as smaller scale reef fisheries.

Our analyses highlighted some opportunities for climate risk reduction of selected species through improvement in the status of exploitation of fisheries resources. As indicated by the Ocean Health Index (fisheries), fisheries resources in these six case study countries are considered to be overexploited. Our indicator analyses suggest that climate risk of considered species could be reduced considerably under more sustainable fishing scenarios. In contrast, continued overfishing coupled with high CO_2 concentrations would devastate fisheries resources. Of course, recovery and resilience of species to climate risk need to be considered through the lens of an integrated ecosystem-based approach to management that will need to consider impacts along a ridge to reef gradient. In other words, achieving current and future sustainability objectives will depend on the development and implementation of coherent strategies (Ali *et al*., 2018) that consider land-use patterns, habitat alterations, pollution as well as improvements in the exploitation status of fisheries resources in the six case study countries. These will need to be supported by adaptive governance frameworks that have been found to be “contingent upon developing holistic, integrated management systems, improving flexibility in existing collaborative decision making processes, augmenting the capacity of local management authorities with support from higher-level government, exploring opportunities for private–social partnerships, and developing adequate social–environmental monitoring programs ” (Pittman *et al*., 2015).

4.2 **Key uncertainties and challenges**

The overall patterns of climate risks and projected impacts elucidated from the indicators are robust. However, there are a number of key uncertainties to the analyses that should be noted when interpreting the findings. Uncertainties associated with the regional-scale analysis generally apply to the analysis of the case study countries as well; we therefore refer the reader to the discussion in the previous chapter in this Collection for details. The following points are highlighted here as they are particularly relevant to the case study analyses.

Although projected changes in ocean conditions are available at high resolution, these projections are based on only one coupled ocean-atmospheric climate model (CM 2.6) and one model realization. The model is new and as of yet, has not been officially released. Consequently, the model’s performance has not been as comprehensively evaluated as the coarser resolution Earth system models (GFDL, IPSL, MPI) that have been used more extensively and were part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). Also, the high-resolution model projections were only based on one idealized scenario of CO_2 emissions. We attempted to harmonize the idealized scenario with specific time periods of the RCPs that are the standard for climate change assessments in recent years; however, comparisons of model outputs among these scenarios should be considered semi-quantitative.

Indices of vulnerability/risk of impact and maximum catch potential were calculated using the coarser resolution CMIP5 models GFDL, IPSL, MPI - see paper A in this Collection. The (relative) coarse resolution of the outputs from these three Earth system models (1^o latitude x 1^o longitude) compared to the spatial expanse of the Caribbean, limits any detailed and specific quantitative interpretation of the projections at the scale of individual countries. However, these indicators were included in our analyses to provide a broad-scale understanding of the level of risks and impacts to climate change and to inform management frameworks designed to address climate change at this broad scale.

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C. ECONOMIC CONSEQUENCES OF CLIMATE CHANGE FOR THE FISHERIES SECTOR IN SIX CARIBBEAN COUNTRIES

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Abstract

The projected economic consequences of climate-induced ecological impacts on fishery production and consumption include:

- Domestic fish prices (averaged across all species groupings) will **increase** by 3.0% (Haiti) to 6.0% (Grenada) and by 3.2% (Haiti) to 6.1% (Grenada) in 2035 and 2055, respectively, under RCP 2.6. Under RCP 8.5, domestic fish prices will **increase** by 4.1% (Haiti) to 7.8% (St Lucia) and by 4.0% (Haiti) to 7.7% (Grenada) in 2035 and 2055, respectively. These **increases** are relative to projected prices in 2035 and 2055 under the reference case.

- Domestic fish consumption (across all species groupings) will **decrease** by 3.6% (Dominica) to 3.8% (Jamaica) and by 3.8% (Dominica) to 4.4% (SVG) in 2035 and 2055, respectively, under RCP 2.6. Under RCP 8.5, domestic fish consumption will **decrease** by 4.7% (Grenada) to 5.2% (Jamaica) and by 4.9% (Dominica) to 5.3% (Grenada) in 2035 and 2055, respectively. These **decreases** are relative to projected prices in 2035 and 2055 under the reference case.

- **Net *annual* income losses** (in 2010 US dollars) associated with the projected climate-induced changes in prices and consumption amount to: $410,000 (2035 under RCP 2.6) to $830,000 (2055 under RCP 8.5) in Dominica; $510,000 (2035 under RCP 2.6) to $930,000 (2055 under RCP 8.5) in Grenada; $4,130,000 (2035 under RCP 2.6) to $7,220,000 (2055 under RCP 8.5) in Haiti; $8,040,000 (2035 under RCP 2.6) to $14,580,000 (2055 under RCP 8.5) in Jamaica; $1,370,000 (2035 under RCP 2.6) to $2,920,000 (2055 under RCP 8.5) in St. Lucia; and $490,000 (2035 under RCP 2.6) to $850,000 (2055 under RCP 8.5) in SVG.

- **Reductions in fish consumption** (kg per capita per day) associated with the projected climate-induced changes in prices and consumption amount are: -3.6% (2035 under RCP 2.6) to -4.9 (2055 under RCP 8.5) in Dominica; -3.7% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in Grenada; -3.7% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in Haiti; -3.8% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in Jamaica; -3.6% (2035 under RCP 2.6) to -4.9% (2055 under RCP 8.5) in St. Lucia; and -3.7% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in SVG.

Simulated economic consequences of climate-induced increases in the intensity of a sample of 111 historical tropical cyclones that affected our case study countries between 1950-2013 include:

- For the central case,[16] climate change is projected to increase production losses from the same sample of 111 tropical cyclones reoccurring, but with increased intensities, by 3.0 kilo tonnes (kt) and 5.2 kt under RCP 2.6 and RCP 8.5, respectively, by the 2050s, and by 2.9 kt and 8.1 kt under RCP 2.6 and RCP 8.5, respectively, by the 2080s. These are incremental (additional) reductions relative to those experienced from the same sample of storm events impacting the case study countries in the absence of further climate change. The corresponding incremental reduction in revenues from landings by the 2050s are $4.8 million and $8.3 million (2010 US dollars) under RCP 2.6 and RCP 8.5, respectively. For the 2080s, incremental lost revenue from landings amounts to $4.6 million and $12.8 million under RCP 2.6 and RCP 8.5, respectively.

- Under RCP 2.6, in no country do projected incremental (production or landed value) losses from climate change impacts on tropical cyclone wind speeds exceed about 0.3% of historic totals. By the 2050s under RCP 8.5, projected incremental losses range from just under 0.4% of historic totals (for St. Lucia and SVG) to just over 0.5% of historic totals (for Jamaica). By the 2080s, the range of projected incremental losses has increased from just under 0.6% of historic totals (for St. Lucia and SVG) to just over 0.8% of historic totals (for Jamaica).

- For the central case, climate change is projected to increase *total* output losses from the sample of 111 tropical cyclones by $5.8 million and $10.1 million (2010 US dollars) under RCP 2.6 and RCP 8.5, respectively, by the 2050s, and by $5.6 million and $15.6 million under RCP 2.6 and RCP 8.5, respectively, by the 2080s. The drop in economic output due to climate change leads to a reduction in household incomes by the 2050s of $1.4 million and $2.4 million under RCP 2.6 and RCP 8.5, respectively. For the 2080s, incremental household income losses amount to $1.3 million and $3.7 million under RCP 2.6 and RCP 8.5, respectively.

- By the 2050s under RCP 2.6 the incremental impact on fish supply *across the six case study countries* equates to, on average, a reduction of about 0.35-0.60% in daily food supply as fish. The corresponding range of reductions in daily food supply as fish for the 2080s under RCP 8.5 is 0.55-0.90%.

1 INTRODUCTION

This chapter contributes to Work Package 1 of the project: *Fishery-Related Ecological and Socio-economic Impact Assessments and Monitoring System*. Specifically, this chapter addresses the following components of the overarching objectives of Work Package 1:

- Assess the socio-economic impacts of climate change and variability on the fisheries resources and sector
- Develop tools and methods for fisheries and marine ecosystem analyses and assessments to quantify the current and future impacts of climate change and variability on fisheries production.

Fisheries and marine resources in the Caribbean region are vulnerable to a range of climate change impacts. Among them, further rising sea surface temperatures (SST), increased ocean acidification, further sea-level rise (SLR), and increases in the (average) intensity of tropical cyclones are likely to exacerbate ongoing challenges facing the sector in the near- and long-term. These climate change impacts

[16] Calculations in the central case use average values for the wind speed coefficient and value for the percentage change in maximum wind speed for each degree Celsius rise in sea surface temperatures of 0.050.

will result in direct and secondary economic consequences for both harvesting and post-harvesting activities in the fisheries sector.

Data availability and interests of project stakeholders shaped the scope of the research in this chapter, which analyzes and presents the economic impacts of changes in fishery production (landings) due to:

- Changing ocean conditions (reflecting rising SSTs and ocean acidification), building on the results of the complementary ecological impact assessment, which generated estimates of changes in fishery production (catch) for each country under different climate scenarios (specifically, RCP (Representative Concentration Pathway) 2.6 and RCP 8.5); and
- Changes to the (average) intensity of tropical cyclones.[17]

We estimated economic impacts at the national level for each of the countries with Pilot Program on Climate Resilience (PPCR) activities: Dominica, Grenada, Haiti, Jamaica, Saint Lucia and Saint Vincent and the Grenadines (SVG). Throughout the chapter we refer to these countries as "case study countries".

2 ECONOMIC IMPACT OF FISH LANDINGS FROM SHIFTS IN OCEAN CONDITIONS

2.1 Methods

The economic impacts of climate-induced changes in fishery production (landings) are assessed using a market supply-demand model developed for our case study countries. It is based on the analytical framework developed by Dey *et al* (2016a), who evaluated the economic impacts of climate change and climate adaptation strategies for the fisheries sectors of Fiji, Solomon Islands, Timor-Leste and Vanuatu (see Dey *et al.*, 2016b; Dey *et al.*, 2016c; and Rosegrant *et al.*, 2016).

The conceptual framework underpinning the market supply-demand model is described below; for the full mathematical specification of the model see Dey *et al.* (2016a).

2.1.1 Conceptual Framework for a Supply-Demand Fish Model

The model is based on a standard supply and demand framework such as that shown in Figure 1. As a starting point, supply and demand curves are specified for major fish species groupings of interest for a base year period—denoted by the subscript "0" in panel (a). Annual average data over the period 2009-2013 is used to create the base year for the study (see Section 2.2.1). These data essentially define base year consumption (Q_0) and price (P_0).

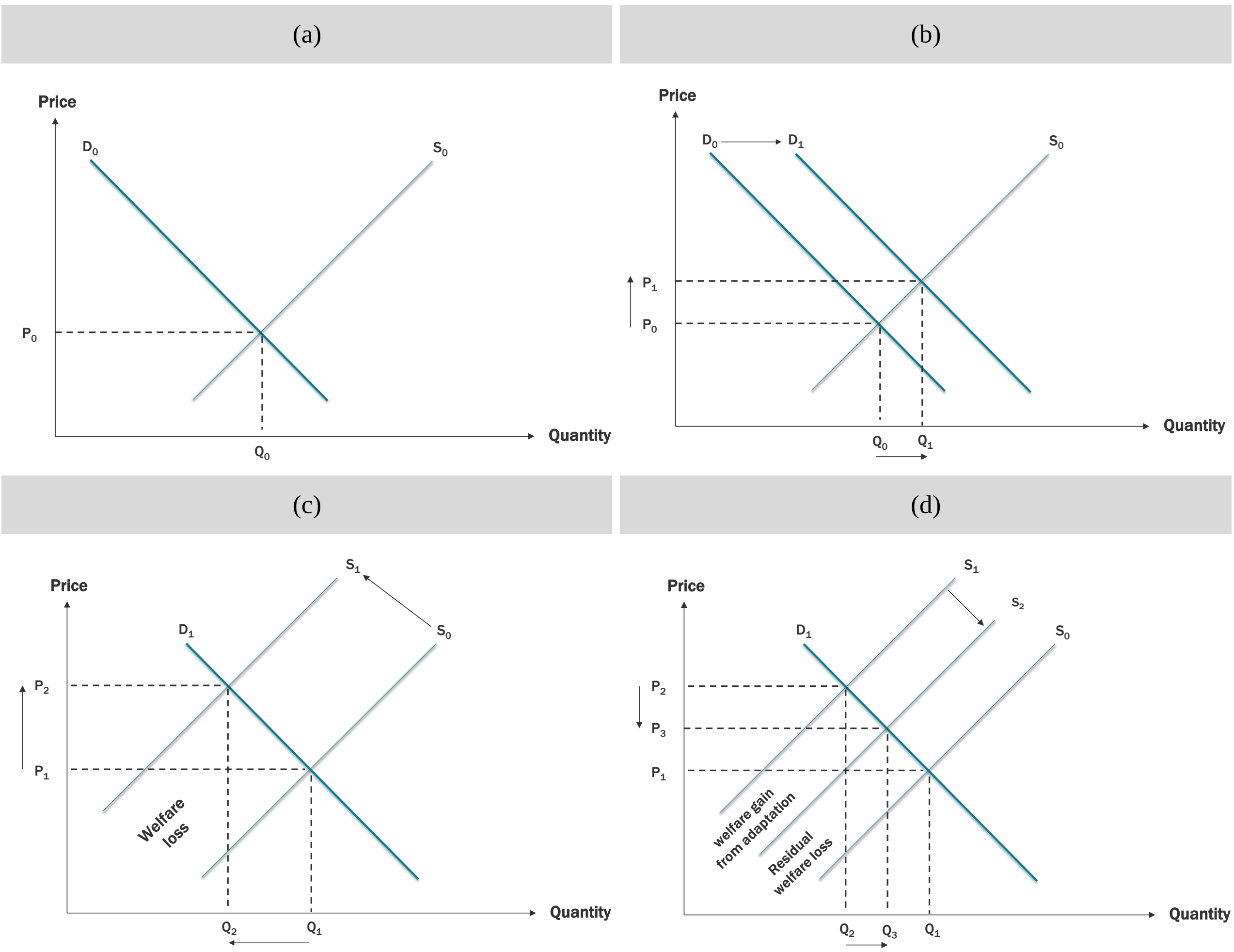
The analysis considers two future periods: the medium-term (2035) and the long-term (2055). These future periods are selected to match output of ecological assessments. In the future, the base year period demand curve (D_0) will shift outward due to growth in population and incomes, as indicated by D_1 in panel (b). All else being equal, this shift will result in higher fish consumption ($Q_0 \rightarrow Q_1$) and price ($P_0 \rightarrow P_1$). Future demand curves are generated for both 2035 and 2055 using the population and income projections outlined in Section 2.3 **Note: the new equilibrium (P_1, Q_1) depicted in panel (b), where D_1 intersects S_0, defines the *reference case* against which the economic impacts of climate change on fishery production are isolated and measured. The economic impacts of climate change are not**

[17] According to the NOAA National Weather Service website (https://www.weather.gov/jetstream/tc_classification): A tropical cyclone is an organized system of clouds and thunderstorms with a defined circulation. Tropical cyclones with maximum sustained winds of 38 miles per hour or less are called a "tropical depressions"; once maximum sustained winds reach 39 miles per hour they are called "tropical storms" and assigned a name. If maximum sustained winds reach 74 miles per hour the cyclone is called a "hurricane" in the North Atlantic Ocean. Hurricanes are further classified according to the Saffir-Simpson Hurricane Wind Scale: A Category 1 (very dangerous winds will produce some damage) to Category 5 (catastrophic damage will occur) rating based on the cyclone's present intensity (as measured by its wind speed).

measured relative to the situation shown in panel (a), namely (P_0, Q_0), since to do so would mix projected consequences of climate change with those due to socio-economic change.

Climate change is introduced into the model through externally-driven ("exogenous") supply shocks. Specifically, estimated percentage reductions in base year landings (by main fish species groupings, by climate scenario, and by future time period) obtained from the ecological assessment, are used to make proportional shifts in the base year supply curves. This is shown by the inward shift of the supply curve in panel (c), from S_0 to S_1. Given the new future demand curve, and all else being equal, the inward shift in the supply curve will result in an increase in fish price ($P_1 \rightarrow P_2$) and a reduction in fish consumption ($Q_1 \rightarrow Q_2$). Traditional economic welfare analysis can then be applied to measure the resultant welfare losses on the consumer side (as lost consumer surplus) and producer side (as lost producer surplus). **The aggregate reduction in consumer and producer surplus, indicated by the green shaded area in panel (c), provides a measure of the dollar value of the welfare loss due to climate-induced impacts on fishery production.** This in turn provides a benchmark against which to appraise the benefits of adaptation strategies in the sector.

Figure 1: Conceptual framework for market supply-demand model



The analysis of adaptation options is outside the scope of this study, nevertheless the model serves these purposes. Panel (d) illustrates how the model can be used to measure the benefits of planned adaptations that target the supply-side of the market, as an input to cost-benefit analysis. Aquaculture or effective fish aggregating devices, for example, would increase fish supply, thereby shifting the supply curve back to the right (from S_1 to S_2.), lowering price ($P_2 \rightarrow P_3$) and increasing consumption ($Q_2 \rightarrow Q_3$). The depicted changes will result in a welfare gain, given by the dollar value of the aggregate increase in consumer and producer surplus. **Note that when appraising adaptation strategies, the appropriate comparison is between panel (d) and panel (c).**

2.1.2 Estimating Total Economic Impacts

Fisheries are a primary extractive sector, where resources are harvested to supply intermediate and final demand elsewhere in the economy. As such, the act of fishing is the start of a value chain linking many secondary economic activities—like, for example, building docks and vessels, repairing gear, supplying ice and diesel fuel, operating fish markets, road transportation, to name a few. Most assessments of the economic impact of fisheries, however, fail to account for these secondary activities (often referred to as "multiplier effects" or, in the context of disasters from natural hazards, "ripple effects"). Indeed, the market supply-demand fish model described above only captures changes to the *direct* economic value of fishery output as a result of climate-induced changes to catch. Consequently, to capture the total economic impact at a national level, we use "multipliers" derived from Dyck and Sumaila (2010), who generated estimates of total economic output and household income attributable to fisheries for each country in the world, including our six case study countries.

The first three columns in Table 1 provide results from Dyck and Sumaila (2010) for the case study countries. The values represent the total gross value of output (column 2) supported by fish landings (column 1) and the total household income (column 3) throughout the economy supported by total gross output in the fishery sector, brought about by indirect and induced effects. Deriving output and income multipliers is relatively straightforward from these results. For example, the reported landed value of capture fisheries in Dominica in 2003 was US $2.87 million. This resulted in total economic output (i.e., direct, indirect and induced sales to final users and other industries in the economy) valued at US $3.49 million and supported household incomes to the tune of US $0.82 million. This implies that the economic output multiplier for fish landings in Dominica is about 1.22 (i.e., $3.49 / $2.87) and the household income multiplier is about 0.29 (i.e., $0.82 / $2.87). Put another way, each dollar of fish landed in Dominica in 2003 generated an additional 1.22 dollars of gross output in the economy and 0.29 dollars of household incomes.

The calculated gross output and household income multipliers in column 4 and column 5, respectively, of Table 1 are applied to projected climate-induced changes in fish landings to approximate total economic impacts. By way of example, and to help contextualize our results, column 1 in Table 2 provides the landed value of capture fisheries considered in this study for our chosen base year period—the annual average of the 5-year period 2009-2013 (see below). Columns 2 and 3 show, respectively, the estimated total economic output and household incomes supported by fish landings, based on the multipliers in Table 1.

Table 1: Output and household income multipliers, by case study country in 2003

Country	Landed value	Total gross output	Total household income	Output multiplier	Income multiplier
	(US$ millions)	(US$ millions)	(US$ millions)		
Dominica	2.87	3.49	0.82	1.216	0.286
Grenada	4.20	5.10	1.19	1.214	0.283
Haiti	26.30	31.96	7.49	1.215	0.285
Jamaica	25.43	30.90	7.24	1.215	0.285
St. Lucia	3.17	3.86	0.90	1.218	0.284
SVG	9.39	11.41	2.67	1.215	0.284
Total	**71.36**	**86.72**	**20.31**	**1.215**	**0.285**

Source: Adapted from Dyck and Sumaila (2010), Table A4, p 240-241. Values in columns 5 and 6 are calculated from columns 2-3.

Table 2: Total economic impact of fishing in base year period (annual average 2009-2013) (2010 prices), by case study country

Country	Landed value during base period	Total gross output	Total household income
	(US$ millions)	(US$ millions)	(US$ millions)
Dominica	4.3	5.2	1.2
Grenada	5.4	6.6	1.5
Haiti	7.5	9.1	2.1
Jamaica	1.0	1.2	0.3
St. Lucia	0.1	0.1	0.0
SVG	7.0	8.5	2.0
Total	**25.3**	**30.7**	**7.1**

Source: Values in column 3 derive from multiplying values in column 2 by output multipliers in Table 1; values in column 4 derive from multipliying values in column 2 by income multipliers in Table 1. Base period = 2009-2013

2.2 **Core Data Inputs**

2.2.1 Data for Aggregate Fish Balance Sheets

The market supply-demand fish model used in the economic analysis requires data for aggregate fish species groups to be structured in a balance sheet, which equates total supply to total demand for a base-year period. The aggregate fish balance sheets for Dominica, Grenada, Jamaica, Haiti, Saint Lucia and Saint Vincent and the Grenadines (SVG) are provided in, respectively, Table 4 through Table 9. To smooth out the effect of relatively low and high annual values, the fish balance sheets provide multi-year averages for the period 2009-2013.

Each fish balance sheet contains estimates of both the weight and value of fish produced for seven different aggregate fish species groupings. The chosen species groupings are described in Table 3. The choice of grouping is largely practical; the market supply-demand fish model requires trade flow data from the Food and Agriculture Organization (FAO), which is only available for specific aggregate fish groupings. In addition, the model also requires estimates of country-specific supply, demand and income elasticities (see Box 1 for an explanation of "elasticity"). Within the scope of this project, elasticities could only be generated for aggregate fish groupings, and not at the level of individual species.

The chosen aggregate fish species groupings are based on the categories used in the FAO statistics, with two exceptions. First, "tuna and billfishes" are split out from other pelagic species, due to the uniqueness of the tuna market (Cai and Leung, 2017). Conversely, data for molluscs (such as oysters) and for cephalopods (such as octopuses) have been combined, due to the relatively low production quantities of these organisms in the case study countries. Furthermore, freshwater and diadromous fish were present at *very* low quantities in the FAO data sets and are thus not included in the fish balance sheets.

Table 3: Description of species groups in fish balance sheets

Fish species group	Description	ISSCAPP* fish groups
Aquaculture	'Farmed' marine species raised in contained environments	Various
Demersal fish	Fish that live and feed on or near the bottom of seas, including flatfish, cod, sharks	31, 32, 33, 34, 38
Pelagic - tuna & billfishes	Tuna and billfishes only	36 (excluding perch-like fishes)
Pelagic – other than tuna & billfishes	Fish that live within the water column, close to neither the top or the bottom, including anchovies, herrings, sardines, but also including "perch-likes" from ISSCAPP 36 (e.g., mackerel, wahoo, cero)	35, 37, 36 (perch-likes only)
Marine fish - other	Unidentified marine fish – includes both demersal and pelagic species	39
Crustaceans	Crabs, lobsters, shrimp	41, 42, 43, 44, 45, 46, 47
Cephalopods & molluscs	Oysters, mussels, octopuses, squids, cuttlefishes	51, 52, 53, 54, 55, 56, 57, 58
Freshwater and diadromous fish	Carp, tilapia, salmon	11, 12, 13, 21, 22, 23, 23, 25

** International Standard Statistical Classification of Aquatic Animals and Plants*

An original set of aggregate fish balance sheets was prepared by the project team, based on the data sources and assumptions described below. These balance sheets were provided to fisheries officers in our six case study countries for validation. Comments and suggested revisions were received from Grenada, Jamaica, Saint Lucia and SVG and the balance sheets were modified accordingly. The validated aggregate fish balance sheets shown in Table 4 through Table 9 should nonetheless be viewed as living data sets and be updated as better information becomes available. For instance, in some cases, fisheries officers stated that other government departments would need to be consulted to validate the import and export data; however, this would have required more time than was available to complete this study.

Aquaculture data were obtained from the FAO (FAO, 2018b). Production data for all other aggregate species groupings were obtained from both the FAO (FAO, 2017a) and the Sea Around Us (SAU) website data portal (SAU, 2016). The FAO production data is based on officially-reported statistics. The reconstructed data available from the SAU website also includes unreported catch (for further details see Zeller et al, 2016 and 2018). For this reason, production data provided in the aggregate fish balance sheets is based on SAU data (inclusive of both reported and reconstructed unreported data). Use of SAU data also maintains consistency with the ecological modelling study (see papers A and B in this Collection), upon which the economic analysis builds.

The capture production data provided in the aggregate fish balance sheets comprises the sum of artisanal, subsistence and recreational tonnages recorded in the SAU data portal. Catch by national fleets within their corresponding Economic Exclusion Zone (EEZ) are included, but not catch by foreign vessels within each EEZ (as per Dey *et al*., 2016a).[18] Estimated discard tonnages are not included. Reported tonnages are "live weight equivalents".[19]

In addition to production data, the balance sheets also contain estimates of the export, import, non-food consumption and total food supply of fish (i.e., consumption) for each aggregate species grouping. Trade flow data for "tuna and billfishes" are unavailable from the FAO. For the purpose of the initial fish balance sheets, it is assumed that 100% of artisanal "tuna & billfishes" catch in the SAU data set is exported and 100% of recreational "tuna & billfishes" catch is destined for domestic food supply. It is further assumed initially that there are no imports of "tuna & billfishes". Unless fisheries officers said otherwise during validation, both these assumptions were adopted. Total food supply of fish is a calculated variable, equal to production *plus* imports *less* exports *less* non-food consumption. Data for the latter three variables are obtained from the FAO (FAO, 2017a).

The aggregate fish balance sheets also provide information on daily food supply from each fish species grouping (in terms of the daily per capita fish food supply and the edible weight of fish, both on a live weight basis). Total food supply from fish is normalized to average annual population estimates over the period 2009-2013 for each case study country to derive a measure of fish food supply per capita (live weight equivalent); population information was obtained from the FAO balance sheets (FAO 2017a; FAO, 2018b). The edible fraction in the final column of each balance sheet is calculated by dividing the estimated fish food supply per capita (live weight equivalent) by indicative factors for converting product weight to live weight for a selection of major fishery commodities from the FAO Handbook of Fishery Statistics (FAO, 1992).

[18] Foreign catch accounts for the following % of total catch from EEZs of our case study countries: Dominica = 0.1%; Grenada = 0.0%; Haiti = 3.7%; Jamaica = 0.2%; St. Lucia = 4.5%; and SVG = 7.7% (SAU, 2016).

[19] See: http://www.fao.org/cwp-on-fishery-statistics/handbook/capture-fisheries-statistics/conversion-factors/en/ and FAO (1992) for conversion factors and explanation of process.

Table 4: Aggregate fish balance sheet: Dominica

Fish species groups	Annual Fish Balance					Price		Daily Food Supply from Fish	
	Estimated Production (tonnes)	Exports (tonnes)	Imports (tonnes)	Non-food consumption (tonnes)	Total food supply (consumption) (tonnes)	Total value of production (US$)	Average (US$ / tonne)	Live weight equivalent (g / capita / day)	Edible weight (g / capita / day)
Aquaculture	10.6	0.0	0.0	0.0	10.6	66 322	6 257	0.4	0.2
Demersal fish	181.8	0.0	236.4	0.0	418.1	970 886	6 341	16.0	10.0
Pelagic - tuna & billfishes	569.3	419.3	0.0	0.0	150.0	1 357 113	2 384	5.8	3.0
Pelagic - other	669.6	294.7	730.3	0.0	1 105.2	1 753 610	2 619	42.4	22.1
Marine fish - other	198.0	0.2	33.4	0.0	231.2	240 722	1 216	8.9	5.9
Crustaceans (capture)	0.0	0.0	45.8	0.0	45.8	NA	7 087	1.8	0.6
Cephalopods & molluscs (capture)	0.0	0.0	4.4	0.0	4.4	NA	NA	0.2	0.1
Total	**1,629.3**	**714.2**	**1,050.3**	**0.0**	**1 965.4**	**4 388 653**		**75.4**	**41.9**

Data sources:
FAO. 2018. Fishery and Aquaculture Statistics. Global aquaculture production 1950-2016 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2018. www.fao.org/fishery/statistics/software/fishstatj/en.
FAO. 2017. Fishery and Aquaculture Statistics. Food balance sheets of fish and fishery products 1961-2013 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2017. www.fao.org/fishery/statistics/software/fishstatj/en.
Sea Around Us. 2016. Fisheries reconstruction data for Jamaica. http://www.seaaroundus.org/.
FAO. 2017. Definitions of FAOSTAT Fish Food Commodities. In: FAO Fisheries Commodities and Trade [online]. Rome. http://www.fao.org/fishery/static/Yearbook/YB2016_USBcard/root/food_balance/appendix2.pdf.
Notes:
All values in the fish balanace sheet are annual averages over the period 2009-2013.
Tonnages are "live weight equivalents".
Prices are "ex-vessel" with the exception of aquaculture production and crustaceans, expressed in 2010 US$. The average import price is used for crustaceans.
Total food supply = production + imports - exports - non-food consumption.
Edible fraction of fish food supply (live weight equivalent) estimated using FAO Handbook of Fishery Statistics "Indicative factors for converting product weight to live weight for a selection of major fishery commodities"
Daily food supply from fish based on population estimates in the FAO balance sheet dataset; the average population in Dominica over the period 2009-2013 was 71,400

"Demersal fish" include ISSCAPP fish groups: 31, 33, 34, 38
"Pelagic - tuna & billfishes" include ISSCAPP fish group: 36 (excluding 'perch-likes')
"Pelagic - other" include ISSCAPP fish groups: 35, 37, 36 ('perch-likes' only)
"Marine fish - other" include ISSCAPP fish group: 39
"Crustaceans (capture)" include ISSCAPP fish groups: 42, 43, 45, 47
"Cephalopods & molluscs (capture)" include ISSCAPP fish groups: 52, 56, 57

Table 5: Aggregate fish balance sheet: Grenada

Fish species groups	**Annual Fish Balance**					**Price**		**Daily Food Supply from Fish**	
	Estimated Production (tonnes)	Exports (tonnes)	Imports (tonnes)	Non-food consumption (tonnes)	Total food supply (consumption) (tonnes)	Total value of production (US$)	Average (US$ / tonne)	Live weight equivalent (g / capita / day)	Edible weight (g / capita / day)
Aquaculture	0.0	0.0	0.0	0.0	0.0	NA	NA	0.0	0.0
Demersal fish	367.1	40.4	394.5	0.0	721.2	974 036	2 653	18.8	11.8
Pelagic - tuna & billfishes	1 403.0	944.0	64.0	0.0	473.0	2 366 830	1 687	12.3	6.5
Pelagic - other	966.7	577.3	633.9	0.0	1 023.3	1 800 517	1 863	26.7	13.9
Marine fish - other	398.6	1.8	421.7	0.0	818.5	388 979	976	21.4	14.3
Crustaceans (capture)	110.5	7.4	33.3	0.0	136.4	598 080	5 412	3.6	1.2
Cephalopods & molluscs (capture)	12.7	0.0	9.1	0.0	21.8	23 607	1 856	0.6	0.2
Total	**3 258.6**	**1 620.9**	**1 556.4**	**0.0**	**3 194.1**	**5 407 395**		**83.3**	**47.9**

Data sources:
FAO. 2018. Fishery and Aquaculture Statistics. Global aquaculture production 1950-2016 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2018. www.fao.org/fishery/statistics/software/fishstatj/en.
FAO. 2017. Fishery and Aquaculture Statistics. Food balance sheets of fish and fishery products 1961-2013 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2017. www.fao.org/fishery/statistics/software/fishstatj/en.
Sea Around Us. 2016. Fisheries reconstruction data for Jamaica. http://www.seaaroundus.org/.
FAO. 2017. Definitions of FAOSTAT Fish Food Commodities. In: FAO Fisheries Commodities and Trade [online]. Rome. http://www.fao.org/fishery/static/Yearbook/YB2016_USBcard/root/food_balance/appendix2.pdf.
Notes:
All values in the fish balanace sheet are annual averages over the period 2009-2013.
Tonnages are "live weight equivalents".
Prices are "ex-vessel" with the exception of aquaculture production, expressed in 2010 US$.
Total food supply = production + imports - exports - non-food consumption.
Edible fraction of fish food supply (live weight equivalent) estimated using FAO Handbook of Fishery Statistics "Indicative factors for converting product weight to live weight for a selection of major fishery commodities"
Daily food supply from fish based on population estimates in the FAO balance sheet dataset; the average population in Grenada over the period 2009-2013 was 105,000
"Demersal fish" include ISSCAPP fish groups: 31, 33, 34, 38
"Pelagic - tuna & billfishes" include ISSCAPP fish group: 36 (excluding 'perch-likes')
"Pelagic - other" include ISSCAPP fish groups: 35, 37, 36 ('perch-likes' only)
"Marine fish - other" include ISSCAPP fish group: 39
"Crustaceans (capture)" include ISSCAPP fish groups: 42, 43, 45, 47
"Cephalopods & molluscs (capture)" include ISSCAPP fish groups: 52, 56, 57

Table 6: Aggregate fish balance sheet: Jamaica

Fish species groups	Annual Fish Balance					Price		Daily Food Supply from Fish	
	Estimated Production (tonnes)	Exports (tonnes)	Imports (tonnes)	Non-food consumption (tonnes)	Total food supply (consumption) (tonnes)	Total value of production (US$)	Average (US$ / tonne)	Live weight equivalent (g / capita / day)	Edible weight (g / capita / day)
Aquaculture	2 289.5	0.0	0.0	0.0	2 289.5	7 470 969	3 263	2.3	1.1
Demersal fish	11 086.9	21.7	210.4	0.0	11 275.7	29 789 562	2 678	11.2	7.0
Pelagic - tuna & billfishes	58.9	55.9	24.6	0.0	27.5	166 670	2 832	0.0	0.0
Pelagic - other	7 339.6	419.8	22 738.6	0.0	29 658.4	6 715 876	915	29.5	15.4
Marine fish - other	12 630.4	298.5	24 047.8	0.0	36 379.8	14 134 851	1 119	36.2	24.2
Crustaceans (capture)	339.4	860.0	2 050.0	0.0	1 529.4	3 161 017	9 315	1.5	0.5
Cephalopods & molluscs (capture)	3 435.0	57.0	1 196.0	0.0	4 574.0	4 626 135	1 347	4.5	1.6
Total	**37 179.7**	**1 712.9**	**50 267.4**	**0.0**	**85 734.2**	**66 065 080**		**85.2**	**49.8**

Data sources:
FAO. 2018. Fishery and Aquaculture Statistics. Global aquaculture production 1950-2016 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2018. www.fao.org/fishery/statistics/software/fishstatj/en.
FAO. 2017. Fishery and Aquaculture Statistics. Food balance sheets of fish and fishery products 1961-2013 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2017. www.fao.org/fishery/statistics/software/fishstatj/en.
Sea Around Us. 2016. Fisheries reconstruction data for Jamaica. http://www.seaaroundus.org/.
FAO. 2017. Definitions of FAOSTAT Fish Food Commodities. In: FAO Fisheries Commodities and Trade [online]. Rome. http://www.fao.org/fishery/static/Yearbook/YB2016_USBcard/root/food_balance/appendix2.pdf.
Notes:
All values in the fish balanace sheet are annual averages over the period 2009-2013.
Tonnages are "live weight equivalents".
Prices are "ex-vessel" with the exception of aquaculture production, expressed in 2010 US$.
Total food supply = production + imports - exports - non-food consumption.
Edible fraction of fish food supply (live weight equivalent) estimated using FAO Handbook of Fishery Statistics "Indicative factors for converting product weight to live weight for a selection of major fishery commodities"
Daily food supply from fish based on population estimates in the FAO balance sheet dataset; the average population in Jamaica over the period 2009-2013 was 2,755,800.
"Demersal fish" include ISSCAPP fish groups: 31, 33, 34, 38
"Pelagic - tuna & billfishes" include ISSCAPP fish group: 36 (excluding 'perch-likes')
"Pelagic - other" include ISSCAPP fish groups: 35, 37, 36 ('perch-likes' only)
"Marine fish - other" include ISSCAPP fish group: 39
"Crustaceans (capture)" include ISSCAPP fish groups: 42, 43, 45, 47
"Cephalopods & molluscs (capture)" include ISSCAPP fish groups: 52, 56, 57

Table 7: Aggregate fish balance sheet: Haiti

Fish species groups	Annual Fish Balance					Price		Daily Food Supply from Fish	
	Estimated Production (tonnes)	Exports (tonnes)	Imports (tonnes)	Non-food consumption (tonnes)	Total food supply (consumption) (tonnes)	Total value of production (US$)	Average (US$ / tonne)	Live weight equivalent (g / capita / day)	Edible weight (g / capita / day)
Aquaculture	541.0	0.0	0.0	0.0	541.0	956 393	1768	0.1	0.1
Demersal fish	8 169.2	0.9	2 428.2	0.0	10 596.5	15 240 067	1866	2.9	1.8
Pelagic - tuna & billfishes	1 360.5	1 360.5	1.4	0.0	1.4	1 667 868	1226	0.0	0.0
Pelagic - other	6 438.7	5 196.3	21 441.7	0.0	22 684.2	9 160 957	1423	6.2	3.2
Marine fish - other	5 874.2	250.0	662.2	0.0	6 286.4	3 853 881	656	1.7	1.1
Crustaceans (capture)	2 374.0	169.4	30.0	0.0	2 234.6	8 034 779	3385	0.6	0.2
Cephalopods & molluscs (capture)	76.0	40.8	7.7	0.0	42.9	134 252	1765	0.0	0.0
Total	**24 833.7**	**7 017.9**	**24 517.2**	**0.0**	**42 387.0**	**39 048 197**		**11.6**	**6.5**

Data sources:
FAO. 2018. Fishery and Aquaculture Statistics. Global aquaculture production 1950-2016 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2018. www.fao.org/fishery/statistics/software/fishstatj/en.
FAO. 2017. Fishery and Aquaculture Statistics. Food balance sheets of fish and fishery products 1961-2013 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2017. www.fao.org/fishery/statistics/software/fishstatj/en.
Sea Around Us. 2016. Fisheries reconstruction data for Jamaica. http://www.seaaroundus.org/.
FAO. 2017. Definitions of FAOSTAT Fish Food Commodities. In: FAO Fisheries Commodities and Trade [online]. Rome. http://www.fao.org/fishery/static/Yearbook/YB2016_USBcard/root/food_balance/appendix2.pdf.
Notes:
All values in the fish balanace sheet are annual averages over the period 2009-2013.
Tonnages are "live weight equivalents".
Prices are "ex-vessel" with the exception of aquaculture production, expressed in 2010 US$.
Total food supply = production + imports - exports - non-food consumption.
Edible fraction of fish food supply (live weight equivalent) estimated using FAO Handbook of Fishery Statistics "Indicative factors for converting product weight to live weight for a selection of major fishery commodities"
Daily food supply from fish based on population estimates in the FAO balance sheet dataset; the average population in Haiti over the period 2009-2013 was 10,037,000
"Demersal fish" include ISSCAPP fish groups: 31, 33, 34, 38
"Pelagic - tuna & billfishes" include ISSCAPP fish group: 36 (excluding 'perch-likes')
"Pelagic - other" include ISSCAPP fish groups: 35, 37, 36 ('perch-likes' only)
"Marine fish - other" include ISSCAPP fish group: 39
"Crustaceans (capture)" include ISSCAPP fish groups: 42, 43, 45, 47
"Cephalopods & molluscs (capture)" include ISSCAPP fish groups: 52, 56, 57

Table 8: Aggregate fish balance sheet: Saint Lucia

Fish species groups	Annual Fish Balance					Price		Daily Food Supply from Fish	
	Estimated Production (tonnes)	Exports (tonnes)	Imports (tonnes)	Non-food consumption (tonnes)	Total food supply (consumption) (tonnes)	Total value of production (US$)	Average (US$ / tonne)	Live weight equivalent (g / capita / day)	Edible weight (g / capita / day)
Aquaculture	24.5	0.0	0.0	0.0	24.5	82 535	3369	0.4	0.2
Demersal fish	235.5	0.0	207.3	0.0	442.8	604 517	2567	6.8	4.2
Pelagic - tuna & billfishes	514.8	0.0	2.0	0.0	516.8	2 557 104	4967	7.9	4.2
Pelagic - other	1 357.9	726.1	1 101.5	248.0	1 485.4	3 331 413	2453	22.8	11.9
Marine fish - other	475.5	0.0	965.6	0.2	1 440.9	1 787 135	3759	22.1	14.8
Crustaceans (capture)	36.2	0.0	163.9	0.0	200.0	338 583	9363	3.1	1.1
Cephalopods & molluscs (capture)	69.9	0.0	71.1	0.0	140.9	587 744	8413	2.2	0.7
Total	**2 714.3**	**726.1**	**2 511.3**	**248.2**	**4 251.3**	**9 289 030**		**65.1**	**37.0**

Data sources:
FAO. 2018. Fishery and Aquaculture Statistics. Global aquaculture production 1950-2016 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2018. www.fao.org/fishery/statistics/software/fishstatj/en.
FAO. 2017. Fishery and Aquaculture Statistics. Food balance sheets of fish and fishery products 1961-2013 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2017. www.fao.org/fishery/statistics/software/fishstatj/en.
Sea Around Us. 2016. Fisheries reconstruction data for Jamaica. http://www.seaaroundus.org/.
FAO. 2017. Definitions of FAOSTAT Fish Food Commodities. In: FAO Fisheries Commodities and Trade [online]. Rome. http://www.fao.org/fishery/static/Yearbook/YB2016_USBcard/root/food_balance/appendix2.pdf.
Notes:
All values in the fish balanace sheet are annual averages over the period 2009-2013.
Tonnages are "live weight equivalents".
Prices are "ex-vessel" with the exception of aquaculture production, expressed in 2010 US$.
Total food supply = production + imports - exports - non-food consumption.
Edible fraction of fish food supply (live weight equivalent) estimated using FAO Handbook of Fishery Statistics "Indicative factors for converting product weight to live weight for a selection of major fishery commodities"
Daily food supply from fish based on population estimates in the FAO balance sheet dataset; the average population in St. Lucia over the period 2009-2013 was 178,800
"Demersal fish" include ISSCAPP fish groups: 31, 33, 34, 38
"Pelagic - tuna & billfishes" include ISSCAPP fish group: 36 (excluding 'perch-likes')
"Pelagic - other" include ISSCAPP fish groups: 35, 37, 36 ('perch-likes' only)
"Marine fish - other" include ISSCAPP fish group: 39
"Crustaceans (capture)" include ISSCAPP fish groups: 42, 43, 45, 47
"Cephalopods & molluscs (capture)" include ISSCAPP fish groups: 52, 56, 57

Table 9: Aggregate fish balance sheet: Saint Vincent and the Grenadines

Fish species groups	Annual Fish Balance					Price		Daily Food Supply from Fish	
	Estimated Production (tonnes)	Exports (tonnes)	Imports (tonnes)	Non-food consumption (tonnes)	Total food supply (consumption) (tonnes)	Total value of production (US$)	Average (US$ / tonne)	Live weight equivalent (g / capita / day)	Edible weight (g / capita / day)
Aquaculture	0.0	0.0	0.0	0.0	0.0	NA	NA	0.0	0.0
Demersal fish	397.2	1.4	68.3	0.0	464.1	1 750 114	4 406	11.7	7.3
Pelagic - tuna & billfishes	3.3	3.3	0.0	0.0	0.0	11 208	3 396	0.0	0.0
Pelagic - other	800.2	607.0	341.0	0.0	534.2	3 134 052	3 917	13.4	7.0
Marine fish - other	192.3	15.7	490.0	0.0	666.6	260 671	1 356	16.8	11.2
Crustaceans (capture)	172.6	36.0	38.2	0.0	174.8	1 627 125	9 428	4.4	1.5
Cephalopods & molluscs (capture)	97.3	1.2	59.7	0.0	155.8	219 093	2 251	3.9	1.4
Total	**1 663.0**	**664.6**	**997.2**	**0.0**	**1 995.6**	**7 002 264**		**50.2**	**28.4**

Data sources:
FAO. 2018. Fishery and Aquaculture Statistics. Global aquaculture production 1950-2016 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2018. www.fao.org/fishery/statistics/software/fishstatj/en.
FAO. 2017. Fishery and Aquaculture Statistics. Food balance sheets of fish and fishery products 1961-2013 (FishstatJ). In: FAO Fisheries and Aquaculture Department [online]. Rome. Updated 2017. www.fao.org/fishery/statistics/software/fishstatj/en.
Sea Around Us. 2016. Fisheries reconstruction data for Jamaica. http://www.seaaroundus.org/.
FAO. 2017. Definitions of FAOSTAT Fish Food Commodities. In: FAO Fisheries Commodities and Trade [online]. Rome. http://www.fao.org/fishery/static/Yearbook/YB2016_USBcard/root/food_balance/appendix2.pdf.
Notes:
All values in the fish balanace sheet are annual averages over the period 2009-2013.
Tonnages are "live weight equivalents".
Prices are "ex-vessel" with the exception of aquaculture production, expressed in 2010 US$.
Total food supply = production + imports - exports - non-food consumption.
Edible fraction of fish food supply (live weight equivalent) estimated using FAO Handbook of Fishery Statistics "Indicative factors for converting product weight to live weight for a selection of major fishery commodities"
Daily food supply from fish based on population estimates in the FAO balance sheet dataset; the average population in St Vincent & the Grenadines over the period 2009-2013 was 109,000
"Demersal fish" include ISSCAPP fish groups: 31, 33, 34, 38
"Pelagic - tuna & billfishes" include ISSCAPP fish group: 36 (excluding 'perch-likes')
"Pelagic - other" include ISSCAPP fish groups: 35, 37, 36 ('perch-likes' only)
"Marine fish - other" include ISSCAPP fish group: 39
"Crustaceans (capture)" include ISSCAPP fish groups: 42, 43, 45, 47
"Cephalopods & molluscs (capture)" include ISSCAPP fish groups: 52, 56, 57

The total value of production is reported in 2010 constant US dollars.[20] Where necessary, production values were converted to 2010 US dollars using the relevant annual local currency exchange rate per US dollar, as reported in the World Bank World Development Indicators (World Bank, 2018), and local Consumer Price Indices, available from the IMF World Economic Outlook Database (IMF, 2018). Unless otherwise stated, the prices provided in the aggregate fish balance sheets are "ex-vessel" (see Tai *et al.*, 2017), except for aquaculture production, which is based on market prices. Only a single average price can be estimated for aquaculture production for each case study country, covering all cultured species. No information was reported by the FAO for the import or export of aquaculture production; hence, values are assumed to be zero, unless otherwise amended by fisheries officers.

2.2.2 Estimates of Price and Income Elasticity

An econometric model is used to estimate the own-price elasticity and income elasticity of fish demand, by aggregate species grouping. The own-price elasticity of fish demand measures the percentage change in the quantity of fish demanded in response to a one per cent change in the price of that fish. The income elasticity of fish demand measures the percentage change in the quantity of fish demanded in response to a one per cent change in income (of people who consume that fish). Further explanation of these concepts appears in Box 1.

The approach used to generate demand and income elasticities closely follows that used by Cai and Leung (2017). The following simplified log-log model is used:

$$ln(Q_{it}) = \alpha + \beta ln(Y_{it}) + \gamma ln(P_{it}) + e_{it} \qquad \text{Equation 1}$$

The dependent variable Q denotes per capita fish consumption. The independent variables Y and P denote, respectively, per capita income and (own) fish price. Subscript i denotes the case study country, while subscript t denotes the year. Coefficient α is the intercept term and parameter e is a residual error. For each country and for all countries collectively, the model is used to run six separate regressions, one for each aggregate fish species group (where relevant); elasticities for cultured fish are extrapolated from the literature (see below).

With the log-log model, the coefficients represent the elasticity of the dependent variable with respect to the independent variable(s). Hence, the coefficient β is the income elasticity of fish demand and the coefficient γ is the own-price elasticity of fish demand.

Each country's per capita fish consumption is constructed by dividing total fish consumption (by aggregate fish species grouping) by population data. Consumption data is sourced from the FAO Food Balance Sheets accessed using FishStatJ (FAO, 2017a). Population data is sourced from the United Nations World Urbanization Prospects: The 2018 Revision (UN, 2018). Gross Domestic Product (GDP) per capita is used as a proxy for per capita income. GDP data is sourced from the International Monetary Fund (IMF) Work Economic Outlook database (IMF, 2018); GDP is measured in Purchasing Power Parity (PPP) international dollars. Population data from UN (2018) is used to calculate GDP per capita adjusted for PPP.

Proxies for domestic fish prices are generated following the same approach used by Cai and Leung (2017), described as follows. Data on aquaculture production by country (both quantity and value) is used to calculate an average price for cultured fish production. This data is sourced from the FAO Fishery and

[20] The purchasing power of dollars changes over time because of general price inflation. To compare dollar values from one year to another, it is thus necessary to convert from current (nominal) dollar values in different years to constant (real) dollar values in a base year—in this case, 2010.

Aquaculture Statistics accessed using FishStatJ (FAO, 2018b). The FAO also provides data on fish imports (both quantity and value), which is used to calculate the price of fish imports for each country. A weighted average of these two calculated prices is then used to construct a proxy for domestic fish prices, by country, assuming domestic fish prices are bounded by the prices of domestically produced cultured fish as well as imported fish (Cai and Leung, 2017).

Box 1: Demand, income and supply elasticities

Changes in the price (P) of a good (like fish) will lead to changes in the quantity (Q) of it purchased; the price elasticity of demand measures this relationship. Specifically, the own-price elasticity of demand ($\varepsilon^D_{Q,P}$) is defined as the percentage change in the quantity demanded in response to a one per cent change in price. In mathematical terms:

$$\varepsilon^D_{Q,P} = \frac{\%\Delta Q}{\%\Delta P} = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}} = \frac{\Delta Q}{\Delta P} \times \frac{P}{Q}$$

Because P and Q move in opposite directions along a demand curve, $\varepsilon^D_{Q,P}$will be negative. For example, a value of $\varepsilon^D_{Q,P}$ of -1 means that a 1% rise in price leads to a 1% decline in the quantity demanded. Similarly, a value of $\varepsilon^D_{Q,P}$ of -2 means that a 1% decrease in price leads to a 2% rise in the quantity demanded. A distinction is often made among absolute values of $\varepsilon^D_{Q,P}$ that are less than 1 (demand is price *inelastic*), equal to 1 (demand is *unit* elastic), or greater than 1 (demand is price *elastic*). In general, if demand is elastic, changes in price affect the quantity demanded significantly; if demand is inelastic, changes in price have a negligible effect on the quantity demanded.

Another type of elasticity in demand analysis is the income elasticity of demand $\varepsilon^D_{Q,Y}$ which measures the relationship between changes in consumer incomes and changes in the quantity demanded. In mathematical terms:

$$\varepsilon^D_{Q,Y} = \frac{\%\Delta Q}{\%\Delta Y} = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta Y}{Y}} = \frac{\Delta Q}{\Delta Y} \times \frac{Y}{Q}$$

In the more common case of a *normal good*, $\varepsilon^D_{Q,Y}$ is positive, since increases in consumer income lead to increases in the quantity purchased. In the case of an *inferior good*, $\varepsilon^D_{Q,Y}$ is negative, implying a rise in consumer income leads to a decline in the quantity purchased. Among normal goods, whether $\varepsilon^D_{Q,Y}$ is less than or greater than one is important. If $\varepsilon^D_{Q,Y}$ is greater than 1 for a normal good, then purchases of that good rise more rapidly than consumer income; these are called *luxury goods*. For example, if $\varepsilon^D_{Q,Y}$ of a good is 1.5, then a 10% increase in income will result in a 15% rise in purchases of that good. In contrast, if $\varepsilon^D_{Q,Y}$ of a good is 0.5, then a 10% increase in income will result in a 5% rise in purchases of that good. According to Engel's law (see, for example, Timmer et al, 1983), most food products, including fish, probably have an income elasticity (much) less than 1. Engel's law implies that the proportion of a household's total expenditures on food decreases as their income level rises. This means that the poorer the household, the higher their share of total expenditure spent on food. In general, the larger the absolute value of $\varepsilon^D_{Q,Y}$, the more responsive purchases are to changes in consumer income.

Changes in the quantity supplied in response to changes in price—at least in the short-term—can be described all along the same lines. The own-price elasticity of supply ($\varepsilon^S_{Q,P}$) is defined as the percentage change in the quantity supplied in response to a one per cent change in price. Because P and Q move in the same direction along a supply curve, $\varepsilon^S_{Q,Y}$ will be positive. For example, if $\varepsilon^S_{Q,Y}$ is 1.5, each 1% rise in price results in a 1.5% increase in the quantity supplied. In this case, the short-run supply of the good is characterized as *elastic*. If, in contrast, a 1% rise in price leads only to 0.5% increase in the quantity supplied, the short-run supply of the good is characterized as *inelastic*.

The weight for cultured fish price (denoted as w) is given by the ratio of aquaculture production relative to fish consumption. If w is greater than one, it is set at one. It follows that the weight for imported fish price is given by 1 – w. The rationale underpinning the weighting scheme provided by Cai and Leung (2017) is that "*the greater a country's aquaculture production is compared to its fish consumption, the* *more its domestic fish price would be under the influence of its cultured fish price*."[21] If imported (cultured) fish prices cannot be calculated, the calculated cultured (import) fish price is used.

The log-log model in Equation 1 is used to estimate the own-price and income elasticity of demand for the six aggregate fish species groupings. Where the model did not estimate statistically-significant income and price elasticity coefficients for aggregate fish specifies groupings for an individual country (because of a limited amount of quality data), values for those countries were extrapolated from the pooled regression (which were all statistically significant at 95%), making adjustments for relative differences in PPP GDP per capita.[22] For aquaculture, elasticities were extrapolated from values in the literature (e.g., Delgado *et al.*, 2003; Dey, 2000; Dey *et al.*, 2008; Dey *et al.*, 2016; Kumar *et al.*, 2005; Lem *et al.*, 2014; Mohammed *et al.,* 2013; Ye, 1999); again, adjusting for relative differences in PPP GDP per capita. Borrowing elasticity estimates from the literature is common practice in the main models that make projections of future fish supply and demand—including those used by the Organization for Economic Cooperation and Development, the World Bank and the International Food Policy Research Institute (Cai and Leung, 2017). The results are presented in the first two rows of Table 10 (Dominica), Table 11 (Grenada), Table 12 (Jamaica), Table 13 (Haiti), Table 14 (Saint Lucia) and Table 15 (SVG).

Estimating own-price elasticities of supply for fish is more problematic than for the demand elasticities, due to the data requirements to specify the supply functions. Hence, supply elasticities are sourced from the literature. However, because of the inherent difficulties in estimating supply elasticities, there are also few empirical studies to draw from. In transferring values from other studies to the case study countries, the original estimates are adjusted for differences in relative diesel fuel and labour costs; two key determinants of the marginal cost of fishing (Lam et al, 2011). In theory, higher variable costs should translate to lower short-term supply responses to rising prices, other things being equal. As evident from Table 10 through Table 15, own-price supply elasticities for capture fisheries are relatively low. Values for aquaculture production, in contrast, are higher because of the greater capacity for expansion and intensification of production (Chan et al, 2002; Delgado et al, 2003).

Due to data limitations for specific combinations of fish species groupings and case study countries, and the resulting need to extrapolate values from the literature, especially for the price elasticities of supply, a medium level of confidence is associated with the values in Table 10 through Table 15.

[21] Also see Tveteras et al, 2012.

[22] The adjustment is made in accordance with Timmer's proposition (Timmer, 1981), that the own-price elasticities of demand are larger in absolute value for lower-income countries than for higher-income countries.

Table 10: Assumed price and income elasticities: Dominica

Demand, supply & income elasticities	Aquaculture	Demersal fish	Pelagic – tuna & billfishes	Pelagic - other	Marine fish - other	Crustaceans (capture)	Cephalopods & molluscs (capture)
Demand elasticities: % change in quantity demanded in response to 1% change in own price	-0.424	-0.589	-0.497	-0.602	-0.596	-0.690	-0.531
Income elasticities: % change in quantity demanded in response to 1% change in real income	0.614	0.798	1.355	0.640	0.719	1.340	1.070
Supply elasticities: % change in quantity supplied in response to 1% change in own price	0.754	0.382	0.634	0.294	0.338	NA	NA

Source: Author's estimation.
Note: N/A indicates no data on domestic production was available fish species groupings, as per the aggregate fish balance sheet.

Table 11: Assumed price and income elasticities: Grenada

Demand, supply & income elasticities	Aquaculture	Demersal fish	Pelagic – tuna & billfishes	Pelagic - other	Marine fish - other	Crustaceans (capture)	Cephalopods & molluscs (capture)
Demand elasticities: % change in quantity demanded in response to 1% change in own price	NA	-0.526	-0.475	-0.538	-0.532	-0.625	-0.505
Income elasticities: % change in quantity demanded in response to 1% change in real income	NA	0.708	1.320	0.554	0.631	1.326	1.012
Supply elasticities: % change in quantity supplied in response to 1% change in own price	NA	0.373	0.219	0.284	0.329	0.291	0.348

Source: Author's estimation.
Note: N/A indicates no data on domestic production was available fish species groupings, as per the aggregate fish balance sheet.

Table 12: Assumed price and income elasticities: Jamaica

Demand, supply & income elasticities	Aquaculture	Demersal fish	Pelagic – tuna & billfishes	Pelagic - other	Marine fish - other	Crustaceans (capture)	Cephalopods & molluscs (capture)
Demand elasticities: % change in quantity demanded in response to 1% change in own price	-0.466	-0.710	-0.540	-0.726	-0.718	-0.820	-0.583
Income elasticities: % change in quantity demanded in response to 1% change in real income	0.645	0.950	1.423	0.807	0.879	1.368	1.186
Supply elasticities: % change in quantity supplied in response to 1% change in own price	0.690	0.398	0.235	0.315	0.357	0.353	0.355

Source: Author's estimation.

Table 13: Assumed price and income elasticities: Haiti

Demand, supply & income elasticities	Aquaculture	Demersal fish	Pelagic – tuna & billfishes	Pelagic - other	Marine fish - other	Crustaceans (capture)	Cephalopods & molluscs (capture)
Demand elasticities: % change in quantity demanded in response to 1% change in own price	-0.600	-1.091	-0.674	-1.116	-1.104	-1.228	-0.744
Income elasticities: % change in quantity demanded in response to 1% change in real income	0.742	1.460	1.638	1.335	1.398	1.457	1.553
Supply elasticities: % change in quantity supplied in response to 1% change in own price	0.560	0.450	0.722	0.380	0.415	0.483	0.595

Source: Author's estimation.

Table 14: Assumed price and income elasticities: Saint Lucia

Demand, supply & income elasticities	Aquaculture	Demersal fish	Pelagic – tuna & billfishes	Pelagic - other	Marine fish - other	Crustaceans (capture)	Cephalopods & molluscs (capture)
Demand elasticities: % change in quantity demanded in response to 1% change in own price	-0.382	-0.469	-0.455	-0.480	-0.475	-0.571	-0.481
Income elasticities: % change in quantity demanded in response to 1% change in real income	0.585	0.640	1.211	0.475	0.558	1.314	0.963
Supply elasticities: % change in quantity supplied in response to 1% change in own price	0.754	0.365	0.323	0.274	0.320	0.271	0.399

Source: Author's estimation.

Table 15: Assumed price and income elasticities: Saint Vincent and the Grenadines

Demand, supply & income elasticities	Aquaculture	Demersal fish	Pelagic – tuna & billfishes	Pelagic - other	Marine fish - other	Crustaceans (capture)	Cephalopods & molluscs (capture)
Demand elasticities: % change in quantity demanded in response to 1% change in own price	NA	-0.569	-0.499	-0.609	-0.589	-0.707	-0.534
Income elasticities: % change in quantity demanded in response to 1% change in real income	NA	0.810	1.359	0.649	0.730	1.344	1.085
Supply elasticities: % change in quantity supplied in response to 1% change in own price	NA	0.382	0.259	0.296	0.339	0.314	0.367

Source: Author's estimation.
Note: N/A indicates no data on domestic production was available fish species groupings, as per the aggregate fish balance sheet.

2.3 Estimating Future Demand

The estimated income elasticities of demand (β) are used to estimate future fish consumption as a function of income growth, as follows (Cai and Leung, 2017):

$$Q_{fp} = Q_{bp} \times \left(\frac{Y_{fp}}{Y_{bp}}\right)^{\beta} \qquad \text{Equation 2}$$

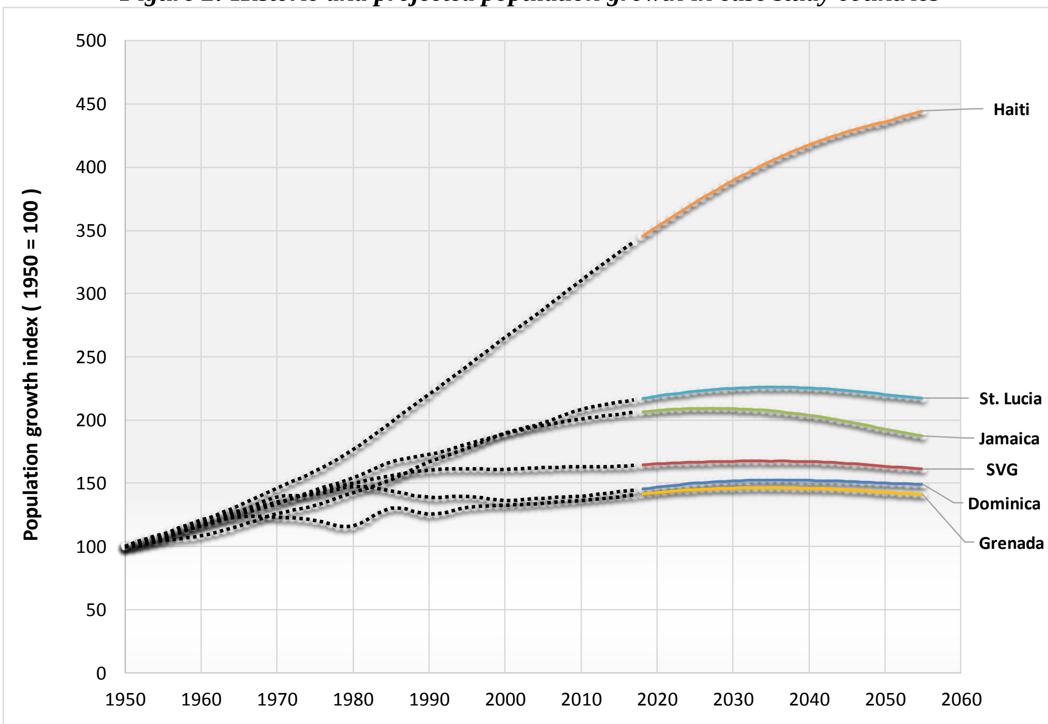
All else being equal, per capita fish consumption in the benchmark period (Q_{bp}) is expected to be Q_{fp} in some future period because of growth in per capita income over the projection period (given by the term in the bracket). The benchmark period for fish consumption and per capita income is defined as 2009-2013. The projection time periods are 2030-2039 and 2050-2059; projections of per capita income are thus required for 2035 and 2055. Projections for per capita income are generated from projections of PPP GDP and population. The latter are extrapolated from the United Nations World Urbanization Prospects: The 2018 Revision (UN, 2018), which contains observed values over the period 1950-2017 and projected values through 2050. To derive population figures for 2055 for our case study countries, we allow the projected population in each country at 2050 to continue changing at the annual average growth rate between 2040 and 2050 (see Figure 2). We use the United Nations projected population values for 2035.

GDP projections are extrapolated from the International Monetary Fund (IMF) Work Economic Outlook 2018 database (IMF, 2018), which contains observed values over the period 1980-2016 and projected values through 2023. To derive GDP figures for 2035 and 2055 for our case study countries, we allow the projected GDP in each country at 2023 to continue changing at the annual average growth rate between 2000 and 2016 (see Figure 3).

Table 16 contains projected population, GDP and income per capita for each case study country, for future years 2035 and 2055, as well as the base year period 2009-13. Relative to the base year period, incomes per capita grow between 0.8% (Dominica and Haiti) and 2.8% (Grenada) per year, on average, by 2035; and between 0.8% (Haiti) and 3.1% (Grenada) per year, on average, by 2055.

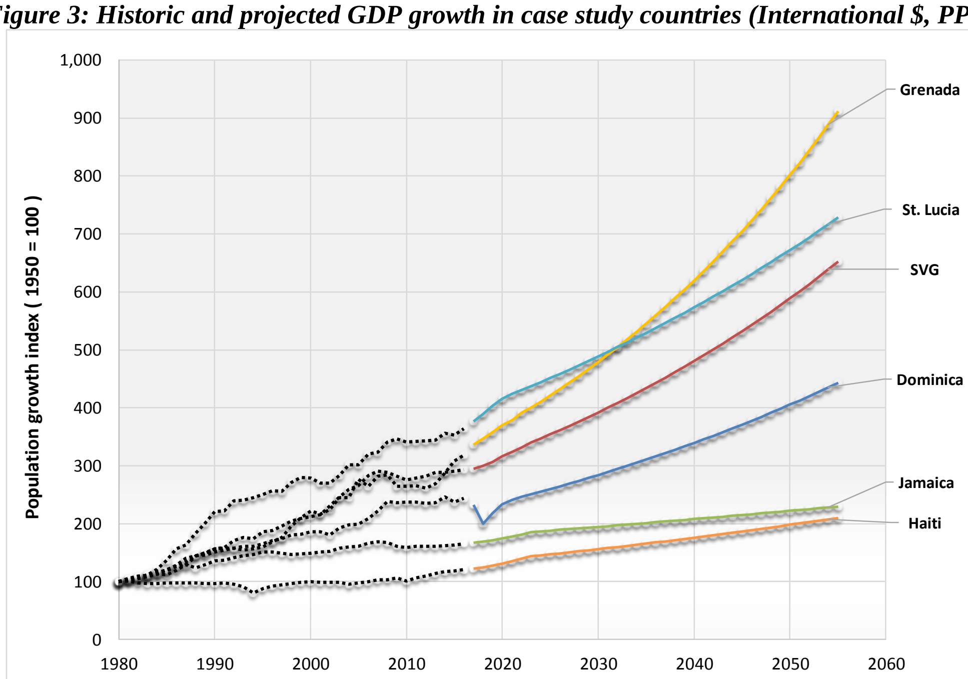
When making projections of future fish demand, the estimated income elasticities of demand (β) are assumed to remain constant over the projection period.

Figure 2: Historic and projected population growth in case study countries



Source: United Nations World Urbanization Prospects: The 2018 Revision. The black dashed lines are observed values; the solid coloured lines are projected values.

Figure 3: Historic and projected GDP growth in case study countries (International $, PPP)



Source: International Monetary Fund (IMF) Work Economic Outlook 2018. The black dashed lines are observed values; the solid coloured lines are projected values.

Table 16: Projected population, GDP and income per capita for 2035 and 2055

		Dominica	Grenada	Haiti	Jamaica	St. Lucia	SVG
2009-13							
Population	Number	71,800	105,100	10,143,700	2,828,700	173,600	109,300
GDP	International PPP $ billion	0.7	1.2	16.0	22.8	2.1	1.1
GDP per capita	International PPP $ per capita	10,124	11,187	1,579	8,069	12,158	10,018
2035							
Population	Number	77,900	112,300	13,036,300	2,908,100	187,200	112,200
AAGR from 2009-13	%	0.3%	0.3%	1.1%	0.1%	0.3%	0.1%
GDP	International PPP $ billion	1.0	2.4	24.7	28.6	3.3	1.7
AAGR from 2009-13	%	1.1%	3.0%	1.8%	0.9%	1.8%	1.8%
GDP per capita	International PPP $ per capita	12,253	21,510	1,892	9,823	17,378	15,055
AAGR from 2009-13	%	0.8%	2.8%	0.8%	0.8%	1.5%	1.7%
2055							
Population	Number	76,200	108,300	14,328,500	2,626,600	180,000	108,000
AAGR from 2035	%	-0.1%	-0.2%	0.5%	-0.5%	-0.2%	-0.2%
GDP	International PPP $ billion	1.4	4.0	31.3	32.6	4.5	2.5
AAGR from 2035	%	1.8%	2.6%	1.2%	0.7%	1.6%	2.1%
GDP per capita	International PPP $ per capita	17,874	37,317	2,184	12,421	24,863	23,501
AAGR from 2035	%	1.9%	2.8%	0.7%	1.2%	1.8%	2.3%

Note: AACGR is the annual average compound growth rate over the specified period. The AACGR is the average rate at which the original value grows over the specified period assuming the value is compounding over that time period.

2.4 Projected Changes in Fishery Production

The projected changes in landings used to introduce supply shocks into the market supply-demand models are provided in Table 17. No projections were available for “cephalopods & molluscs” and “other marine” groupings. The former is omitted from the analysis. For the latter, a (production) weighted average change in landings was generated from the projections for “demersals” and “other pelagics”. This was done separately, for each case study country; by way of example, the values for “other marine” in Table 17 are for Jamaica. “Aquaculture” was included in the market supply-demand models to allow for its future appraisal as an adaptation option; it is not included in the current analysis.

Table 17: Projected changes in landings for 2035 and 2055 under climate scenarios RCP 2.6 and RCP 8.5, by fish species groupings.

	RCP 2.6		**RCP 8.5**	
	2035	2055	2035	2055
Aquaculture	NA	NA	NA	NA
Demersals	-8.7%	-11.2%	-12.0%	-12.3%
Tuna & billfishes	-9.1%	-10.9%	-12.5%	-14.5%
Other pelagic	-9.4%	-11.3%	-12.7%	-15.0%
Other marine	-9.2%	-11.3%	-12.6%	-14.4%
Crustaceans	-10.3%	-12.9%	-13.2%	-12.9%
Celphalopods & molluscs	NA	NA	NA	NA

Source: Cheung, Reygondeau and Wabnitz (Part B of this Collection of research papers). Estimates for "other marine groupings" are a (production) weighted average change in landings generated from the projections for "demersals" and "other pelagics". This was done for each case study country. The values in this table are for Jamaica, as an example.

2.5 Results

Projected economic consequences of climate-induced impacts on fishery production for our six case study countries are presented below; **these are generated from the market S-D fish model described in Section 2.1.1**. For each country, the following estimated outcomes are provided below in separate sections:

- Tables 18, 20, 22, 24, 26 and 28 contain projected annual (%) changes in domestic fish consumption nationally under RCP 2.6 and RCP 8.5. Projected changes are measured relative to projected future demand in 2035 and 2055 under the reference case. Recalling Figure 1, the % changes are calculated as $(Q_2 - Q_1)/Q_1$. Projected tonnages under the reference case (i.e., Q_1) are also provided for 2035 and 2055.
- Tables 19, 21, 23, 25, 27 and 29 contain projected (%) changes in domestic fish prices under RCP 2.6 and RCP 8.5 relative to projected future prices in 2035 and 2055 under the reference case. Recalling Figure 1, the % changes are calculated as $(P_2 - P_1)/P_1$. Projected prices under the reference case (i.e., P_1) are also provided for 2035 and 2055.
- Figures 4, 6, 8, 10, 12 and 14 show estimates of net annual welfare losses (in monetary units) associated with the projected climate-induced changes in prices and consumption.
- Figures 5, 7, 9, 11, 13 and 15 show estimates of changes in fish food consumption per capita per day associated with the projected climate-induced changes in prices and consumption.

2.5.1 Dominica

Table 18: Dominica: Projected annual changes in fish consumption by population under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(tonnes)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	445	513		-14	-18		-19	-19
Tuna & billfishes	175	248		-2	-3		-3	-3
Other pelagic	1,152	1,264		-49	-59		-67	-79
Other marine	244	273		-9	-11		-12	-14
Crustaceans	54	77		-0	-0		-0	-0
All species	**2,070**	**2,375**		**-74**	**-90**		**-101**	**-116**

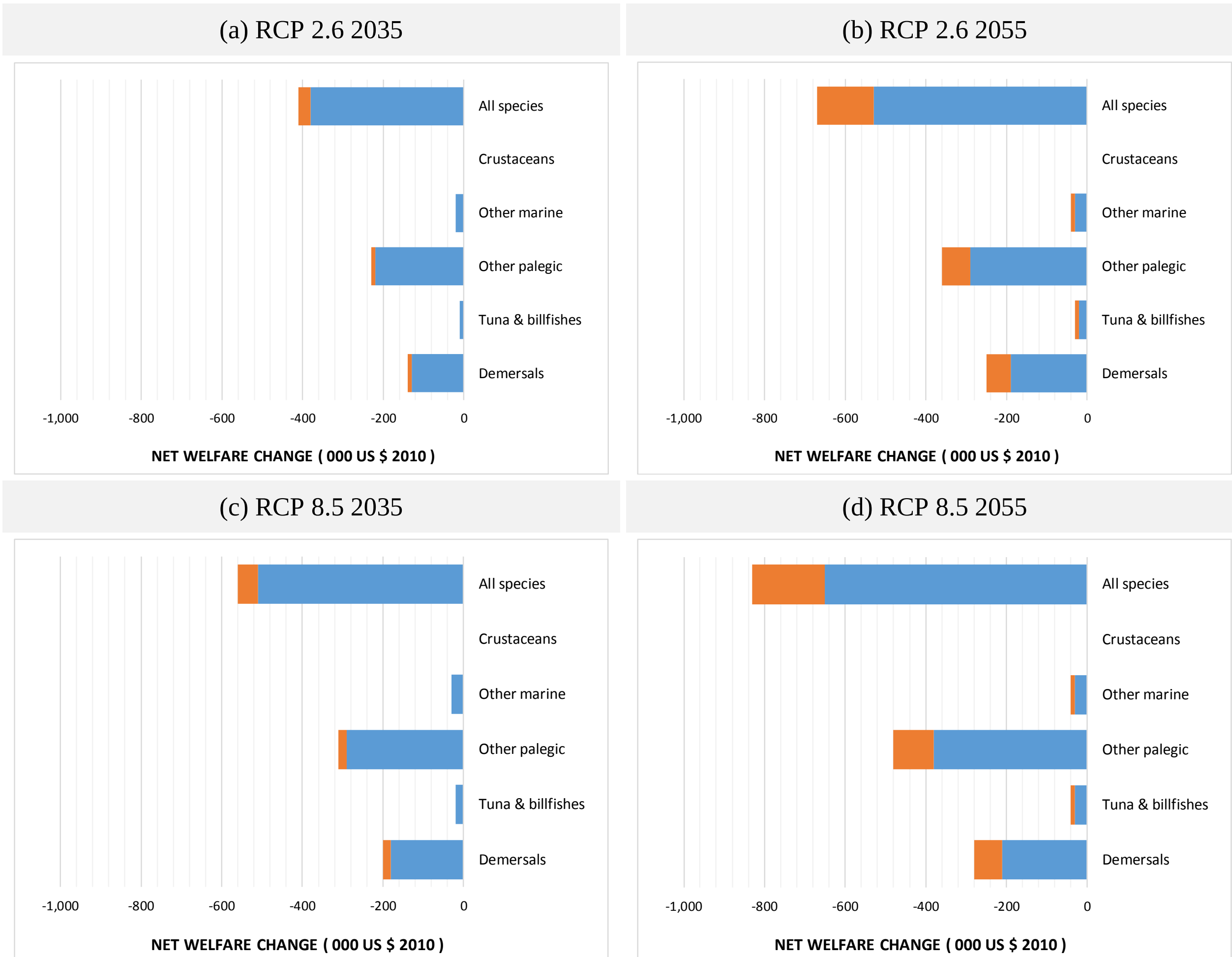
Note: quantities are in tonnes. Output from market S-D fish model.

Table 19: Dominica: Projected changes in fish prices under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(US$ per tonne)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	6,246	8,498		+294	+381		+408	+417
Tuna & billfishes	3,006	4,829		+70	+84		+96	+112
Other pelagic	2,999	3,901		+193	+233		+262	+310
Other marine	1,407	1,873		+79	+97		+108	+124
Crustaceans	8,309	11,875		+0	+0		+0	+0
All species	**3,648**	**5,014**		**+195**	**+243**		**+266**	**+309**

Note: prices are in US $ per tonne in 2010 prices. Output from market S-D fish model.

Figure 4: Dominica: Net annual welfare losses (thousand US $ per year in 2010 prices) due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5

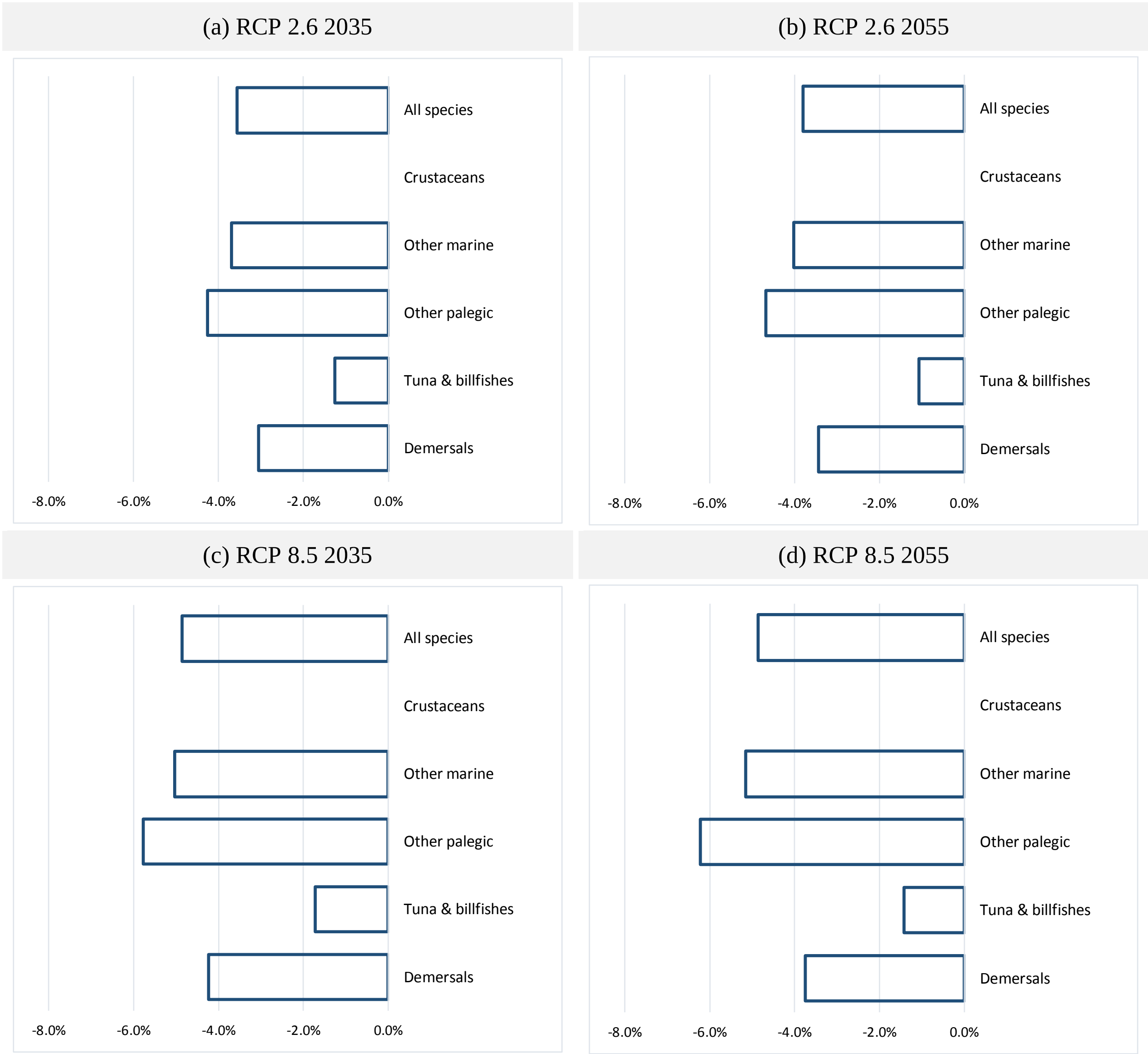


Note: the blue shaded bar shows changes in consumer surplus; the orange bar shows changes in producer surplus. Impacts to "crustaceans" are lost when rounding the results. Output from market S-D fish model.

For "all species", estimated annual welfare losses for each scenario are:

- **RCP 2.6** in **2035**: US$ 410,000; equivalent to a 3.5% reduction in the projected Reference Case.
- **RCP 2.6** in **2055**: US$ 670,000; equivalent to a 4.0% reduction in the projected Reference Case.
- **RCP 8.5** in **2035**: US$ 560,000; equivalent to a 4.8% reduction in the projected Reference Case.
- **RCP 8.5** in **2055**: US$ 830,000; equivalent to a 4.9% reduction in the projected Reference Case.

Figure 5: Dominica: Estimated change in fish food consumption per capita per day due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5



Note: figures show percentage change in 2035 and 2055 under each climate scenario, relative to projected reference case for 2035 and 2055. Impacts to "crustaceans" are lost when rounding the results. Output from market S-D fish model.

2.5.2 Grenada

Table 20: Grenada: Projected annual changes in fish consumption by population under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(tonnes)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	804	891		-23	-30		-32	-32
Tuna & billfishes	496	518		-23	-28		-32	-37
Other pelagic	1,095	1,167		-45	-54		-61	-72
Other marine	894	971		-31	-38		-42	-48
Crustaceans	145	155		-7	-8		-9	-9
All species	**3,434**	**3,702**		**-129**	**-158**		**-175**	**-198**

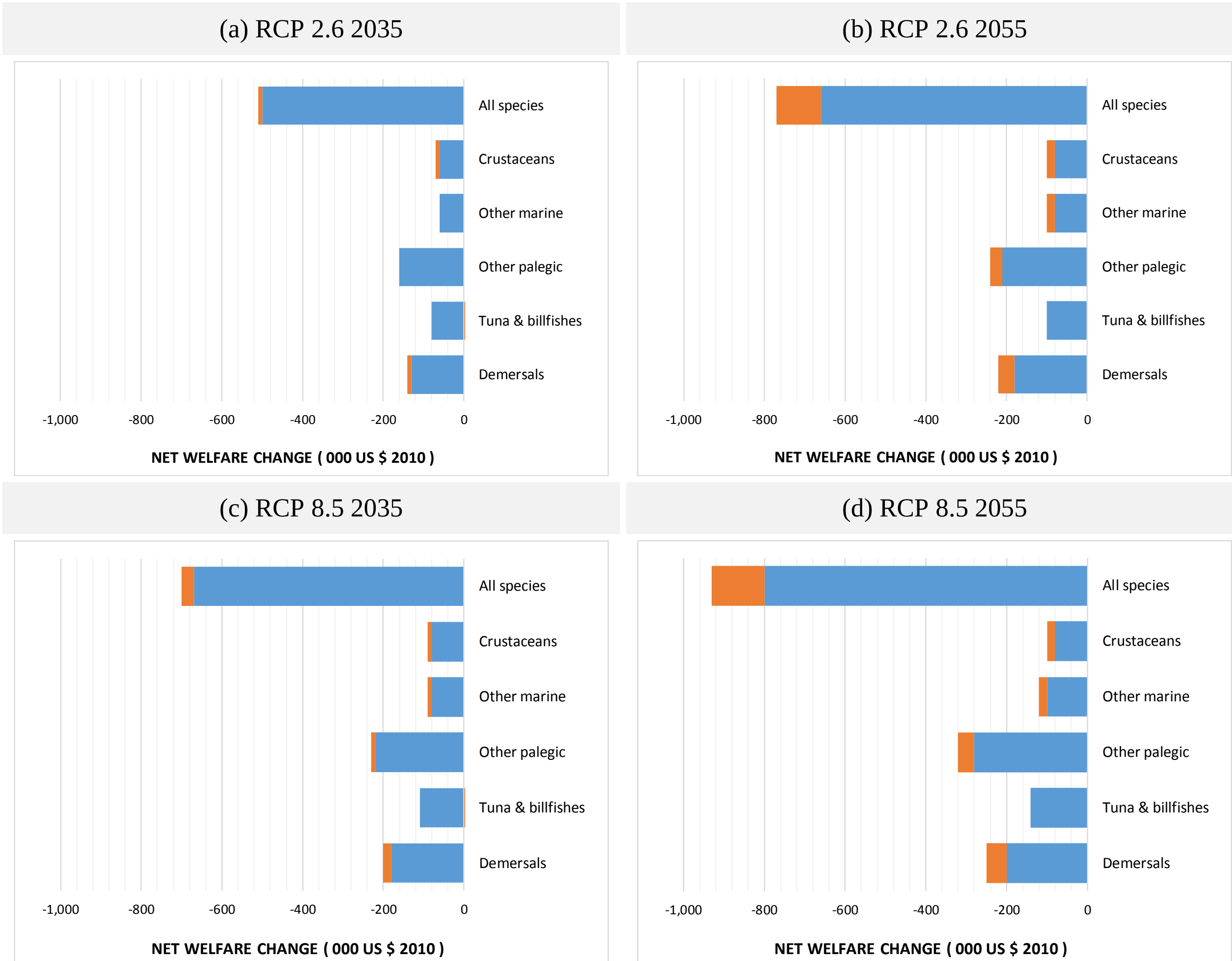
Note: quantities are in tonnes. Output from market S-D fish model.

Table 21: Grenada: Projected changes in fish prices under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(US$ per tonne)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	3,469	4,328		+160	+207		+222	+227
Tuna & billfishes	2,061	2,421		+173	+208		+237	+275
Other pelagic	2,325	2,787		+152	+183		+206	+244
Other marine	1,248	1,527		+70	+86		+95	+108
Crustaceans	6,650	7,893		+431	+539		+551	+540
All species	**2,457**	**2,989**		**+147**	**+182**		**+201**	**+227**

Note: prices are in US $ per tonne in 2010 prices. Output from market S-D fish model.

Figure 6: Grenada: Net annual welfare losses (thousand US $ per year in 2010 prices) due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5

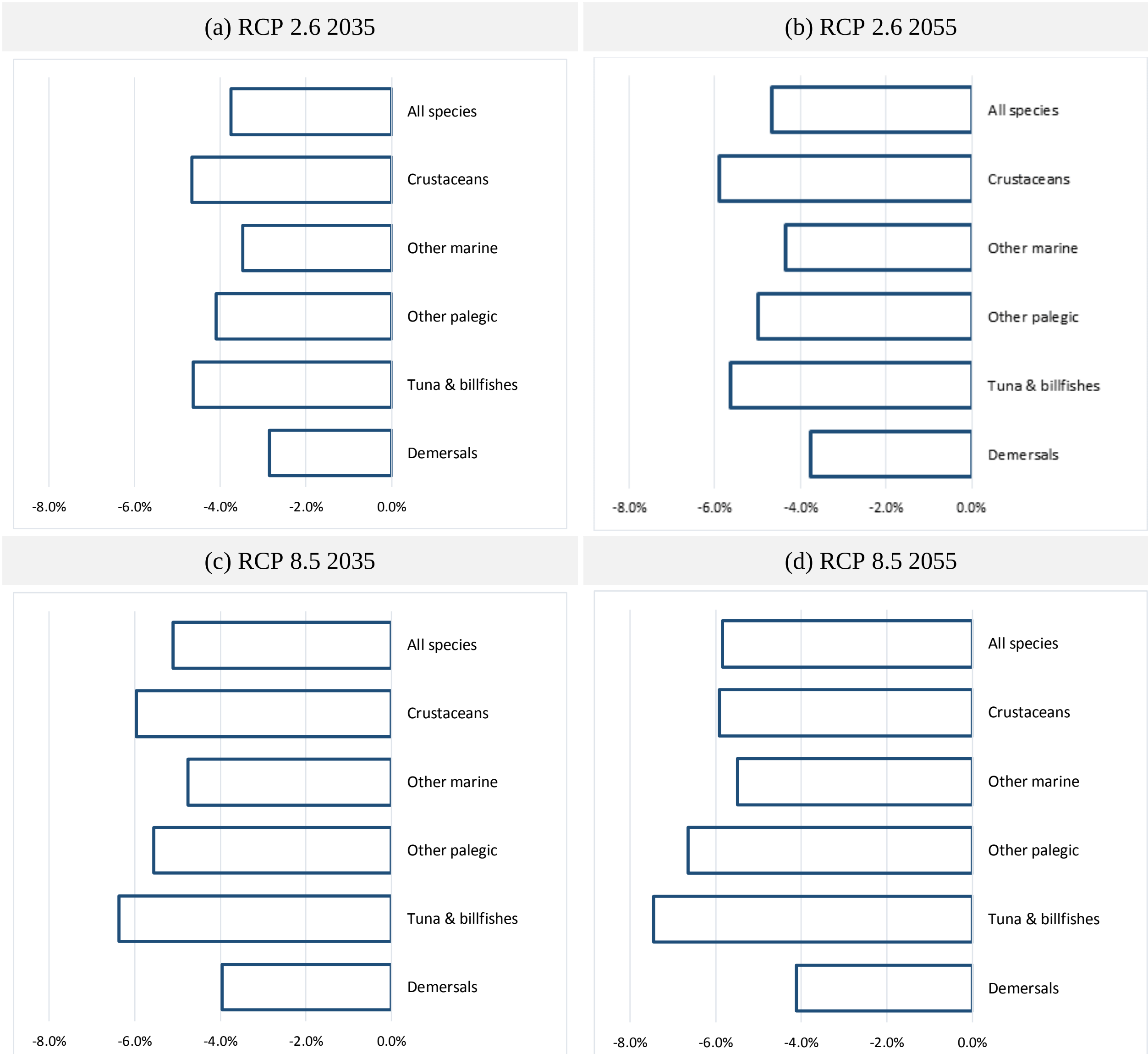


Note: the blue shaded bar shows changes in consumer surplus; the orange bar shows changes in producer surplus. Output from market S-D fish model.

For "all species", estimated annual welfare losses for each scenario are:

- **RCP 2.6** in **2035**: US$ 510,000; equivalent to a 3.7% reduction in the projected Reference Case.
- **RCP 2.6** in **2055**: US$ 770,000; equivalent to a 4.6% reduction in the projected Reference Case.
- **RCP 8.5** in **2035**: US$ 700,000; equivalent to a 5.1% reduction in the projected Reference Case.
- **RCP 8.5** in **2055**: US$ 930,000; equivalent to a 5.6% reduction in the projected Reference Case.

Figure 7: Grenada: Estimated change in fish food consumption per capita per day due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5



Note: figures show percentage change in 2035 and 2055 under each climate scenario, relatve to projected reference case for 2035 and 2055. Output from market S-D fish model.

2.5.3 Haiti

Table 22: Haiti: Projected annual changes in fish consumption by population under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(tonnes)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	11,532	12,471		-357	-463		-496	-506
Tuna & billfishes	2	2		-0	-0		-0	-0
Other palegic	24,258	25,807		-982	-1,182		-1,332	-1,575
Other marine	6,780	7,272		-240	-300		-329	-360
Crustaceans	2,425	2,616		-85	-107		-109	-107
All species	**44,996**	**48,167**		**-1,664**	**-2,052**		**-2,266**	**-2,548**

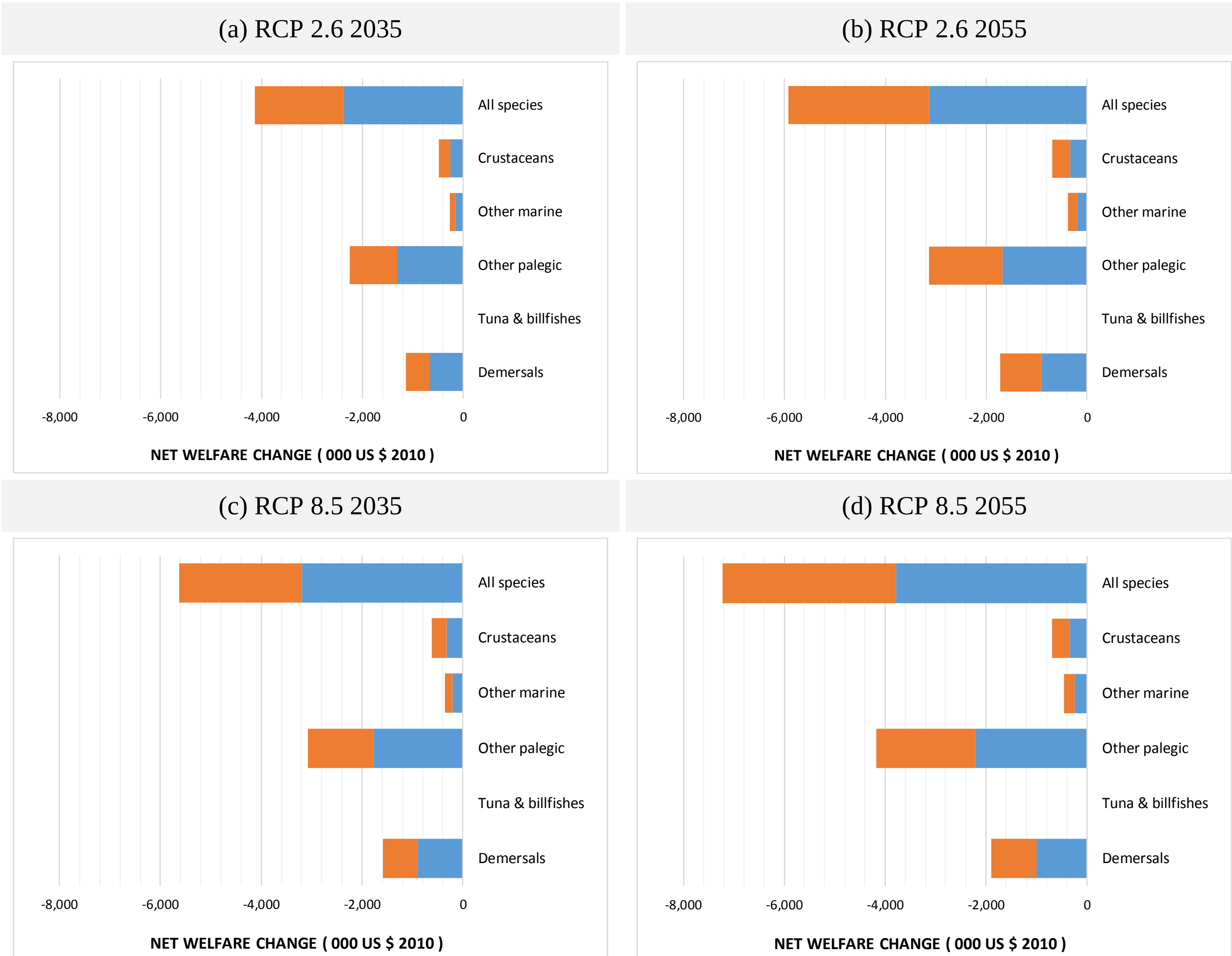
Note: quantities are in tonnes. Output from market S-D fish model.

Table 23: Haiti: Projected changes in fish prices under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(US$ per tonne)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	2,231	2,599		+58	+75		+80	+82
Tuna & billfishes	1,529	2,842		+22	+27		+31	+35
Other pelagic	1,682	1,938		+55	+66		+75	+89
Other marine	780	904		+23	+28		+31	+34
Crustaceans	3,981	4,580		+105	+132		+135	+132
All species	**1,811**	**2,097**		**+54**	**+67**		**+74**	**+84**

Note: prices are in US $ per tonne in 2010 prices. Output from market S-D fish model.

Figure 8: Haiti: Net annual welfare losses (thousand US $ per year in 2010 prices) due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5

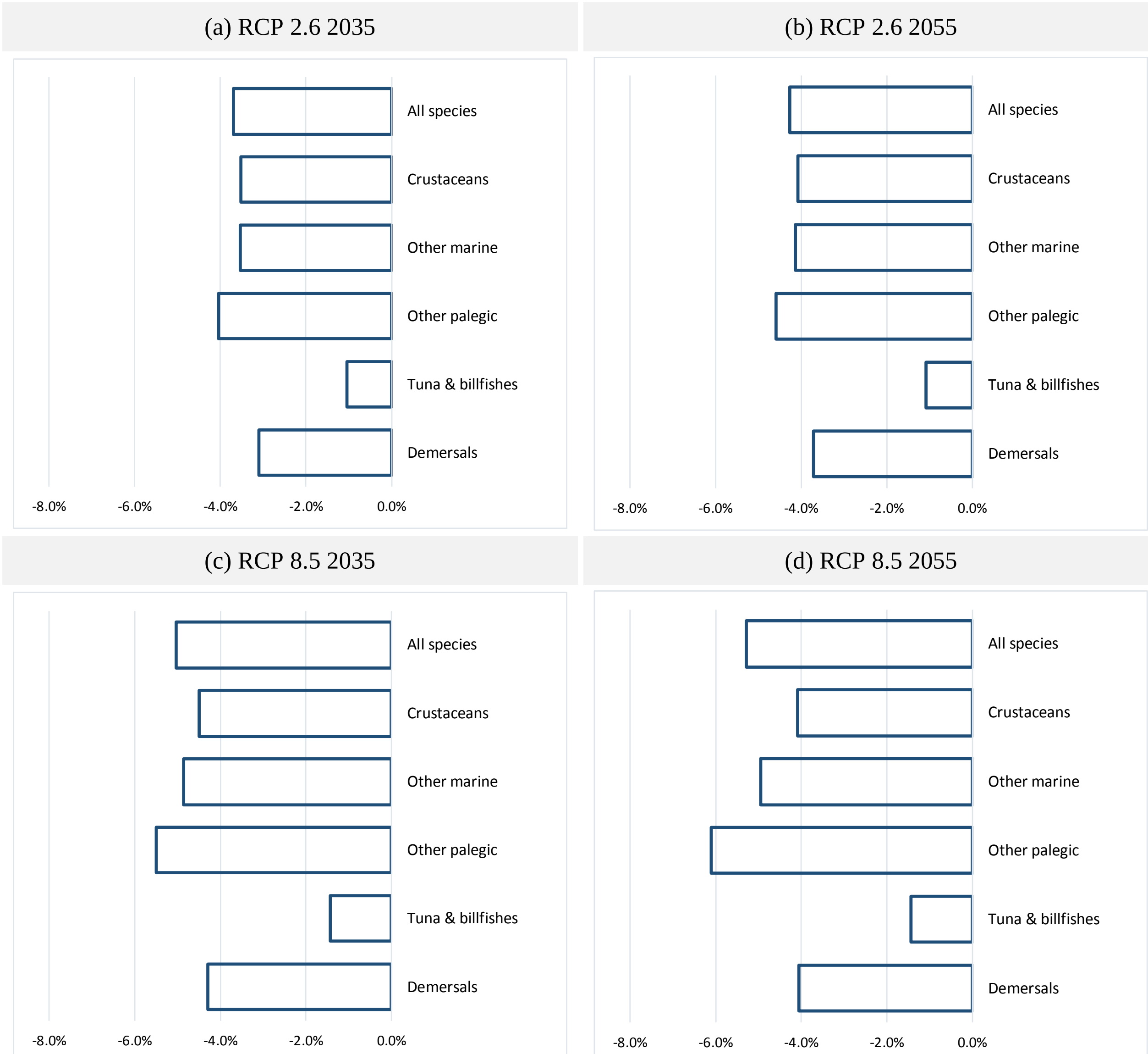


Note: the blue shaded bar shows changes in consumer surplus; the orange bar shows changes in producer surplus. Output from market S-D fish model.

For "all species", estimated annual welfare losses for each scenario are:

- **RCP 2.6** in **2035**: US$ 4,130,000; equivalent to a 3.7% reduction in the projected Reference Case.
- **RCP 2.6** in **2055**: US$ 5,920,000; equivalent to a 5.2% reduction in the projected Reference Case.
- **RCP 8.5** in **2035**: US$ 5,630,000; equivalent to a 5.9% reduction in the projected Reference Case.
- **RCP 8.5** in **2055**: US$ 7,220,000; equivalent to a 6.3% reduction in the projected Reference Case.

Figure 9: Haiti: Estimated change in fish food consumption per capita per day due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5



Note: figures show percentage change in 2035 and 2055 under each climate scenario, relatve to projected reference case for 2035 and 2055. Output from market S-D fish model.

2.5.4 Jamaica

Table 24: Jamaica: Projected annual changes in fish consumption by population under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(tonnes)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	12,108	13,327		-377	-488		-522	-534
Tuna & billfishes	30	35		-1	-2		-2	-2
Other pelagic	31,202	33,395		-1,326	-1,597		-1,799	-2,127
Other marine	38,660	41,950		-1,397	-1,755		-1,919	-2,088
Crustaceans	1,671	1,899		-71	-89		-91	-89
All species	**83,672**	**90,607**		**-3,172**	**-3,930**		**-4,334**	**-4,839**

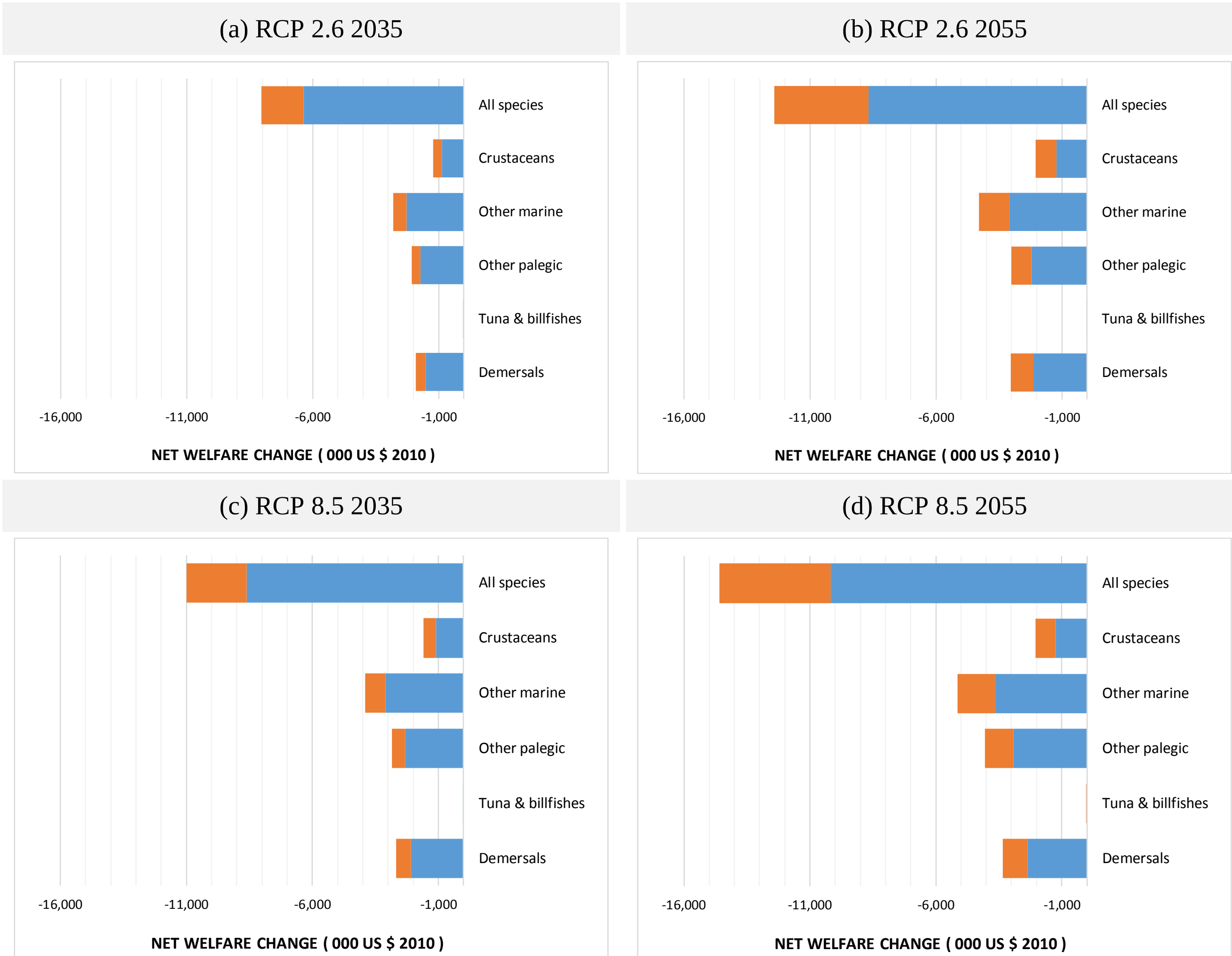
Note: quantities are in tonnes. Output from market S-D fish model.

Table 25: Jamaica: Projected changes in fish prices under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(US$ per tonne)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	3,185	3,915		+126	+164		+175	+179
Tuna & billfishes	4,012	5,929		+254	+306		+349	+405
Other pelagic	1,066	1,281		+56	+68		+76	+90
Other marine	1,316	1,599		+60	+75		+82	+89
Crustaceans	11,766	15,700		+529	+661		+676	+663
All species	**1,703**	**2,120**		**+79**	**+100**		**+108**	**+123**

Note: prices are in US $ per tonne in 2010 prices. Output from market S-D fish model.

Figure 10: Jamaica: Net annual welfare losses (thousand US $ per year in 2010 prices) due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5

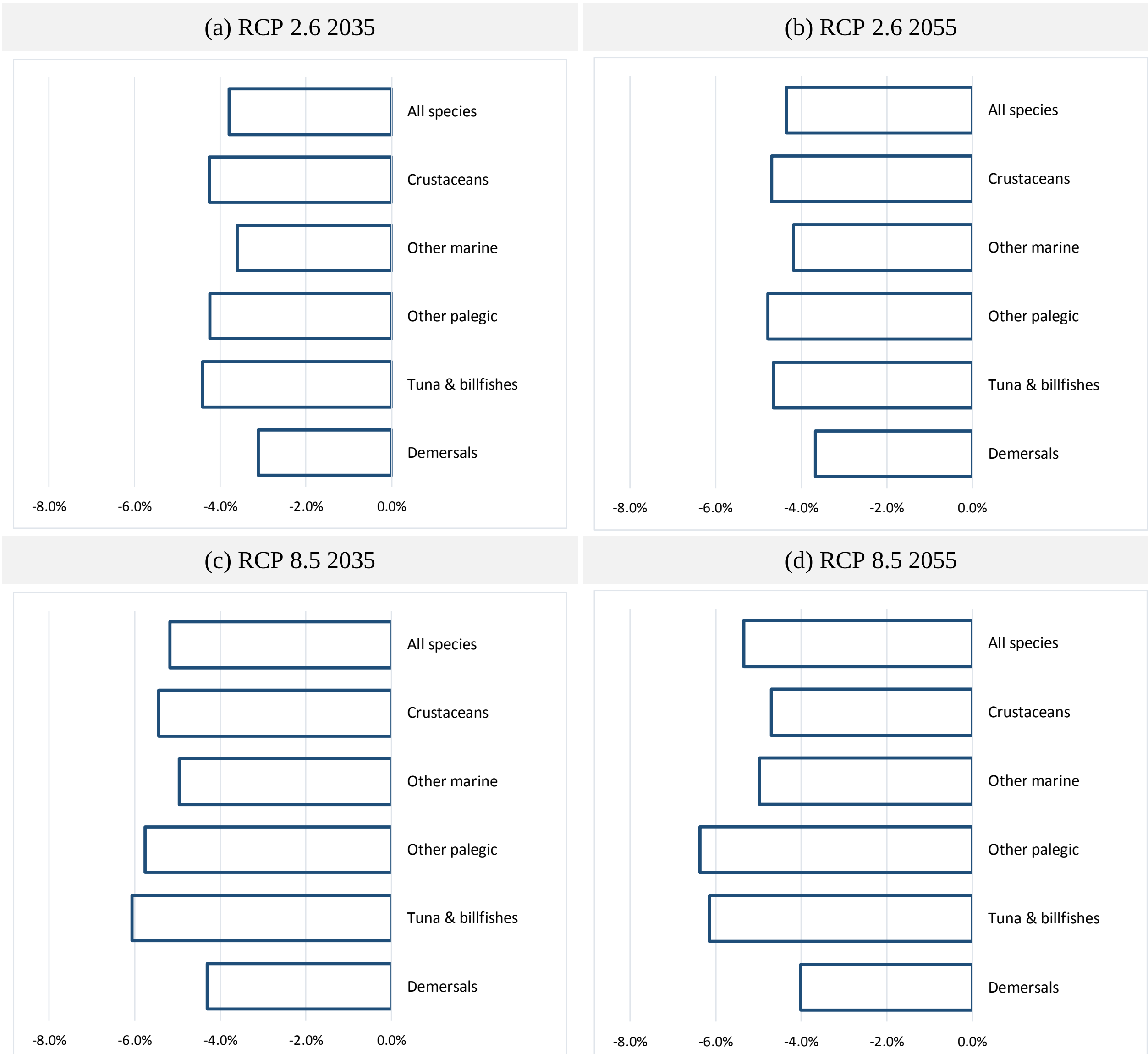


Note: the blue shaded bar shows changes in consumer surplus; the orange bar shows changes in producer surplus. Impacts on "tuna & billfishes" are lost when rounding the results. Output from market S-D fish model.

For "all species", estimated annual welfare losses for each scenario are:

- **RCP 2.6** in **2035**: US$ 8,040,000; equivalent to a 4.0% reduction in the projected Reference Case.
- **RCP 2.6** in **2055**: US$ 12,410,000; equivalent to a 4.9% reduction in the projected Reference Case.
- **RCP 8.5** in **2035**: US$ 11,000,000; equivalent to a 5.4% reduction in the projected Reference Case.
- **RCP 8.5** in **2055**: US$ 14,580,000; equivalent to a 5.7% reduction in the projected Reference Case.

Figure 11: Jamaica: Estimated change in fish food consumption per capita per day due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5



Note: figures show percentage change in 2035 and 2055 under each climate scenario, relatve to projected reference case for 2035 and 2055. Output from market S-D fish model.

2.5.5 St. Lucia

Table 26: St. Lucia: Projected annual changes in fish consumption by population under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(tonnes)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	493	555		-14	-18		-19	-19
Tuna & billfishes	633	813		-19	-22		-26	-30
Other pelagic	1,585	1,704		-64	-77		-87	-103
Other marine	1,569	1,725		-54	-66		-74	-85
Crustaceans	239	300		-10	-13		-13	-13
All species	**4,518**	**5,098**		**-161**	**-196**		**-219**	**-250**

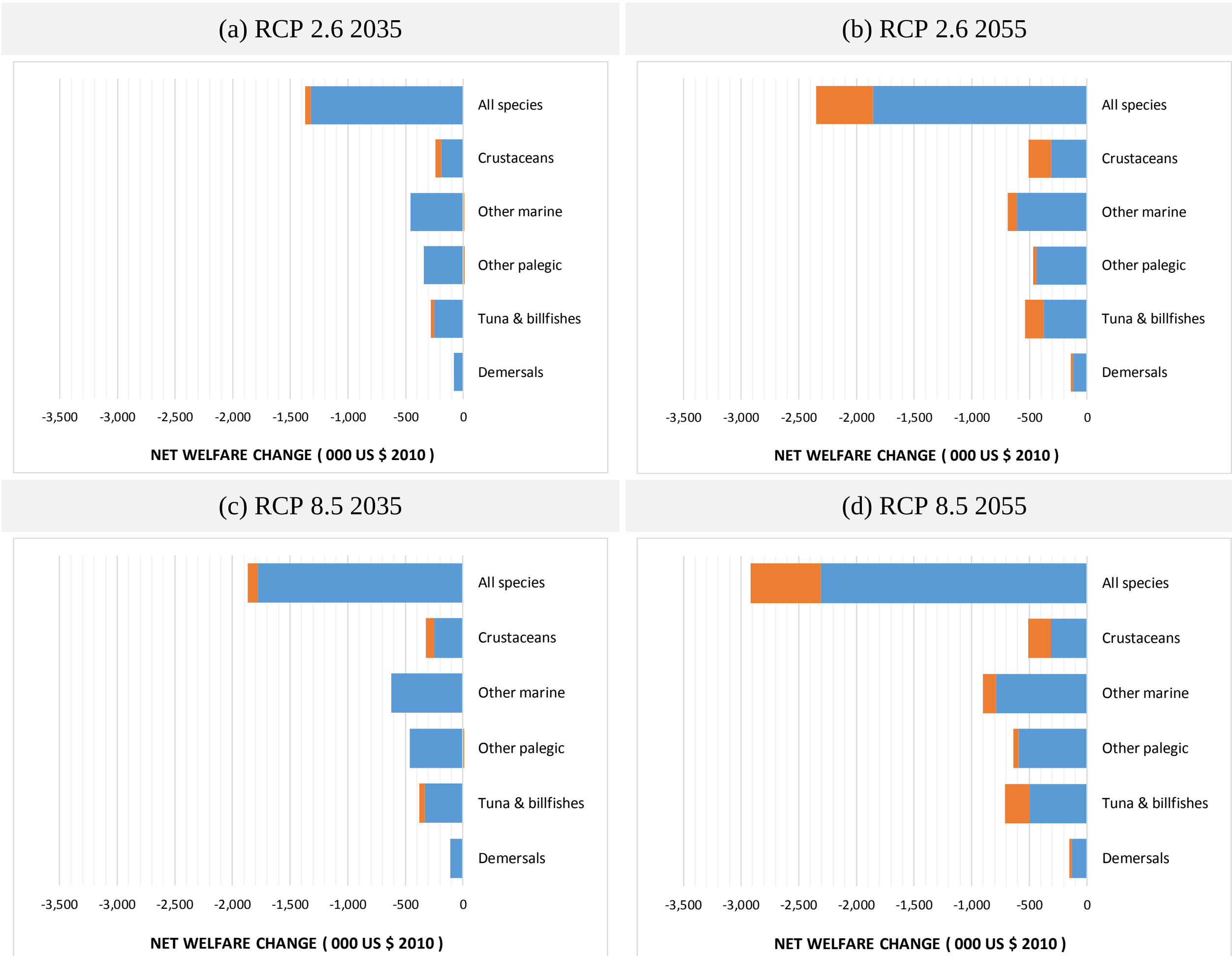
Note: quantities are in tonnes. Output from market S-D fish model.

Table 27: St. Lucia: Projected changes in fish prices under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case			**Projected Climate Scenarios**				
	(US$ per tonne)			**RCP 2.6**			**RCP 8.5**	
	2035	2055		2035	2055		2035	2055
Demersals	3,357	4,354		+169	+219		+235	+240
Tuna & billfishes	8,422	13,766		+393	+473		+540	+627
Other pelagic	3,055	3,770		+221	+266		+300	+355
Other marine	4,802	6,078		+298	+362		+405	+470
Crustaceans	16,024	26,711		+834	+1,043		+1,067	+1,046
All species	**5,131**	**7,560**		**+299**	**+386**		**+407**	**+497**

Note: prices are in US $ per tonne in 2010 prices. Output from market S-D fish model.

Figure 12: St. Lucia: Net annual welfare losses (thousand US $ per year in 2010 prices) due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5

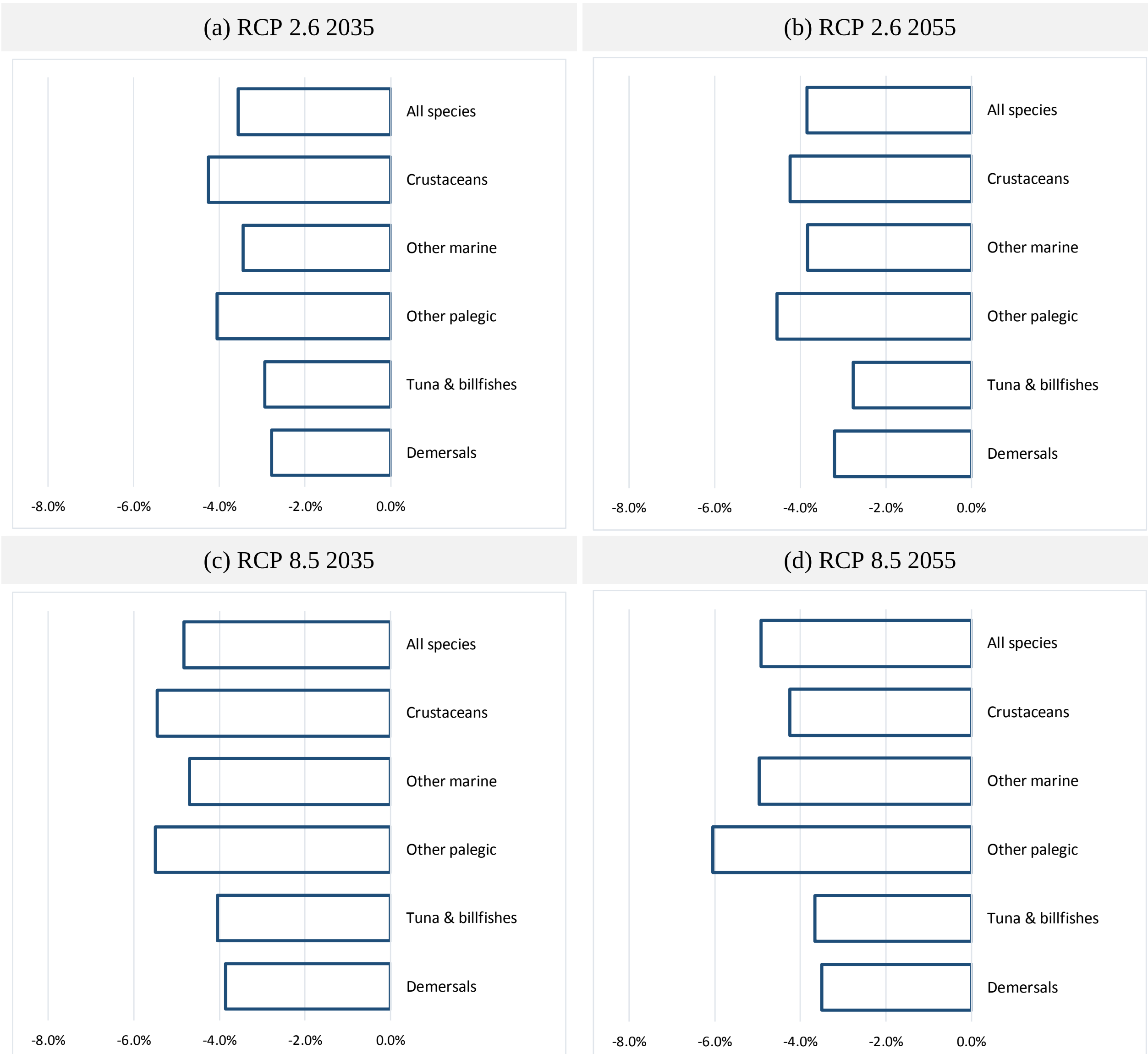


Note: the blue shaded bar shows changes in consumer surplus; the orange bar shows changes in producer surplus. Output from market S-D fish model.

For "all species", estimated annual welfare losses for each scenario are:

- **RCP 2.6** in **2035**: US$ 1,370,000; equivalent to a 3.6% reduction in the projected Reference Case.
- **RCP 2.6** in **2055**: US$ 2,350,000; equivalent to a 4.3% reduction in the projected Reference Case.
- **RCP 8.5** in **2035**: US$ 1,870,000; equivalent to a 4.9% reduction in the projected Reference Case.
- **RCP 8.5** in **2055**: US$ 2,920,000; equivalent to a 5.3% reduction in the projected Reference Case.

Figure 13: St. Lucia: Estimated change in fish food consumption per capita per day due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5



Note: figures show percentage change in 2035 and 2055 under each climate scenario, relatve to projected reference case for 2035 and 2055. Output from market S-D fish model.

2.5.6 St. Vincent and the Grenadines

Table 28: SVG: Projected annual changes in fish consumption by population under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case (tonnes)			Projected Climate Scenarios RCP 2.6			RCP 8.5	
	2035	2055		2035	2055		2035	2055
Demersals	496	536		-15	-19		-21	-21
Tuna & billfishes	2	2		-0	-0		-0	-0
Other pelagic	557	584		-24	-29		-32	-38
Other marine	703	748		-26	-31		-35	-39
Crustaceans	182	191		-9	-11		-11	-11
All species	**1,939**	**2,062**		**-73**	**-90**		**-99**	**-109**

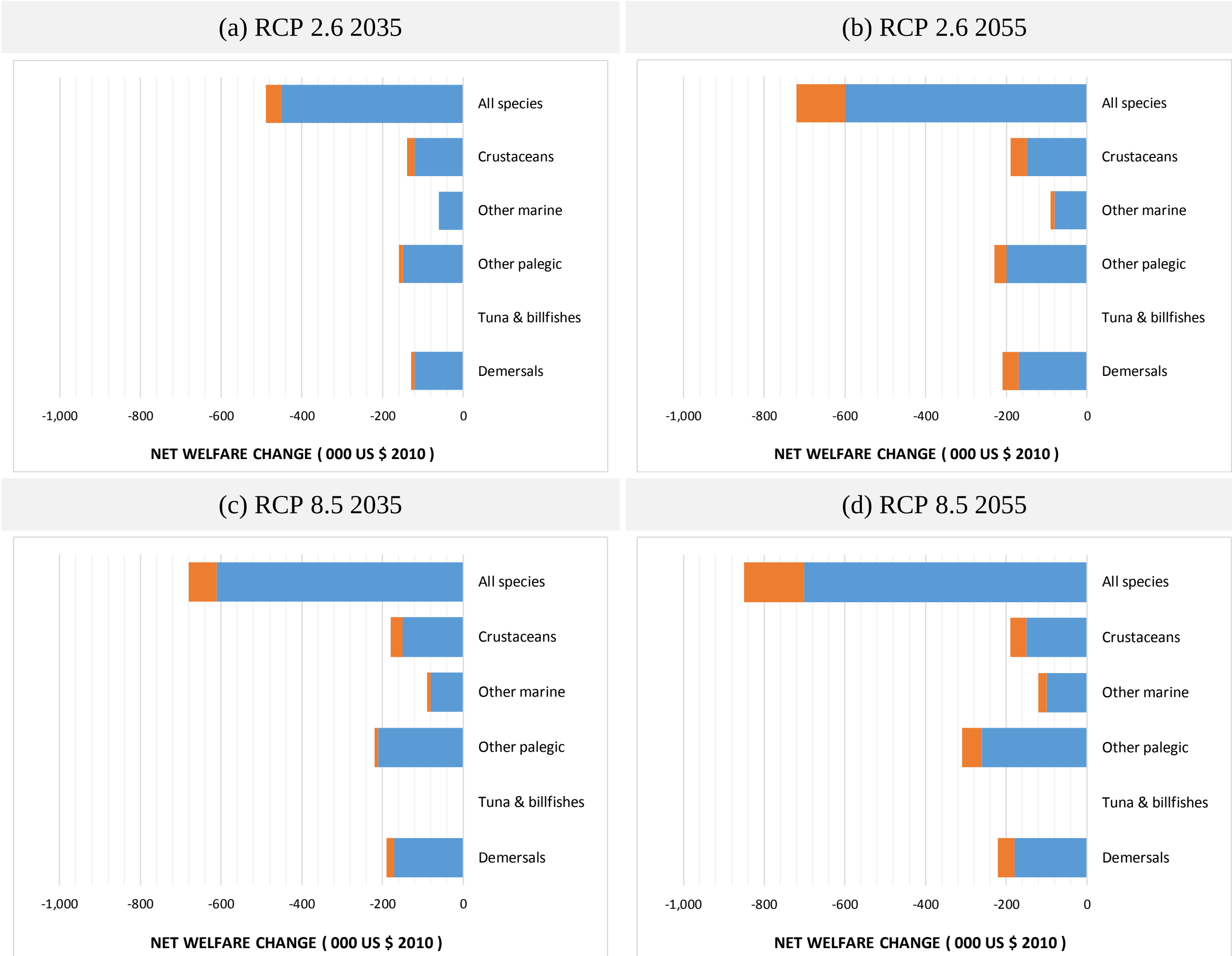
Note: quantities are in tonnes. Output from market S-D fish model.

Table 29: SVG: Projected changes in fish prices under RCP 2.6 and RCP 8.5 relative to reference case in 2035 and 2055

	Projected Reference Case (US$ per tonne)			Projected Climate Scenarios RCP 2.6			RCP 8.5	
	2035	2055		2035	2055		2035	2055
Demersals	5,186	6,189		+248	+321		+344	+351
Tuna & billfishes	3,895	4,504		+302	+363		+415	+481
Other pelagic	4,471	5,159		+285	+343		+387	+457
Other marine	1,572	1,845		+88	+109		+120	+136
Crustaceans	10,688	12,263		+652	+815		+834	+817
All species	**4,186**	**4,883**		**+233**	**+287**		**+316**	**+348**

Note: prices are in US $ per tonne in 2010 prices. Output from market S-D fish model.

Figure 14: SVG: Net annual welfare losses (thousand US $ per year in 2010 prices) due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5

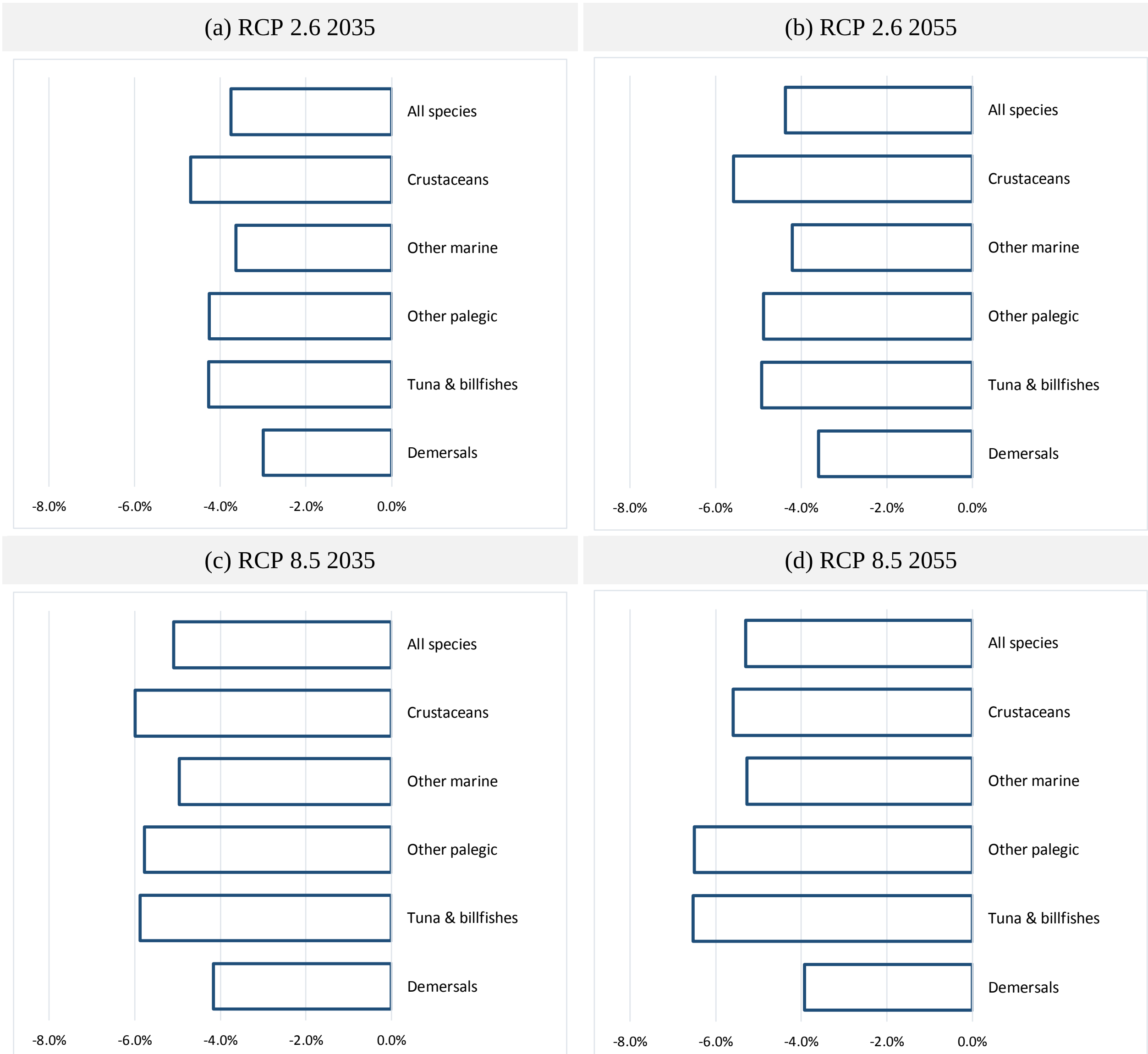


Note: the blue shaded bar shows changes in consumer surplus; the orange bar shows changes in producer surplus. Impacts on "tuna & billfishes" are lost when rounding the results. Output from market S-D fish model.

For "all species", estimated annual welfare losses for each scenario are:

- **RCP 2.6** in **2035**: US$ 490,000; equivalent to a 3.9% reduction in the projected Reference Case.
- **RCP 2.6** in **2055**: US$ 720,000; equivalent to a 4.8% reduction in the projected Reference Case.
- **RCP 8.5** in **2035**: US$ 680,000; equivalent to a 5.4% reduction in the projected Reference Case.
- **RCP 8.5** in **2055**: US$ 850,000; equivalent to a 5.7% reduction in the projected Reference Case.

Figure 15: SVG: Estimated change in fish food consumption per capita per day due to the impact of climate change on fisheries production in 2035 and 2055, under RCP 2.6 and RCP 8.5



Note: figures show percentage change in 2035 and 2055 under each climate scenario, relative to projected reference case for 2035 and 2055. Output from market S-D fish model.

3 ECONOMIC IMPACT OF FISHERY PRODUCTION FROM MORE INTENSE TROPICAL CYCLONES IN A CHANGING CLIMATE

In this section, we investigate the projected economic impact of tropical cyclones on fisheries production in our six case study countries under different climate scenarios. We start with a brief literature review on the topic.

3.1 **Economic Sensitivity to Tropical Cyclone Events**

Small island states are particularly vulnerable to tropical cyclones—tropical storms and hurricanes. Cyclones can encompass entire islands, affect significant proportions of the population, buildings, property, infrastructure and natural resources, result in catastrophic socio-economic consequences at the national level (Acevedo *et al*., 2017) and hamper long-term economic growth (Hsiang et al, 2014). The average annual economic cost of tropical cyclones across the Caribbean between 1950 and 2014 has been estimated at equivalent to 2% of GDP (Acevedo, 2016). These losses do not include important non-market impacts, including damages to marine environments and resources, like coral reefs, and ecosystem services.

The sector is vulnerable to adverse impacts from tropical cyclones. Focusing on "agriculture, hunting and fishing", Hsiang (2010) found significant reductions in output from the sector in the Caribbean and Central America because of tropical cyclone events, with output reduction of 1.8% in the year of the event and 0.6% in the year following. Exploration of the economic impacts of hurricanes on local crop production in Jamaica using quarterly data over the period 1999-2008, likewise, found negative effects on output for selected crops (excluding important export crops like bananas, coco, sugar and citrus) (Spencer and Polachek, 2015). Over the study period, hurricanes resulted in about US $ 120 million in lost revenues from the included crops (Spencer and Polachek, 2015). An examination of agricultural exports from countries in the Caribbean and Central America over the period 1961-2009, shows that damage from hurricanes has a significant and negative impact on exports in both the year storms strike and in the following year, at both the sectoral and product levels (Mohan and Strobl, 2013a), with the smaller islands being more adversely impacted (Mohan 2016). A study of the economic impact of hurricanes strikes on sugar exports from the Caribbean from 1700 to 1960 found similar significant and negative impacts on exports in both the year storms strike and in the subsequent two years (Mohan and Strobl, 2013b).

Belhabib *et al.* (2018) examined the impacts of anthropogenic and natural disasters on fisheries—albeit, at a global scale. Tropical cyclones were among the natural disasters investigated, though economic impacts were not estimated. In 48 of 52 tropical cyclones studied, storms were associated with negative impacts on catch; only in four storms were positive effects on catch noted, whereby increased effort in the small-scale sector acted as a compensatory ("buffer") mechanism (Belhabib *et al.*, 2018).

Several studies have examined the projected impact of climate change on damages from tropical cyclones, including a couple focused on the Caribbean.

- Mendelsohn *et al.* (2012) find climate change is projected to increase global economic damages from tropical cyclones by US $54 billion per year by 2100 at 2010 prices (representing a 100% increase on baseline damages). This damage cost estimate is broken down by country, including our six case study countries: Dominica (+US $22 million per year); Grenada (+US $24 million per year); Haiti (+US $22 million per year); Jamaica (+US $140 million per year); Saint Lucia (+US $2 million per year); and SVG (+US $0.5 million per year) (Mendelsohn et al, 2012). For Dominica and Grenada, these damages are equivalent to 0.5% and 0.3% of projected GDP, respectively.

- Acevedo (2016) estimated the relationship (elasticity of damages) between tropical cyclone damage and wind speeds for the Caribbean using historical data, and then used the estimated elasticity of damages to determine the impact of climate change on tropical cyclone costs. Under a high emission scenario (RCP 8.5), average annual economic damages from tropical cyclones in the Caribbean are projected to increase by 22% to 77% by 2100 (depending on the magnitude of warming under RCP 8.5) (Acevedo, 2016).
- Winston *et al.* (2017) investigate the impact of climate change on the socio-economic consequences of tropical cyclones in the Caribbean and provide disaggregated results for the agricultural sector; though not specifically for the fisheries sector. Under a high emissions scenario, Winston *et al.* (2017) estimate that the Caribbean region is projected to face average annual losses of US $550 million at 2010 prices (or about 17% of 2010 GDP) by 2100. Projected agricultural losses are estimated to be, on average, US $2.2 million per year and US $10.5 million per year by, respectively, 2050 and 2100 (Winston *et al.*, 2017).
- Lorde *et al.* (2013) provide estimates of economic losses specific to fisheries in the Caribbean; cumulative losses to Caribbean fisheries (2010-2050) from tropical cyclones would range from US$ 7.5 to US $13.3 million. The former estimate is based on 4 events per year through 2050 under a lower emission scenario (IPCC SRES B2), while the latter assumes 28 events per year through 2050 under a higher emission scenario (IPCC SRES A2). The number of events is based on, respectively, the year with the lowest and highest number of named cyclones during 1851 and 2010.

3.2 **Methods**

To assess the impact of climate change on the economic consequences of tropical cyclones for fisheries, a three-staged process is followed, like that used by Nordhaus (2010) and Acevedo (2016):

a) Historical data is used to estimate a damage-intensity function, in which a measure of fishery output (dependent variable) is related to a measure of tropical cyclone intensity (independent variable) among other things;
b) The measure of tropical cyclone intensity is modified (i.e., uprated) to reflect the impact of projected climate change; and
c) The modified tropical cyclone intensity metric is integrated into the estimated damage-intensity function and used to determine fishery losses attributable to climate change, all else being equal.

Studies that investigate the economic damages of tropical cyclones typically estimate a damage-intensity function of the following form:

$$\frac{D_{ijt}}{Y_{it}} = MaxWind_{ijt}^{\beta} \qquad \text{Equation 3}$$

Where D is the estimated total economic damages (in current prices) in country i from storm j in year t; Y is the nominal GDP of country i in year t; and $MaxWind$ is the maximum sustained wind speed of storm j.[23] Equation 3 is estimated as a log-log model of the following form:

$$ln\left(\frac{D_{ijt}}{Y_{it}}\right) = \alpha + \beta ln\left(MaxWind_{ijt}\right) + \varepsilon_{ijt} \qquad \text{Equation 4}$$

[23] Economic damages are normalized to nominal GDP to "*correct for economic growth, assuming no adaptation and neutral changes in technology and the location and structure of economic activity*" (Nordhaus, 2010).

The main advantage of this functional form is that the estimated coefficient, β, can be interpreted as the elasticity of damages with respect to changes in maximum sustained wind speeds. The standard assumption in the geophysics literature is that economic damage from tropical cyclones is a square or cubic function of wind speed (Pielke and Landsea, 1999; Emanuel, 2005). However, estimates in the economics literature for β tend to be higher—e.g., Mendelsohn (2012) ≅ 5; Bouwer and Botzen (2011) ≅ 6-8; and Nordhaus ≅ 9. These values are derived from U.S. tropical cyclone damages. For tropical cyclones affecting the Caribbean region between 1950 and 2014, Acevedo (2016) estimated a value for β of 2-3 (i.e., economic damages increase between 2% to 3% when maximum sustained wind speeds increase by 1%).

Time series data on economic damages at a *national level* caused by tropical cyclones are available for Caribbean countries, including our case study countries, from the Emergency Events Database (EM-DAT) (https://www.emdat.be/). Acevedo (2016) identified damage estimates for 59 tropical cyclones impacting the case study countries between 1950 and 2014. However, specific data for the fisheries sector is sparse, and insufficient to estimate Equation 4; only a handful of post-disaster damage assessments were available for fisheries (see Box 2). As a result, a different model specification was necessary—one employing a different dependent variable. Other studies that have investigated the economic impact of tropical cyclones on the agricultural sector in the Caribbean region have used physical output per unit of time as the dependent variable (e.g., Mohan and Strobl, 2013a and 2013b; Spencer and Polachek, 2015; Mohan, 2016). We likewise use physical output per year as the dependent variable, and estimate a range of damage-intensity functions based on the following generic formulation:

$$Production = MaxWind + Distance + Year + Time\ invariant + error \qquad \text{Equation 5}$$

The coefficient of primary interest remains that for $MaxWind$, since this is the coefficient that we modify to allow for the impact of climate change on fishery production. Various specifications of Equation 5 are examined. In all cases modelled, two specifications of the dependent variable are tested: the percentage change in absolute production or the percentage change per capita production—both relative to a 5-year moving average. For any given year the percentage change in (per capita) production is calculated as: $100 \times (Q - A)/A$, where Q is the yearly production or per capita production (either in tonnes or kilograms per person, respectively) and A is a 5-year moving average of production or per capita production (either in tonnes or kilograms per person, respectively). Note that A is calculated differently for the first two years and last two years in the data set (1950, 1951, 2012, 2013). For the year 1950, A is the average of 1950, 1951, 1952 and for 1951, A is the average of 1950, 1951, 1952, 1953. Similarly, A is the average of 2010, 2011, 2012, 2013 for the year 2012 and the average of 2011, 2012, 2013 for the year 2013. If the percentage change in (per capita) production is negative, this implies that production (per capita) is lower than the "norm", as measured by the 5-year moving average of (per capita) production. It is calculated for total production, as well as for production of each fish species groupings; both pooled and by case study country. The primary motive for specifying the dependent variable as a percentage change in (per capita) production is that it can be incorporated directly into the market S-D fish model (Section 2).

Box 2: Examples of impacts with economic consequences from tropical cyclone damage assessments for fisheries in case study countries

Country: Dominica
Storm: Hurricane Maria, September 2017
Examples of reported impacts:

- A total of 3,394 items (e.g., fishing boats and gear) were reported to have been damaged, with an estimated total value of XCD $11,271,520. (1XCD = 0.37 US$ in 2017)
- 319 out of 437 boats (73% of the fleet) were reported as having been affected.
- Approximately 29% of boats affected were damaged and 71% were destroyed or lost. The total cost of replacing these boats is estimated at XCD $4,499,000.
- Out of 395 marine engines, 295 (or about 75%) were reported to be negatively affected. Out of the 295 affected engines, about 16% were damaged and 84% destroyed or lost. The total value of marine engines affected is estimated at XCD $3,525,680.
- Out of 7,241 fishing gear or sets of gear according to 2011 Fishery Industry Census figures, Hurricane Maria caused damage to 2,263 (or about 31%). Of the gear affected, about 8% were damaged and 92% destroyed or lost. The total value for all gear affected is estimated at XCD $1,487,760.

Country: Jamaica
Storm: Hurricanes Dennis & Emily, July 2005
Examples of reported impacts:
The St. Elizabeth fishers, which include fishers from Great Bay, Frenchman's Cove, Billings Bay, Calabash Bay and the general Treasure Beach area, reported preliminary damage estimates amounting to J $330 million. This accounts exclusively for damage to fish traps. Damage to infrastructure and beaches were not reported. (1 J $ = 0.016 US$ in 2005.)

Country: Jamaica
Storm: Ivan, September 2004
Examples of reported impacts:
The estimated total number of traps lost after the passage of Hurricane Ivan across the island was 300,000. Given that one trap contains an average of 2 kg of fish, then 300,000 traps would capture about 600,000 kg. As a result, about 600 tonnes of fish were caught by traps that were 'ghost-fishing' after the hurricane. This represents a significant quantity of fish. Total fish production for 2004 was 9,495 tonnes; hence, the total quantity of fish potentially caught by lost fishing gears was about 6% of the total fish production for 2004.

Country: Jamaica
Storm: Tropical storm Gustav, August 2008
Examples of reported impacts:
The fisheries sector sustained losses of J $14 million, mostly due to the loss of equipment, particularly that which was out at sea at the time of the storm. The most significant losses were food fish and damage to infrastructure, such as dykes and access roads. Fishers based at Manchioneal fishing beach reported considerable losses; 68% of the total cost of damages (approximately J $9 million). This was largely due to loss of pots and gear sheds. In addition, several beach areas important to the fishing sector, reported extensive erosion as a result of the storm. (1 J $ = 0.014 US$ in 2008.)

Country: Jamaica
Storm: Hurricane Sandy, October 2012
Examples of reported impacts:
Hurricane Sandy caused extensive damage to the fisheries and aquaculture sectors, totaling more than J $90 million. Over 1,600 fishers suffered losses of just under J $77 million, while 23 fish farmers sustained losses of approximately J $14 million. For fishers, most of the damage suffered was loss of traps, while fish farmers lost fish and suffered minor damage to farm infrastructure. (1 J $ = 0.011 US$ in 2012.)

Country: Jamaica
Storm: Hurricane Dean, August 2007
Examples of reported impacts:
About 90% of those employed in the fishery sector (approximately 10,000 fisher folk) from St. Thomas, St. Catherine, Clarendon, Manchester and St. Elizabeth were directly affected. For the south coast, 70% of fishers were directly affected and each fisher, on average, lost 50 traps or fishing gear units. Each trap or gear unit is valued at about J $4, 000. (1 J $ = 0.014 US$ in 2007.)

Like Acevedo (2016), different distance variables are tested in the model to allow for the fact that not all the storms included in the data set make landfall; the distance variables are described in Section 3.3. As

Acevedo (2016) shows, half of the largest damages in the Caribbean countries studied are due to non-landfall storms. It is thus important they are included in the assessment. A year variable is also tested in the model to allow for year-specific effects common to all countries that may be correlated with production figures (Mohan and Strobl, 2013a and 2013b). An additional variable is included to allow for time-invariant country-specific factors that may influence fishery production and tropical cyclone impacts (Mohan and Strobl, 2013a and 2013b; Acevedo, 2016). Table 30 lists the time-invariant country characteristics tested in the model estimated using a standard regression.

Various specifications of Equation 5 are estimated using panel fixed effects and standard (ordinary least squares) regression. Results are presented in Section 3.5.

Table 30: Examples of time-invariant country characteristics

Country	Size of EEZ (km^2)	Area of country (km^2)	Length of coastline (km)	Ratio of coastline to area (%)	Elevation span (m)
Dominica	28,593	751	148	19.7	1,447
Grenada	26,133	344	121	35.2	840
Haiti	123,525	27,750	1,771	6.4	2,688
Jamaica	263,284	10,992	1,022	9.3	2,256
Saint Lucia	15,472	617	158	25.6	958
SVG	36,304	389	84	21.6	1,234

3.3 Tropical Cyclone Data

The tropical cyclone dataset was generated using information from the National Oceanic and Atmospheric Administration (NOAA) Historical Hurricane Tracks Tool (NOAA, 2019), and the Caribbean Hurricane Network StormCarib website (Stormcarib, 2011). The dataset is composed of 111 storms between 1950 and 2013 that (see Table 31):[24]

- Passed within approximately 60 nautical miles of shore for the islands of Dominica, Grenada, Jamaica, Haiti, St. Lucia, and St. Vincent and the Grenadines (SVG); and
- At the time of their passing or crossing, were classified as either tropical storms or hurricanes.

[24] Storms occurring after 2013 were not included in the dataset, since corresponding production data for the case study islands was only available for the period 1950-2013.

Table 31: Tropical storm dataset

Year	Day	Month	Name	Name of location	Coordinates	Wind speed (miles per hr)	Storm category	CPOA to measurement point (miles)	Landfall	CPOA to any part of the island shore (miles)	If landfall, miles of country land the storm path crossed (miles)
1951	18	Aug	CHARLIE	Montego Bay, Jamaica	18.50N 77.92W	92	h1	25	Yes	0	73
1958	15	Sept	GERDA	Montego Bay, Jamaica	18.50N 77.92W	40	ts	9	No	6	0
1974	31	Aug	CARMEN	Montego Bay, Jamaica	18.50N 77.92W	86	h1	89	No	47	0
1980	6	Aug	ALLEN	Montego Bay, Jamaica	18.50N 77.92W	132	h4	42	No	21	0
1988	12	Sep	GILBERT	Montego Bay, Jamaica	18.50N 77.92W	127	h3	28	Yes	0	71
1994	13	Nov	GORDON	Montego Bay, Jamaica	18.50N 77.92W	40	ts	58	Yes	0	41
2001	7	Oct	IRIS	Montego Bay, Jamaica	18.50N 77.92W	86	h1	81	No	31	0
2002	18	Sep	ISIDORE	Montego Bay, Jamaica	18.50N 77.92W	52	ts	43	No	13	0
2002	30	Sep	LILI	Montego Bay, Jamaica	18.50N 77.92W	69	ts	23	No	13	0
2004	12	Aug	CHARLEY	Montego Bay, Jamaica	18.50N 77.92W	86	h1	69	No	42	0
2004	11	Sep	IVAN	Montego Bay, Jamaica	18.50N 77.92W	144	h4	63	No	26	0
2005	7	Jul	DENNIS	Montego Bay, Jamaica	18.50N 77.92W	115	h3	84	No	28	0
2007	20	Aug	DEAN	Montego Bay, Jamaica	18.50N 77.92W	144	h4	68	No	27	0
2008	29	Aug	GUSTAV	Montego Bay, Jamaica	18.50N 77.92W	69	ts	25	Yes	0	96
2012	24	Oct	SANDY	Montego Bay, Jamaica	18.50N 77.92W	86	h1	87	Yes	0	21
1954	12	Oct	HAZEL	Port au Prince, Haiti	18.57N 72.30W	121	h3	96	Yes	0	50
1955	17	Oct	KATIE	Port au Prince, Haiti	18.57N 72.30W	63	ts	42	Yes	5	*
1955	13	Sept	HILDA	Port au Prince, Haiti	18.57N 72.30W	81	h1	124	No	24	0
1958	1	Sep	ELLA	Port au Prince, Haiti	18.57N 72.30W	109	h2	60	Yes	0	53
1958	15	Sep	GERDA	Port au Prince, Haiti	18.57N 72.30W	52	ts	17	Yes	0	169
1963	4	Oct	FLORA	Port au Prince, Haiti	18.57N 72.30W	144	h4	66	Yes	0	35
1964	27	Aug	CLEO	Port au Prince, Haiti	18.57N 72.30W	150	h1	77	Yes	0	10
1966	29	Sep	INEZ	Port au Prince, Haiti	18.57N 72.30W	115	h3	28	Yes	0	35
1967	11	Sep	BEULAH	Port au Prince, Haiti	18.57N 72.30W	92	h1	65	No	45	0
1979	1	Sep	DAVID	Port au Prince, Haiti	18.57N 72.30W	115	h3	53	Yes	0	78
1979	6	Sept	FREDERIC	Port au Prince, Haiti	18.57N 72.30W	40	ts	93	No	4	0
1979	18	Sep	ELOISE	Port au Prince, Haiti	18.57N 72.30W	58	ts	85	Yes	0	50
1987	23	Sep	EMILY	Port au Prince, Haiti	18.57N 72.30W	81	h1	60	Yes	0	46
1998	23	Sep	GEORGES	Port au Prince, Haiti	18.57N 72.30W	75	h1	32	Yes	0	63
2000	24	Aug	DEBBY	Port au Prince, Haiti	18.57N 72.30W	46	ts	91	Yes	0	31
2005	23	Oct	ALPHA	Port au Prince, Haiti	18.57N 72.30W	40	ts	7	Yes	0	124
2007	29	Oct	NOEL	Port au Prince, Haiti	18.57N 72.30W	52	ts	21	Yes	0	35
2007	12	Dec	OLGA	Port au Prince, Haiti	18.57N 72.30W	46	ts	36	Yes	0	67
2008	16	Aug	FAY	Port au Prince, Haiti	18.57N 72.30W	46	ts	13	Yes	0	84
2008	26	Aug	GUSTAV	Port au Prince, Haiti	18.57N 72.30W	81	h1	46	Yes	0	35
2008	3	Sep	HANNA	Port au Prince, Haiti	18.57N 72.30W	58	ts	108	No	23	0
2010	5	Nov	TOMAS	Port au Prince, Haiti	18.57N 72.30W	86	h1	128	No	15	0
2012	24	Aug	ISAAC	Port au Prince, Haiti	18.57N 72.30W	63	ts	32	Yes	0	25
1951	2	Sep	DOG	St. Vincent	13.13N 61.20W	109	h2	67	No	55	0
1954	6	Oct	HAZEL	St. Vincent	13.13N 61.20W	86	h1	22	No	67	0
1955	22	Sep	JANET	St. Vincent	13.13N 61.20W	121	h3	53	No	35	0
1960	10	Jul	ABBY	St. Vincent	13.13N 61.20W	75	h1	48	No	37	0
1963	25	Sep	EDITH	St. Vincent	13.13N 61.20W	86	h1	65	No	44	0

Year	Day	Month	Name	Name of location	Coordinates	Wind speed (miles per hr)	Storm category	CPOA to measurement point (miles)	Landfall	CPOA to any part of the island shore (miles)	If landfall, miles of country land the storm path crossed (miles)
1967	7	Sep	BEULAH	St. Vincent	13.13N 61.20W	52	ts	57	No	39	0
1974	2	Oct	GERTRUDE	St. Vincent	13.13N 61.20W	40	ts	38	No	38	0
1980	4	Aug	ALLEN	St. Vincent	13.13N 61.20W	132	h4	34	No	15	0
1986	8	Sep	DANIELLE	St. Vincent	13.13N 61.20W	58	ts	42	No	42	0
1987	21	Sep	EMILY	St. Vincent	13.13N 61.20W	52	ts	5	Yes	4	0
1994	10	Sep	DEBBY	St. Vincent	13.13N 61.20W	69	ts	56	No	39	0
2001	17	Aug	CHANTAL	St. Vincent	13.13N 61.20W	40	ts	2	Yes	0	7
2001	8	Oct	JERRY	St. Vincent	13.13N 61.20W	52	ts	23	No	5	0
2002	23	Sep	LILI	St. Vincent	13.13N 61.20W	58	ts	37	No	37	0
2003	8	Jul	CLAUDETTE	St. Vincent	13.13N 61.20W	40	ts	26	No	7	0
2010	31	Oct	TOMAS	St. Vincent	13.13N 61.20W	98	h2	15	Yes	0	5
2012	3	Aug	ERNESTO	St. Vincent	13.13N 61.20W	46	ts	40	No	20	0
2013	9	Jul	CHANTAL	St. Vincent	13.13N 61.20W	63	ts	70	No	54	0
1954	6	Oct	HAZEL	Grenada	12.00N 61.78W	86	h1	59	Yes	0	7
1955	23	Sep	JANET	Grenada	12.00N 61.78W	115	h3	25	No	23	0
1961	20	Jul	ANNA	Grenada	12.00N 61.78W	52	ts	22	No	22	0
1963	1	Oct	FLORA	Grenada	12.00N 61.78W	127	h3	31	No	31	0
1978	11	Aug	CORA	Grenada	12.00N 61.78W	52	ts	0	Yes	0	1
1986	8	Sep	DANIELLE	Grenada	12.00N 61.78W	58	ts	44	No	24	0
1988	14	Oct	JOAN	Grenada	12.00N 61.78W	52	ts	7	Yes	0	9
1990	25	Jul	ARTHUR	Grenada	12.00N 61.78W	58	ts	1	No	1	0
2000	1	Oct	JOYCE	Grenada	12.00N 61.78W	40	ts	30	No	30	0
2002	24	Sep	LILI	Grenada	12.00N 61.78W	58	ts	45	No	27	0
2004	15	Aug	EARL	Grenada	12.00N 61.78W	52	ts	4	No	4	0
2004	8	Sep	IVAN	Grenada	12.00N 61.78W	132	h4	7	No	7	0
2005	14	Jul	EMILY	Grenada	12.00N 61.78W	86	h1	1	No	1	0
2007	1	Sep	FELIX	Grenada	12.00N 61.78W	58	ts	10	Yes	0	9
1951	2	Sep	DOG	St. Lucia	13.75N 60.95W	109	h2	24	No	3	0
1958	30	Aug	ELLA	St. Lucia	13.75N 60.95W	40	ts	61	No	9	0
1960	10	Jul	ABBY	St. Lucia	13.75N 60.95W	75	h1	2	Yes	0	12
1963	25	Sep	EDITH	St. Lucia	13.75N 60.95W	98	h2	20	Yes	0	7
1967	8	Sep	BEULAH	St. Lucia	13.75N 60.95W	63	ts	13	Yes	0	10
1970	20	Aug	DOROTHY	St. Lucia	13.75N 60.95W	69	ts	54	No	28	0
1980	4	Aug	ALLEN	St. Lucia	13.75N 60.95W	132	h4	11	No	11	0
1987	21	Sep	EMILY	St. Lucia	13.75N 60.95W	52	ts	50	No	50	0
1988	9	Sep	GILBERT	St. Lucia	13.75N 60.95W	40	ts	63	No	39	0
1993	14	Aug	CINDY	St. Lucia	13.75N 60.95W	40	ts	50	No	25	0
1994	10	Sep	DEBBY	St. Lucia	13.75N 60.95W	69	ts	11	Yes	0	11
1995	26	Aug	IRIS	St. Lucia	13.75N 60.95W	58	ts	47	No	38	0
2001	17	Aug	CHANTAL	St. Lucia	13.75N 60.95W	40	ts	42	No	40	0
2001	8	Oct	JERRY	St. Lucia	13.75N 60.95W	52	ts	23	No	22	0
2003	8	Jul	CLAUDETTE	St. Lucia	13.75N 60.95W	40	ts	19	No	19	0
2007	17	Aug	DEAN	St. Lucia	13.75N 60.95W	104	h2	39	No	14	0
2010	31	Oct	TOMAS	St. Lucia	13.75N 60.95W	98	h2	31	No	31	0
2012	3	Aug	ERNESTO	St. Lucia	13.75N 60.95W	46	ts	4.5	No	1	0

Year	Day	Month	Name	Name of location	Coordinates	Wind speed (miles per hr)	Storm category	CPOA to measurement point (miles)	Landfall	CPOA to any part of the island shore (miles)	If landfall, miles of country land the storm path crossed (miles)
2013	9	July	CHANTAL	St. Lucia	13.75N 60.95W	63	ts	25	No	1	0
1950	22	Aug	BAKER	Dominica	15.53N 61.30W	104	h2	113	No	112	0
1951	15	Aug	CHARLIE	Dominica	15.53N 61.30W	69	ts	18	No	18	0
1956	11	Aug	BETSY	Dominica	15.53N 61.30W	109	h2	15	No	15	0
1958	30	Aug	ELLA	Dominica	15.53N 61.30W	40	ts	32	No	44	0
1959	18	Aug	EDITH	Dominica	15.53N 61.30W	58	ts	32	Yes	0	10
1961	1	Oct	FRANCES	Dominica	15.53N 61.30W	52	ts	42	No	32	0
1963	26	Oct	HELENA	Dominica	15.53N 61.30W	52	ts	6	No	1	0
1964	22	Aug	CLEO	Dominica	15.53N 61.30W	132	h4	26	No	20	0
1966	27	Sep	INEZ	Dominica	15.53N 61.30W	127	h3	44	No	35	0
1970	21	Aug	DOROTHY	Dominica	15.53N 61.30W	63	ts	67	No	45	0
1979	29	Aug	DAVID	Dominica	15.53N 61.30W	144	h4	22	No	2	0
1981	8	Sep	GERT	Dominica	15.53N 61.30W	52	ts	18	No	12	0
1988	10	Sep	GILBERT	Dominica	15.53N 61.30W	46	ts	52	No	29	0
1989	17	Sep	HUGO	Dominica	15.53N 61.30W	138	h4	54	No	46	0
1993	15	Aug	CINDY	Dominica	15.53N 61.30W	40	ts	59	No	38	0
1995	26	Aug	IRIS	Dominica	15.53N 61.30W	52	ts	7	No	3	0
1995	15	Sep	MARILYN	Dominica	15.53N 61.30W	86	h1	4	Yes	0	19
1996	8	Sep	HORTENSE	Dominica	15.53N 61.30W	63	ts	39	No	32	0
2009	2	Sep	ERIKA	Dominica	15.53N 61.30W	40	ts	53	No	44	0
2011	21	Aug	IRENE	Dominica	15.53N 61.30W	52	ts	55	No	53	0
2011	2	Aug	EMILY	Dominica	15.53N 61.30W	46	ts	44	No	22	0
2012	23	Aug	ISAAC	Dominica	15.53N 61.30W	52	ts	22	No	13	0

Notes:

* Made landfall in the Dominican Republic. CPOA to shore is the distance from storm path to border between Haiti and the Dominican Republic.

The storm categories are: “h1” = category 1 hurricane (sustained wind speeds 75-95 mph); “h2” = category 2 hurricane (sustained wind speeds 96-110 mph); “h3” = category 3 hurricane (sustained wind speeds 111-129 mph); “h4” = category 4 hurricane (sustained wind speeds 130-156 mph); and “h5” = category 5 hurricane (sustained wind speeds >157 mph).

The data sources record data in imperial units. 1 mile = 1.60934 km.

CPOA = closet point of approach; defined as the shortest distance between the location of interest (on land) and the eye of the storm.

Figure 16 shows the distribution of all storms that passed within approximately 60 nautical miles of the island shorelines (Panel a) and landfall storms (Panel b). Haiti and Dominica were affected most, each with 23 and 22 storms, respectively, passing within 60 nautical miles of shore. However, only two storms made landfall in Dominica, while 18 storms made landfall in Haiti. The number of storms making landfall in Dominica, Jamaica, Grenada, St. Lucia and SVG ranged from two to five. In terms of storm intensity, 64 events in the dataset are categorized as tropical storms, with the remaining 47 events categorized as hurricanes (see Figure 17). No category 5 hurricanes (based on the Saffir-Simpson Hurricane Wind Scale) were recorded. However, each case study country experienced at least one category 4 hurricane over 1950-2013. Overall, the six case study countries were impacted by nineteen category 1, nine category 2, nine category 3 and ten category 4 hurricanes.

Figure 16: Distribution of landfall and non-landfall storms by case study countries

(a) All storms (n = 111)

(b) Landfall storms (n = 36)

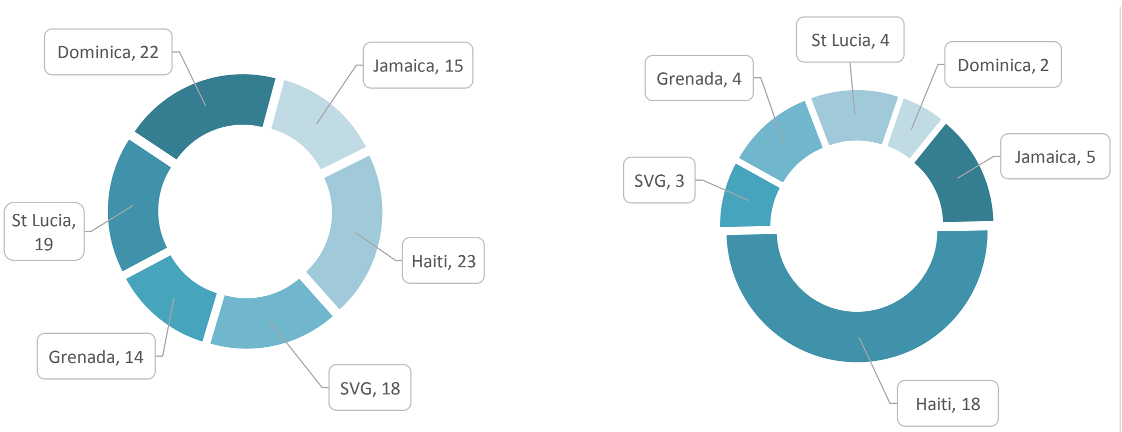
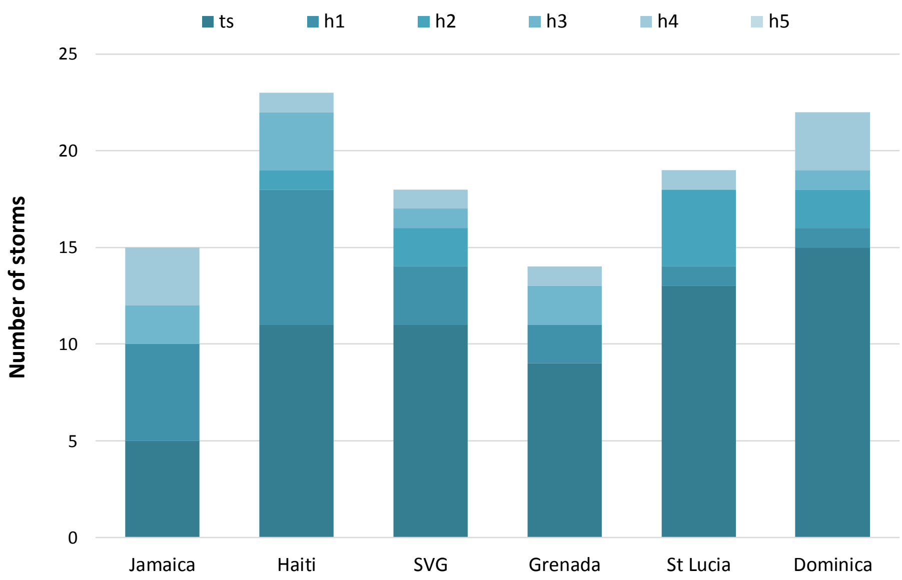


Figure 17: Number of storms affecting each case study country, by storm category (n = 111)

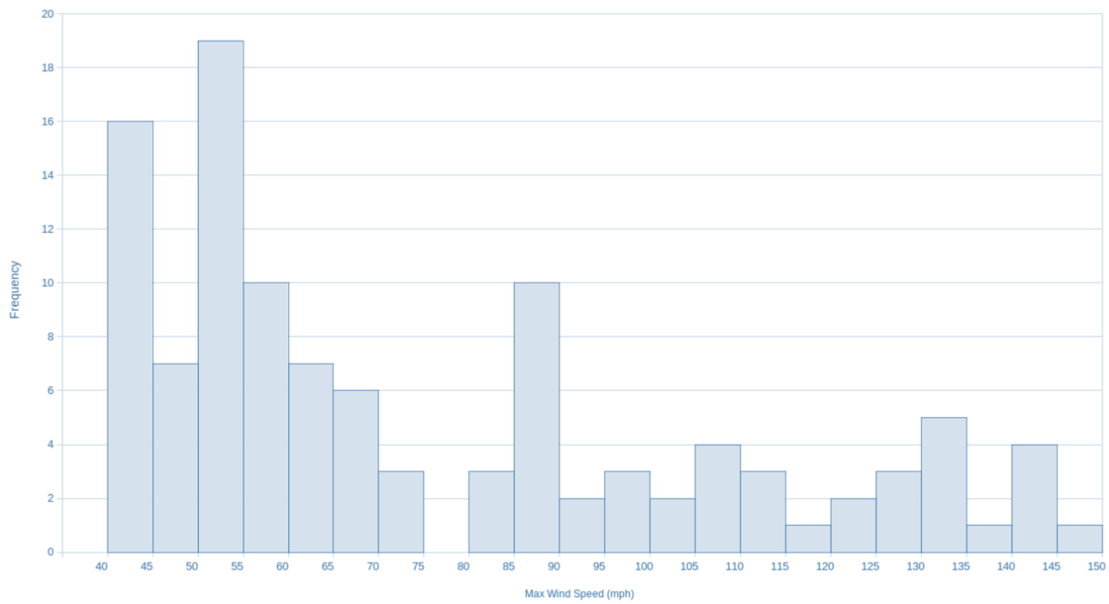


Information on the maximum sustained wind speed of each storm (measured in miles per hour) at its closest approach to an island, and the date of that occurrence, were found using both the Historical Hurricane Tracks Tool and the StormCarib measurements. Like Acevedo (2016), wind speeds have been adjusted to reflect differences in measurement techniques pre and post 1970. The following adjustment (via Equation 6) is made for wind speeds between 45 and 120 knots for all storms occurring before 1970 (Emanuel, 2005):

$$MaxWind^{*} = MaxWind \times \left(1 - 0.14 sin\left(\frac{\pi \times (MaxWind - 45)}{75}\right)\right) \qquad \text{Equation 6}$$

Where $MaxWind$ is the original recorded maximum sustained windspeed and the adjusted value is $Max\ Wind^{*}$. The mean wind speed of storms in the dataset is 75 miles per hour [standard deviation = 32; median = 63; min = 40; and max = 150]. Figure 18 presents a wind speed histogram for the 111 tropical cyclones in the data set.

Figure 18: Histogram of maximum sustained wind speeds of tropical cyclone data set (n = 111)



Data were generated for three different measures of distance (measured in miles):

- The distance of the closest point of approach (CPOA) of a storm to an island's weather station (generally at the airport);
- The CPOA of a storm to any part of the island shore; and
- If a storm made landfall, the approximate length the eye (center) of the storm tracked across the island. In other words, the distance travelled by the eye of the storm over land.

The CPOA of a storm to an island's weather station (1 above) for all storms between 1950 and 2010 were obtained from StormCarib. All other distances metrics were calculated by entering the geographic coordinates of island weather stations (from StormCarib) and storm track locations (from the Hurricane Tracks Tool) into Google Earth, and then measuring the required distances using the distance measurement tool. Table 32 provides summary statistics of storm intensity for the tropical cyclone data set, by case study country.

Table 32: Distributive statistics of tropical cyclone data set, by case study country (n = 111)

Country	Storm count	Avg. maximum sustained wind speed (mph)	Max. maximum sustained wind speed (mph)	% of all storms making landfall	Avg. distance of eye from shore (miles)	Avg. storm travel over land (miles)
Dominica	22	72.6	144.0	8.7	27.7	1.3
Grenada	14	73.3	132.0	28.6	12.1	1.9
Jamaica	15	91.3	144.0	33.3	17.0	20.1
Haiti	23	78.8	149.6	78.3	5.0	43.0
Saint Lucia	19	67.8	132.0	21.1	17.4	2.1
SVG	18	71.0	132.0	16.7	29.9	0.7

3.4 **Impact of Climate Change on Tropical Cyclones**

Climate change is likely to alter the characteristics of tropical cyclones, including their frequency, size, intensity and geographic distribution (Bengtsson *et al.*, 2007; Nordhaus, 2010). Rising temperatures and increased water vapor provide more energy for tropical cyclones, so that when favorable conditions exist, the higher sea surface temperature (SST) and higher specific humidity should, in theory, contribute to more intense storm events. Analyses of historic records detect trends in tropical cyclone metrics consistent with climate change, with Emanuel (2005), Webster et al (2005), Elsner et al (2008), Peduzzi et al (2012), and Kossin (2013) all finding significant increases in intensity over time (in terms of changes in wind speeds). Elsner et al (2008) and Kossin (2013) find the largest increases in intensity in the North Atlantic basin.

There is a growing consensus from both theory and numerical simulations that the average intensity of tropical cyclones will increase with climate change; this is due to a projected increase in the frequency of very intense storms in a warmer climate, as opposed to an increase in the number of storms (Knutson *et al.*, 2010; Bacmeister *et al.*, 2016). Indeed, the global frequency of tropical cyclones is projected to remain the same or slightly decrease (Kossin *et al.*, 2017).

For the North Atlantic basin, precipitation rates (and the potential for flooding) are also projected to increase with climate change, in addition to the average intensity of storms (Knutson *et al.*, 2010; Knutson *et al.*, 2015; Bacmeister *et al.*, 2016; Kossin *et al.*, 2017; Thomas *et al.*, 2018). Furthermore, damages to coastal (fishing) infrastructure will be higher during tropical cyclones due to increased storm surge, as sea levels continue to rise. A more complete assessment of the economic impact of tropical cyclones on the fishery sector should explicitly take these cumulative hazards into account. Nevertheless, as noted by Acevedo (2016), increased storm surge and higher precipitation rates are somewhat correlated with maximum sustained wind speeds and therefore captured in the estimated coefficient for $MaxWind$.

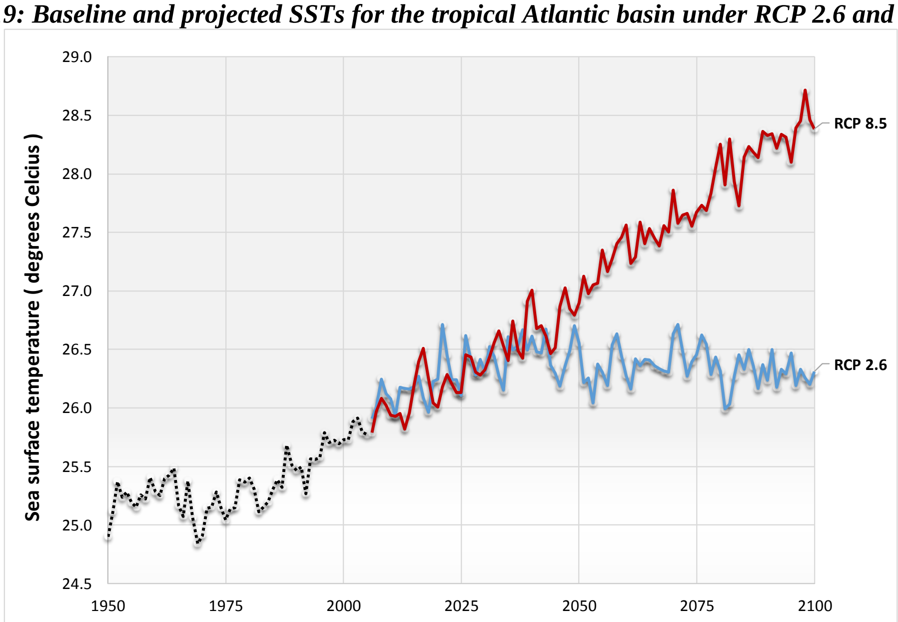
As per Nordhaus (2010), the influence of climate change on the impact of tropical cyclones on fishery production is calculated by multiplying $MaxWind$ in the damage-intensity function (Equation 5) by the following expression:

$$(1 + \gamma \times \Delta SST_t) \qquad \text{Equation 7}$$

Where γ is the "semi-elasticity of maximum wind speed with respect to sea surface temperature (SST)"—i.e., the percentage change in maximum wind speed for each degree Celsius rise in SST (Nordhaus, 2010). Regarding estimates for γ, in simulating differences in tropical cyclone intensity globally under current climate conditions vis-à-vis a climate with a doubling of CO_2 concentrations, Knutson and Tuleya (2004) found that maximum wind speeds are enhanced by an average of 5.8% in response to SST warming of 2.2-2.7°C. These simulations indicate γ is 0.024. Emanuel (2005) found that the peak wind speed of tropical cyclones increased by about 5% for every +1.0°C change in tropical SST, suggesting that γ is equal to 0.05. A substantially higher estimate for γ of 0.08 (+20% divided by +2.5°C) was generated by Oouchi *et al.* (2006) for the North Atlantic basin.

The second variable in Equation 7, ΔSST_t, is the projected change in SST at time t relative to the base year period. Projected SSTs for the tropical Atlantic basin under RCP 2.6 and RCP 8.5 are shown in Figure 19. Table 33 shows projected changes in SST under both climate scenarios for the 2050s (2040-2069) and 2080s (2070-2099) relative to 1971-2000. Corresponding wind speed multipliers (derived from Equation 7) are also shown for three different estimates of γ (the semi-elasticity of maximum wind speed with respect to SST). Looking at the 2080s, for example, if γ is assumed to be 0.05, then maximum sustained wind speeds are projected to increase by 4.8% and 13.4% under RCP 2.6 and RCP 8.5, respectively.

Figure 19: Baseline and projected SSTs for the tropical Atlantic basin under RCP 2.6 and RCP 8.5



Source: IPCC, average of GFDL, MPI and IPSL models. The black dashed lines are modeled baseline values (1950-2005); the solid coloured lines are projected values (2006-2100).

Table 33: Estimated (%) changes in tropical cyclone wind speeds due to projected changes in SST for the tropical Atlantic basin under RCP 2.6 and RCP 8.5

	2050s (2040-2069)		**2080s** (1970-2099)	
	RCP 2.6	**RCP 8.5**	**RCP 2.6**	**RCP 8.5**
SST				
Baseline (1971-2000)	25.39°C	25.39°C	25.39°C	25.39°C
Projected	26.38°C	27.13°C	26.35°C	28.07°C
Change	+0.99°C	+1.74°C	+0.96°C	+2.68°C
Multipliers (% changes in wind speeds)				
γ =0.024	1.0238 (+2.4%)	1.0416 (+4.2%)	1.0231 (+2.3%)	1.0643 (+6.4%)
γ =0.050	1.0496 (+5.0%)	1.0867 (+8.7%)	1.0481 (+4.8%)	1.1340 (+13.4%)
γ =0.080	1.0794 (+7.9%)	1.1387 (+13.9%)	1.0769 (+7.7%)	1.2143 (+21.4%)

3.5 Results

Numerous different specifications of Equation 5 were estimated. Some of the variants tested are discussed below. In general, most specifications performed poorly, producing results that were not statistically significant. This result is not entirely surprising upon review of the plots in the appendices (see Section 6.1). It is evident from these plots that there is no consistent pattern of sharp negative (or even positive) impacts on fishery production in the year of a tropical cyclone, or a lag effect in the following year. The selection of damage assessments in Box 2 would nevertheless suggest otherwise—i.e., that fishery production is impaired by tropical cyclones as infrastructure and equipment is damaged and fleets are grounded. Indeed, of the 52 global storm events studied by Belhabib *et al.* (2018), negative impacts were reported in 48 cases. Some of the models estimated for Equation 5 are consistent with this finding.

Those models that performed best—with a statistically significant negative coefficient for our variable of interest $MaxWind$—are presented in Table 34. Recall that the coefficient for $MaxWind$ shows the percentage change in production relative to the 5-year moving average for a 1-unit change in wind speed (i.e., 1 additional mile per hour). A negative coefficient indicates that production will fall below the 5-year moving average if storm wind speeds increase. The first two models in Table 34, (1) and (2), treat each country independently and estimate corresponding fixed effects; the models in the latter four columns, models (3) to (6), do not and are based on pooled (OLS) estimation.

Two different specifications of the dependent variable were tested—one based on total annual production and one based on annual per capita production. Both performed equivalently. However, working with the former to analyze the impacts of climate change is more tractable; hence, only models based on total annual production were used for estimating impacts. Having to work with annual data, as opposed to quarterly data, may also partially explain the poor performance and relatively small effects of many estimated models. Negative impacts in one or more quarters may be offset by compensatory positive impacts in another quarter.

Models were also estimated separately for each fish species grouping (recall Table 3); however, except for "demersals" and "marine other", they all performed poorly. As a result, all the models retained for estimating climate change impacts are based on total production across all fish species groupings. This is an unfortunate outcome, since from an adaptation policy perspective, some form of disaggregation of the fishery sector is desirable. Separate regression models could be tested for the different fishery segments (e.g., industrial, artisanal, subsistence, recreation), as opposed to species groupings tried herein—however, there was not the time to do so in this study.

In addition, models were also estimated with lags to test if impacts are short-term or medium-term. Interestingly, in all specifications the coefficient for the year $t-1$ lag was positive, indicating a compensatory impact in the year following a storm event. The estimated coefficients were insignificant, however, and thus not retained.

In all specifications tested, the year and distance variable(s) were not statistically significant, and thus dropped. Related to the effect of distance, whether a storm made landfall produced interesting results. Other things being equal, it appears that non-landfall storm events have a more significant and negative impact on fishery production than landfall storms. For instance, contrast the coefficient for $MaxWind$ in model (5) in Table 34, which included only observations from non-landfall storms, with the coefficient in model (6), which included only observations from landfall storms.

It is also worth noting that the only difference between model (3) and (4) is that the latter included non-landfall storms as an independent variable in addition to $MaxWind$. Likewise, in contrast to model (1), model (2) included non-landfall storms as an independent variable in addition to $MaxWind$ and time fixed effects.

Table 34: Estimated damage-intensity functions for total production, all fish species groupings

	(1)	(2)	(3)	(4)	(5)	(6)
MaxWind	-0.069**	-0.066**	-0.066**	-0.066**	-0.082**	-0.028
Constant	+10.212***	+13.300**	+5.505***	+7.227**	+5.817*	+4.453
Overall P-value	0.109	0.085	0.040	0.068	0.050	0.564
Adjusted R^2	0.068	0.087	0.054	0.048	0.052	0.010
Observations	111	111	111	111	75	36
Fixed effects	Yes	Yes	No	No	No	No

Note: Statistical significance at the ***1%, **5% and *10% levels. In all models, the dependent variable is the percentage change in total production relative to the 5-year moving average. Models (3), (5) and (6) only include $MaxWind$ as an independent variable; all other independent variables tested were not statistically significant. The coefficient for $MaxWind$ indicates the percentage change in production relative to the 5-year moving average for a 1-unit change in wind speed (i.e., 1 additional mile per hour); being negative, production will fall below the 5-year moving average if storm wind speeds increase. Looking at model (1), for example, an increase in wind speed of 100 mph will result in a 6.9% fall in production below the 5-year moving average.

Although it would have been preferable to work with separate damage-intensity functions for non-landfall and landfall storm events (as per Acevedo, 2016), the poor performance of models that included only observations for landfall events (as illustrated with model (6) in Table 34), means our benchmark model is estimated from the entire sample of storms. **Model (3) was chosen as the benchmark model**; while models (1) and (2) have slightly higher adjusted R^2 values, they are all relatively low. The statistical significance (p-values) of the overall model and the main coefficient of interest ($MaxWind$) is higher for model (3). Therefore, model (3) in Table 34 is used in combination with multipliers in Table 33 to *simulate* the incremental impact of climate change on fishery production for our six case study countries. This is accomplished by calculating what would have been the impact on fishery production from the same tropical cyclones that impacted each country over the period 1950-2013 had they occurred in the warmer climate projected for the 2050s and 2080s under RCP 2.6 and RCP 5.8. In other words, we assume that the number of storms and their tracks remain unchanged by climate change, and the only change is because of the impact of higher SSTs on storm intensities, as measured by increased sustained wind speeds. These are necessary assumptions, since it is beyond the scope of this study to develop a tropical cyclone model capable of simulating "synthetic" storm frequencies, intensities and paths.

An important point to note when considering the results presented below is that they measure the incremental or additional impact of climate change over and above the impacts that these storms would have otherwise caused in the absence of further warming. Hence, even though the incremental impact of climate change may seem relatively low, the absolute impact of individual tropical cyclones may still be catastrophic.

Table 35 shows the full range of estimated incremental direct impacts on fisheries production for the six case-study countries if the wind speeds of all historical storms (1950-2013) increased in response to rising SSTs projected under RCP 2.6 and RCP 8.5 by the 2050s. The same type of results but for the 2080s is presented in Table 36. Each table provides estimated direct production losses (in tonnes of fish, all species groupings), along with corresponding reductions in landing revenues (in thousands of 2010 constant US dollars). Losses are shown for three different estimates of γ. Taking a central estimate of 0.050 for γ, climate change is projected to increase production losses from our sample of 111 tropical cyclones by 3.0 [1.3-4.7] kt and 5.2 [2.2-8.2] kt under RCP 2.6 and RCP 8.5, respectively, by the 2050s, and by 2.9 [1.2-4.6] kt and 8.1 [3.5-12.7] kt under RCP 2.6 and RCP 8.5, respectively, by the 2080s. The corresponding reduction in revenues from landings by the 2050s are $4.8 [$2.0-$7.5] million and $8.3 [$3.6-$13.0] million under RCP 2.6 and RCP 8.5, respectively. For the 2080s, incremental lost revenue from landings amounts to $4.6 [$2.0-$7.2] million and $12.8 [$5.5-$20.1] million under RCP 2.6 and RCP 8.5, respectively.

Losses by the 2080s under RCP 2.6 are less relative to the 2050s, since the rise in SST by the 2080s (relative to the 1971-2000 baseline) is lower than by the 2050s (recall Figure 19).

Figure 20 presents the same information in graphical format, by case study country. The coloured box in each graph represents the mean estimate for the wind speed coefficient from Table 34 and γ = 0.050; the lower bar represents the lower boundary for the 75th confidence interval (CI) for the estimated wind speed coefficient *and* γ = 0.024; and the upper bar represents the upper boundary for the 75th CI for the estimated wind speed coefficient *and* γ = 0.080.

To put the estimated losses in context, Figure 21 provides graphs that express the losses in Table 35 and Table 36 as a percentage of total historical production and landed revenue in all years when storm event(s) impacted each country. For example, in our data set Grenada was impacted by 14 tropical cyclones over the period 1950-2013. Across all years when these storms occurred, total production amounted to 28 kt of fish with a total corresponding landed value of $42.8 million. Estimated losses in Table 35 and Table 36 are normalized to these totals and presented in Figure 21. Results are summarized for a central case only (i.e., for the mean estimated wind speed coefficient and γ = 0.050).

Under RCP 2.6, in no countries do projected incremental (production or landed value) losses from climate change impacts on tropical cyclone wind speeds exceed about 0.3% of historic totals. By the 2050s under RCP 8.5, projected incremental losses range from just under 0.4% of historic totals (for St. Lucia and SVG) to just over 0.5% of historic totals (for Jamaica). By the 2080s, the range of projected incremental losses has increased from just under 0.6% of historic totals (for St. Lucia and SVG) to just over 0.8% of historic totals (for Jamaica).

The simulated outcomes provided in Table 35 and Table 36 reflect direct production losses and associated reductions in *economic* output. **Using the multipliers in Table 1, total losses in output and household incomes (inclusive of direct, indirect and induced effects) were estimated.** The results for the 2050s under RCP 2.6 and RCP 8.5 are shown in Table 37, for each estimate of γ. Table 38 presents a similar set of results for the 2080s. Taking a central estimate of 0.050 for γ, climate change is projected to increase *total* output losses from our sample of 111 tropical cyclones by $5.8 [$2.5-$9.1] million and $10.1 [$4.3-$15.8] million under RCP 2.6 and RCP 8.5, respectively, by the 2050s, and by $5.6 [$2.4-$8.8] million and $15.6 [$6.7-$24.5] million under RCP 2.6 and RCP 8.5, respectively, by the 2080s. The corresponding reduction in household incomes by the 2050s are $1.4 [$0.6-$2.1] million and $2.4 [$1.0-$3.7] million under RCP 2.6 and RCP 8.5, respectively. For the 2080s, incremental household income losses amount to $1.3 [$0.6-$2.1] million and $3.7 [$1.6-$5.7] million under RCP 2.6 and RCP 8.5, respectively.

To explore the potential implications for food security, estimated incremental production losses by country are expressed as an average daily reduction in per capita food supply of fish (obtained from the aggregate fish balances in Table 4 through Table 9). The results are shown in Figure 22 for each case study country, by epoch and RCP. The coloured box in each graph represents the mean estimate for the wind speed coefficient from Table 34 and $\gamma = 0.050$; the lower bar represents the lower boundary for the 75th CI for the estimated wind speed coefficient and $\gamma = 0.024$; and the upper bar represents the upper boundary for the 75th CI for the estimated wind speed coefficient and $\gamma = 0.080$.

By the 2050s under RCP 2.6, for example, the incremental impact of climate change on fish supply across the six case study countries (because of increases to the intensity of tropical cyclone wind speeds) equates to, over average, a reduction of about 0.35-0.60 [within a range of 0.05-1.45] % in daily food supply as fish.[25] The corresponding range of reductions in daily food supply as fish for the 2080s under RCP 8.5 is 0.55-0.90 [within a range of 0.10-2.25] %.

[25] The lower value in the brackets is based on the lower boundary for the 75^{th} CI for wind speed coefficient *and* $\gamma = 0.024$ and higher value in the brackets is the upper boundary for the 75^{th} CI for wind speed coefficient *and* $\gamma = 0.080$.

Table 35: Direct effects: incremental climate change impact of tropical cyclones on fisheries production and landed value if all historical storms (1950-2013) had projected wind speed intensities under RCP 2.6 and RCP 8.5 by the 2050s (landed value losses in thousand US $ 2010)

	Storm events	Production losses	Landed value losses	Production losses	Landed value losses	Production losses	Landed value losses
		γ = 0.024		γ = 0.050		γ = 0.080	
	(number)	(tonnes)	(US $ 2010)	(tonnes)	(US $ 2010)	(tonnes)	(US $ 2010)
RCP 2.6							
Dominica	22	40 [20, 60]	50 [20, 80]	70 [30, 110]	110 [50, 170]	120 [50, 180]	170 [70, 270]
Grenada	14	30 [10, 50]	40 [20, 70]	60 [30, 100]	90 [40, 150]	100 [40, 160]	150 [60, 230]
Haiti	15	400 [170, 630]	420 [180, 660]	840 [360, 1 320]	880 [380, 1 380]	1 350 [580, 2 120]	1 400 [600, 2 200]
Jamaica	23	920 [390, 1 440]	1 660 [710, 2 610]	1 910 [820, 3 000]	3 460 [1 480, 5 440]	3 060 [1 310, 4 800]	5 530 [2 370, 8 700]
St. Lucia	19	30 [10, 40]	40 [20, 70]	60 [30, 90]	90 [40, 140]	90 [40, 150]	150 [60, 230]
SVG	18	20 [10, 40]	60 [30, 90]	50 [20, 80]	120 [50, 190]	80 [30, 130]	190 [80, 310]
	111	**1 440 [610, 2 260]**	**2 270 [980, 3 580]**	**2 990 [1 290, 4 700]**	**4 750 [2 040, 7 470]**	**4 800 [2 050, 7 540]**	**7 590 [3 240, 11 940]**
RCP 8.5							
Dominica	22	60 [30, 100]	90 [40, 140]	130 [50, 200]	190 [80, 300]	200 [90, 320]	300 [130, 480]
Grenada	14	50 [20, 90]	80 [30, 120]	110 [50, 180]	160 [70, 260]	180 [80, 290]	260 [110, 410]
Haiti	15	710 [300, 1 110]	730 [310, 1 150]	1 470 [630, 2 310]	1530 [660, 2 400]	2 350 [1 010, 3 700]	2 450 [1 050, 3 850]
Jamaica	23	1 600 [690, 2 520]	2 900 [1 240, 4 560]	3 340 [1 430, 5 240]	6 040 [2 590, 9 500]	5 340 [2 290, 8 390]	9 670 [4 140, 15 190]
St. Lucia	19	50 [20, 80]	80 [30, 120]	100 [40, 160]	160 [70, 250]	160 [70, 260]	260 [110, 400]
SVG	18	40 [20, 70]	100 [40, 160]	90 [40, 140]	210 [90, 330]	140 [60, 220]	340 [150, 530]
	111	**2 510 [1 080, 3 970]**	**3 980 [1 690, 6 250]**	**5 240 [2 240, 8 230]**	**8 290 [3 560, 13 040]**	**8 370 [3 600, 13 180]**	**13 280 [5 690, 20 860]**

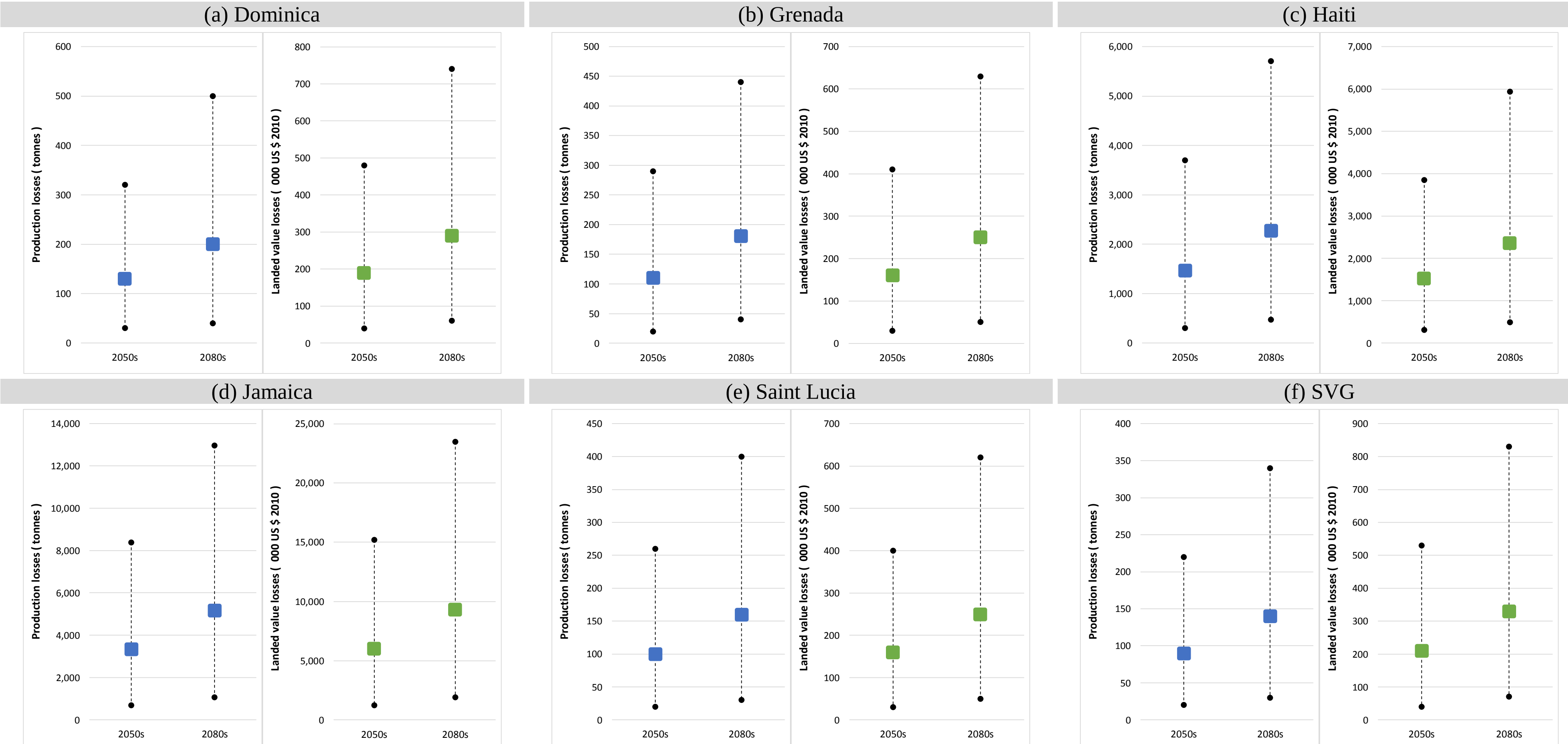
Note: bracketed values are lower and upper boundaries for the 75% CI of estimated wind speed coefficient

Table 36: Direct effects: incremental climate change impact of tropical cyclones on fisheries production and landed value if all historical storms (1950-2013) had projected wind speed intensities under RCP 2.6 and RCP 8.5 by 2080s (landed value losses in thousand US $ 2010)

	Storm events	Production losses γ = 0.024	Landed value losses γ = 0.024	Production losses γ = 0.050	Landed value losses γ = 0.050	Production losses γ = 0.080	Landed value losses γ = 0.080
	(number)	(tonnes)	(US $ 2010)	(tonnes)	(US $ 2010)	(tonnes)	(US $ 2010)
RCP 2.6							
Dominica	22	30 [10, 50]	50 [20, 80]	70 [30,110]	110 [50, 170]	110 [50, 180]	170 [70, 260]
Grenada	14	30 [10, 50]	40 [20, 70]	60 [30,100]	90 [40, 140]	100 [40, 160]	140 [60, 230]
Haiti	15	390 [170, 610]	410 [170, 640]	820 [350,1 280]	850 [360, 1 330]	1 300 [560, 2 050]	1 360 [580, 2 130]
Jamaica	23	890 [380, 1 400]	1 610 [690, 2 530]	1 850 [790,2 910]	3 350 [1 440, 5 270]	2 960 [1 270, 4 650]	5 360 [2300, 8 420]
St. Lucia	19	30 [10, 40]	40 [20, 70]	60 [20, 90]	90 [40, 140]	90 [40, 140]	140 [60, 220]
SVG	18	20 [10, 40]	60 [20, 90]	50 [20,80]	120 [50, 190]	80 [30, 120]	190 [80, 300]
	111	**1 390 [590, 2 190]**	**2 210 [940, 3 480]**	**2 910 [1 240, 4 570]**	**4 610 [1 980, 7 240]**	**4 640 [1 990, 7 300]**	**7 360 [3 150, 11 560]**
RCP 8.5							
Dominica	22	90 [40, 150]	140 [60, 220]	200 [80, 310]	290 [130, 460]	320 [140, 500]	470 [200, 740]
Grenada	14	80 [40, 130]	120 [50, 190]	180 [80, 280]	250 [110, 390]	280 [120, 440]	400 [170, 630]
Haiti	15	1 090 [470, 1 710]	1 130 [490, 1 780]	2 270 [970, 3 570]	2 360 [1 010, 3 710]	3 630 [1 560, 5 710]	3 780 [1 620, 5 940]
Jamaica	23	2 470 [1 060, 3 890]	4 480 [1 920, 7 040]	5 160 [2 210, 8 100]	9 340 [4 000, 14 670]	8 250 [3 530, 12 960]	14 940 [6 400, 23 470]
St. Lucia	19	80 [30, 120]	120 [50, 190]	160 [70, 250]	250 [110, 390]	250 [110, 400]	390 [170, 620]
SVG	18	70 [30, 100]	160 [70, 250]	140 [60, 220]	330 [140, 520]	220 [90, 340]	530 [230, 830]
	111	**3 880 [1 670, 6 100]**	**6 150 [2 640, 9 670]**	**8 110 [3 470, 12 730]**	**12 820 [5 500, 20 140]**	**12 950 [5 550, 20 350]**	**20 510 [8 790, 32 230]**

Note: bracketed values are lower and upper boundaries for the 75% CI of estimated wind speed coefficient

Figure 20: Incremental climate change impact of tropical cyclones on fisheries production and landed value, by country, if all historical storms (1950-2013) had projected wind speed intensities under RCP 8.5 by 2050 and 2080s (landed value losses in thousand US $ 2010)



Note: for each epoch, the box is for the central estimate for wind speed coefficient and γ = 0.050; the lower bar is the lower boundary for the 75th CI for wind speed coefficient *and* γ = 0.024; and the upper bar is upper boundary for the 75th CI for wind speed coefficient *and* γ = 0.080.

Figure 21: Incremental losses in production and landed value from Table 35 and Table 36 (central case), expressed as a percentage of total historical values in all years when storm event(s) impacted each country

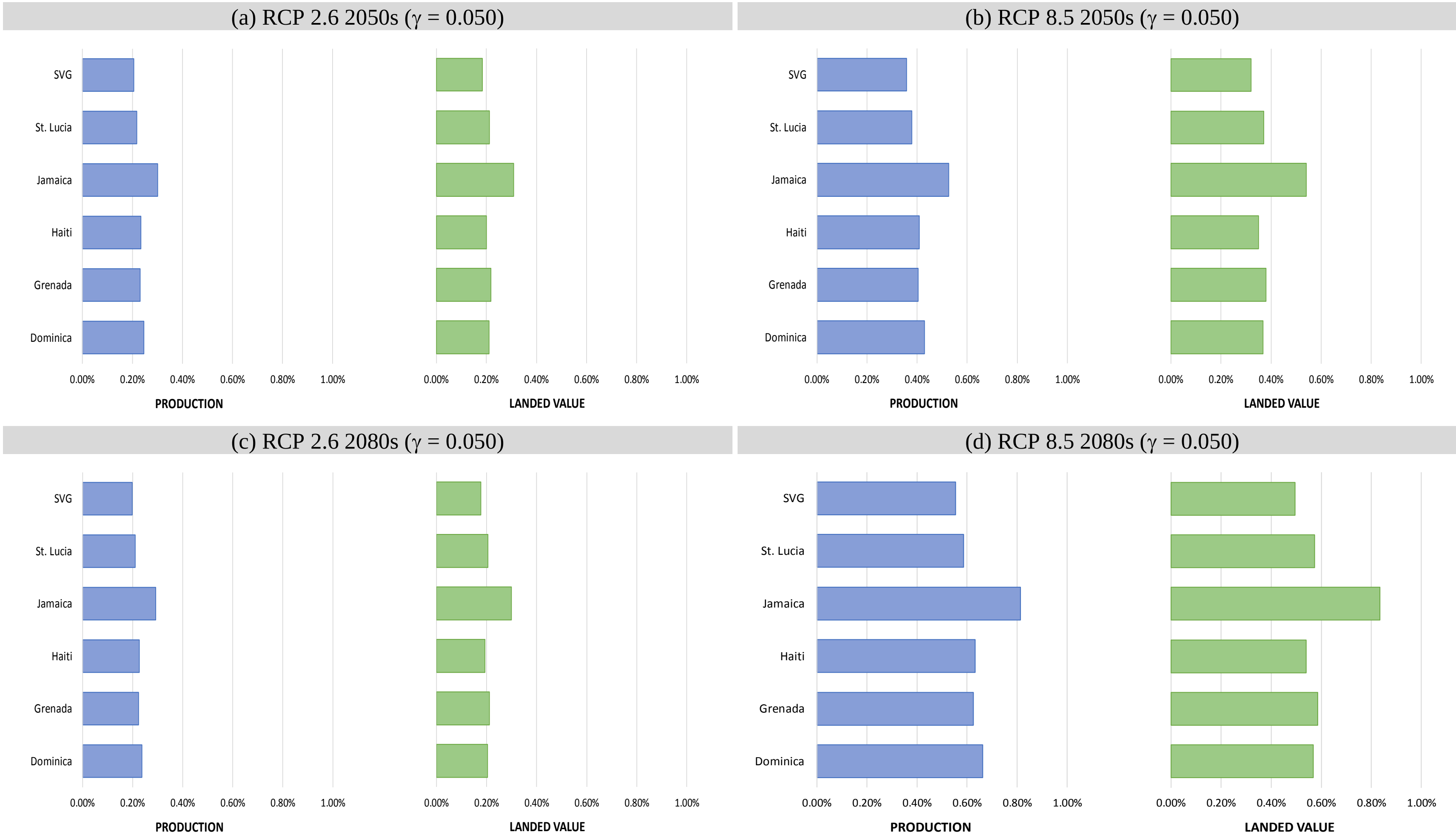


Table 37: Total effects: incremental climate change impact of tropical cyclones on output and household income if all historical storms (1950-2013) had projected wind speed intensities under RCP 2.6 and RCP 8.5 by the 2050s (landed value losses in thousand US $ 2010)

	Storm events	Total output losses	Total household income losses	Total output losses	Total household income losses	Total output losses	Total household income losses
		γ = 0.024		γ = 0.050		γ = 0.080	
	(number)	(US $ 2010)	(US $ 2010)	(US $ 2010)	(US $ 2010)	(US $ 2010)	(US $ 2010)
RCP 2.6							
Dominica	22	61 [24, 97]	14 [6, 23]	134 [61, 207]	31 [14, 49]	207 [85, 328]	49 [20, 77]
Grenada	14	49 [24, 85]	11 [6, 20]	109 [49, 182]	26 [11, 43]	182 [73, 279]	43 [17, 65]
Haiti	15	510 [219, 802]	120 [51, 188]	1 069 [462, 1 677]	251 [108, 393]	1 701 [729, 2 673]	399 [171, 627]
Jamaica	23	2 017 [863, 3 171]	473 [202, 743]	4 204 [1 798, 6 610]	985 [421, 1 549]	6 720 [2 880, 10 571]	1 574 [675, 2 477]
St. Lucia	19	49 [24, 85]	11 [6, 20]	110 [49, 170]	26 [11, 40]	183 [73, 280]	43 [17, 65]
SVG	18	73 [36, 109]	17 [9, 26]	146 [61, 231]	34 [14, 54]	231 [97, 377]	54 [23, 88]
	111	**2 759 [1 190, 4 349]**	**646 [280, 1 020]**	**5 772 [2 480, 9 077]**	**1 353 [579, 2 128]**	**9 224 [3 937, 14 508]**	**2 162 [923, 3 399]**
RCP 8.5							
Dominica	22	109 [49, 170]	26 [11, 40]	231 [97, 365]	54 [23, 86]	365 [158, 584]	86 [37, 137]
Grenada	14	97 [36, 146]	23 [9, 34]	194 [85, 316]	45 [20, 74]	316 [134, 498]	74 [31, 116]
Haiti	15	887 [377, 1 397]	208 [88, 328]	1 859 [802, 2 917]	436 [188, 683]	2 977 [1 276, 4 679]	698 [299, 1 096]
Jamaica	23	3 524 [1 507, 5 541]	826 [353, 1 298]	7 339 [3 147, 11 543]	1 720 [737, 2 705]	11 750 [5 031, 18 457]	2 753 [1 179, 4 325]
St. Lucia	19	97 [37, 146]	23 [9, 34]	195 [85, 304]	45 [20, 71]	317 [134, 487]	74 [31, 114]
SVG	18	122 [49, 194]	28 [11, 45]	255 [109, 401]	60 [26, 94]	413 [182, 644]	97 [43, 151]
	111	**4 836 [2 055, 7 594]**	**1 134 [481, 1 779]**	**10 073 [4 325, 15 846]**	**2 360 [1 014, 3 713]**	**16 138 [6 915, 25 349]**	**3 782 [1 620, 5 939]**

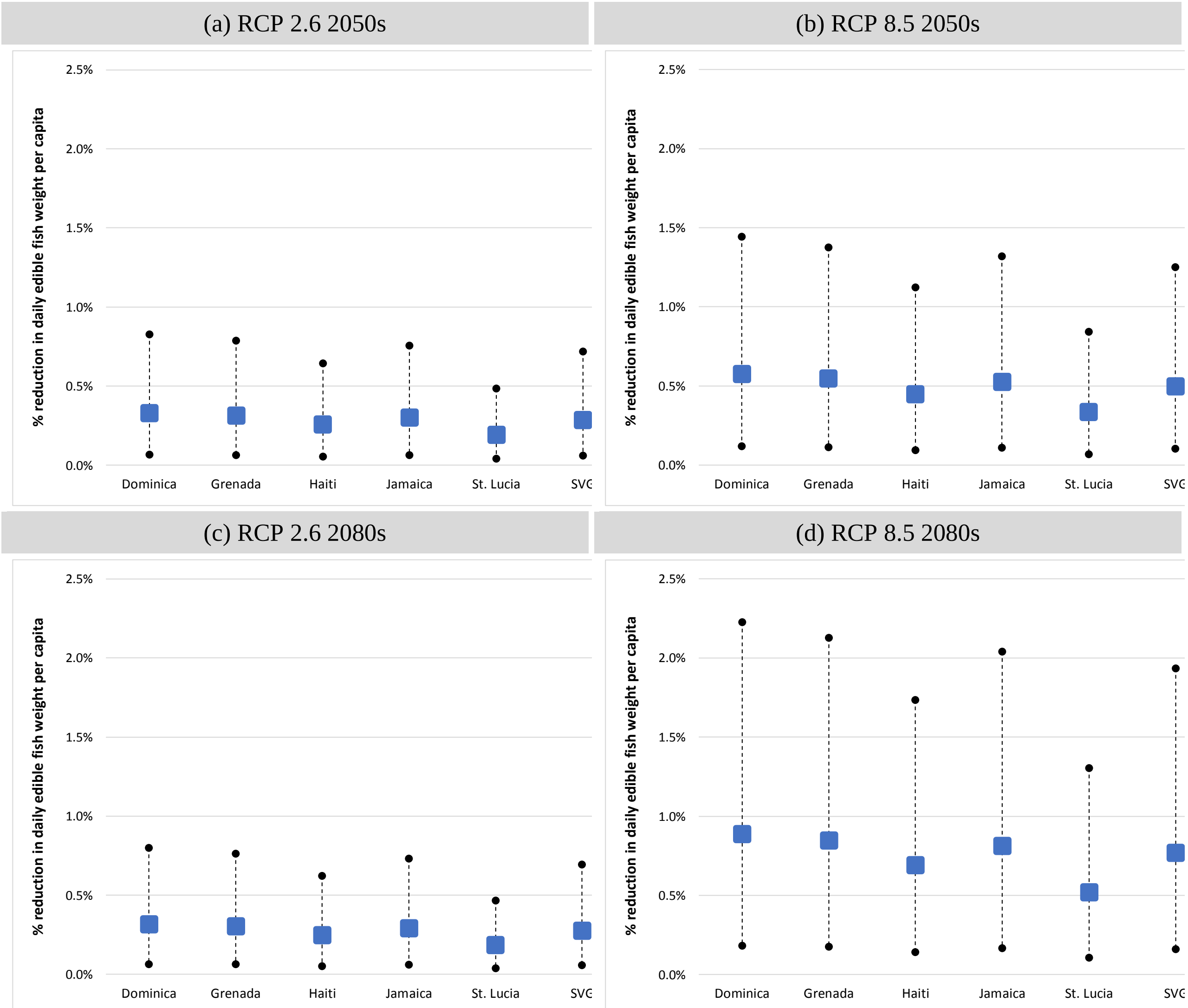
Note: bracketed values are lower and upper boundaries for the 75% CI of estimated wind speed coefficient

Table 38: Total effects: incremental climate change impact of tropical cyclones on output and household income if all historical storms (1950-2013) had projected wind speed intensities under RCP 2.6 and RCP 8.5 by 2080s (landed value losses in thousand US $ 2010)

	Storm events	Total output losses	Total household income losses	Total output losses	Total household income losses	Total output losses	Total household income losses
		γ = 0.024		γ = 0.050		γ = 0.080	
	(number)	(US $ 2010)	(US $ 2010)	(US $ 2010)	(US $ 2010)	(US $ 2010)	(US $ 2010)
RCP 2.6							
Dominica	22	61 [24, 97]	14 [6, 23]	134 [61,207]	31 [14, 49]	207 [85, 316]	49 [20, 74]
Grenada	14	49 [24, 85]	11 [6, 20]	109 [49,170]	26 [11, 40]	170 [73, 279]	40 [17, 65]
Haiti	15	498 [207, 778]	117 [48, 182]	1 033 [437,1 616]	242 [103, 379]	1 653 [705, 2 588]	387 [165, 607]
Jamaica	23	1 956 [838, 3 074]	458 [196, 720]	4 071 [1 750,6 404]	954 [410, 1 500]	6 513 [2795, 10 231]	1 526 [655, 2 397]
St. Lucia	19	49 [24, 85]	11 [6, 20]	110 [49,170]	26 [11, 40]	170 [73, 268]	40 [17, 62]
SVG	18	73 [24, 109]	17 [6, 26]	146 [61, 231]	34 [14, 54]	231 [97, 365]	54 [23, 85]
	111	**2 686 [1 141, 4 228]**	**628 [268, 991]**	**5 603 [2 407, 8 798]**	**1 313 [563, 2 062]**	**8 944 [3 828, 14 047]**	**2 096 [897, 3 290]**
RCP 8.5							
Dominica	22	170 [73, 268]	40 [17, 63]	353 [158, 559]	83 [37, 131]	572 [243, 900]	134 [57, 211]
Grenada	14	146 [61, 231]	34 [14, 54]	304 [134, 474]	71 [31, 111]	486 [206, 765]	113 [48, 179]
Haiti	15	1 373 [595, 2 163]	322 [140, 507]	2 868 [1 227, 4 508]	672 [288, 1 057]	4 593 [1 969, 7 218]	1 077 [461, 1 692]
Jamaica	23	5 444 [2 333, 8 554]	1 275 [547, 2 004]	11 349 [4 860, 17 826]	2 659 [1 139, 4 177]	18 154 [7 777, 28 518]	4 253 [1 822, 6 682]
St. Lucia	19	146 [61, 231]	34 [14, 54]	304 [134, 475]	71 [31, 111]	475 [207, 755]	111 [48, 176]
SVG	18	194 [85, 304]	45 [20, 71]	401 [170, 632]	94 [40, 148]	644 [279, 1 009]	151 [65, 236]
	111	**7 473 [3 208, 11 751]**	**1 750 [752, 2 753]**	**15 579 [6 683, 24 474]**	**3 650 [1 566, 5 735]**	**24 924 [10 681, 39 165]**	**5 839 [2 501, 9 176]**

Note: bracketed values are lower and upper boundaries for the 75% CI of estimated wind speed coefficient

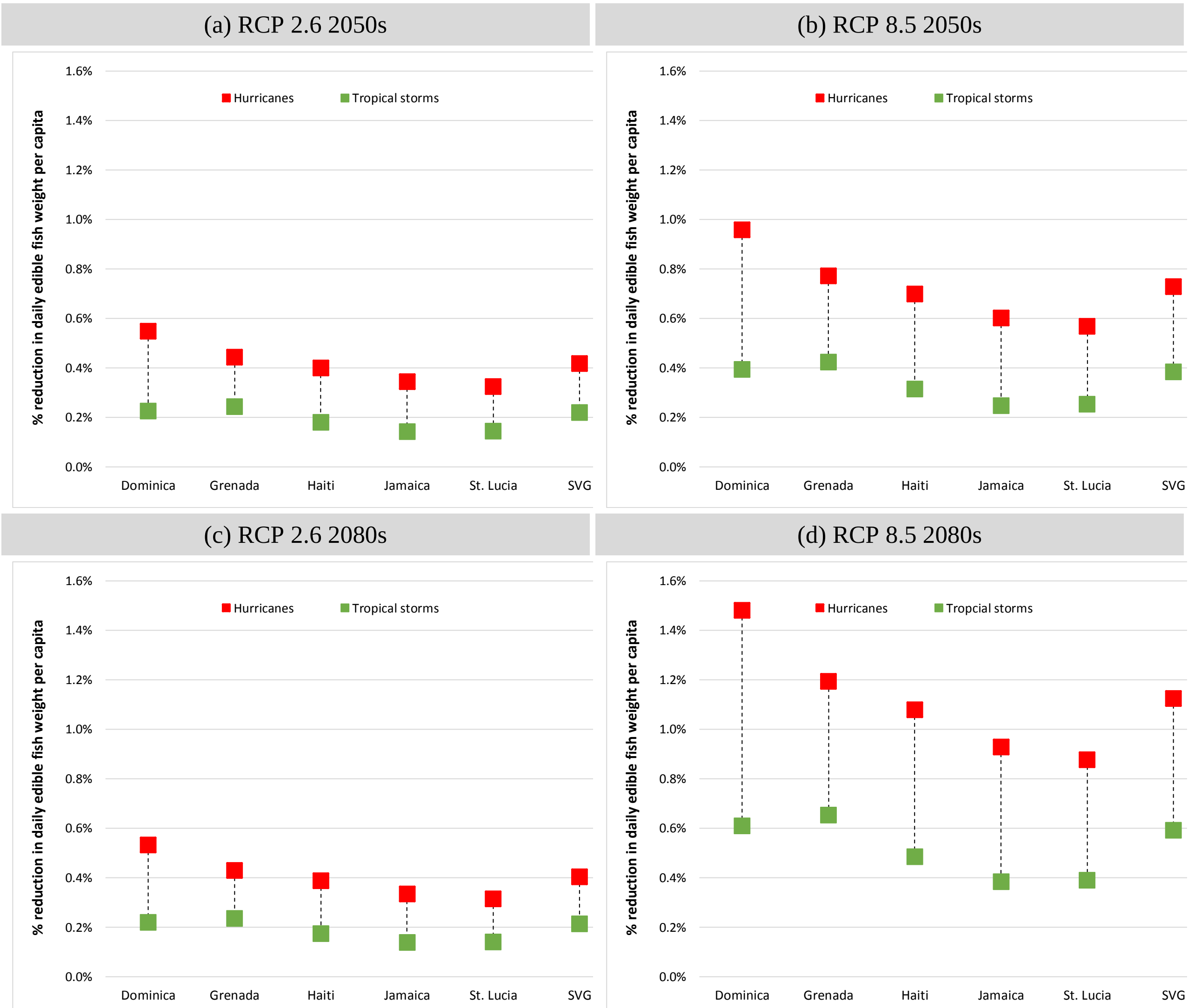
Figure 22: Average reduction in fish supply for consumption (grams of edible fraction per capita per day, average 2009-13) because of production losses from more intense tropical cyclones with climate change: assuming historical storms had projected wind speed intensities under RCP 2.6 and RCP 8.5 by 2050s and 2080s



Note: for each climate scenario and epoch, blue box is central estimate for wind speed coefficient and $\gamma = 0.050$, lower bar is the lower boundary for the 75th CI for wind speed coefficient *and* $\gamma = 0.024$, and the upper bar is the upper boundary for the 75th CI for wind speed coefficient *and* $\gamma = 0.080$. Percentage reductions are based on the average reduction across all historical storm events impacting each country.

Figure 23 presents the same results for the central case only (i.e., for the mean estimated wind speed coefficient and $\gamma = 0.050$), differentiating between hurricanes and tropical storms. As expected, the central values (given by the blue boxes) presented in Figure 22 average out larger incremental impacts on food security that would occur with the more intense hurricanes as a result of climate change.

Figure 23: Hurricanes vs tropical storms: average reduction in fish supply for consumption (grams of edible fraction per capita per day, average 2009-13) because of production losses from more intense tropical cyclones with climate change: assuming historical storms had projected wind speed intensities under RCP 2.6 and RCP 8.5 by 2050s and 2080s



Note: for each climate scenario and epoch, boxes are for central estimate for wind speed coefficient *and* $\gamma = 0.050$. Percentage reductions are based on the average reduction across all historical storm events, by category, impacting each country.

4 CONCLUSIONS

4.1 Key Findings

Projected economic consequences of climate-induced ecological impacts on fishery production include:

- Domestic fish prices (averaged across all species groupings) will **increase** by 3.0% (Haiti) to 6.0% (Grenada) and by 3.2% (Haiti) to 6.1% (Grenada) in 2035 and 2055, respectively, under RCP 2.6. Under RCP 8.5, domestic fish prices will **increase** by 4.1% (Haiti) to 7.8% (St Lucia) and by 4.0% (Haiti) to 7.7% (Grenada) in 2035 and 2055, respectively. These **increases** are relative to projected prices in 2035 and 2055 under the reference case.

- Domestic fish consumption (across all species groupings) will **decrease** by 3.6% (Dominica) to 3.8% (Jamaica) and by 3.8% (Dominica) to 4.4% (SVG) in 2035 and 2055, respectively, under RCP 2.6. Under RCP 8.5, domestic fish consumption will **decrease** by 4.7% (Grenada) to 5.2% (Jamaica) and by 4.9% (Dominica) to 5.3% (Grenada) in 2035 and 2055, respectively. These **decreases** are relative to projected prices in 2035 and 2055 under the reference case.

- **Net *annual* income losses** (in 2010 US dollars) associated with the projected climate-induced changes in prices and consumption amount to: $410,000 (2035 under RCP 2.6) to $830,000 (2055 under RCP 8.5) in Dominica; $510,000 (2035 under RCP 2.6) to $930,000 (2055 under RCP 8.5) in Grenada; $4,130,000 (2035 under RCP 2.6) to $7,220,000 (2055 under RCP 8.5) in Haiti; $8,040,000 (2035 under RCP 2.6) to $14,580,000 (2055 under RCP 8.5) in Jamaica; $1,370,000 (2035 under RCP 2.6) to $2,920,000 (2055 under RCP 8.5) in St. Lucia; and $490,000 (2035 under RCP 2.6) to $850,000 (2055 under RCP 8.5) in SVG.

- **Reductions in fish consumption** (kg per capita per day) associated with the projected climate-induced changes in prices and consumption amount are: -3.6% (2035 under RCP 2.6) to -4.9 (2055 under RCP 8.5) in Dominica; -3.7% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in Grenada; -3.7% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in Haiti; -3.8% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in Jamaica; -3.6% (2035 under RCP 2.6) to -4.9% (2055 under RCP 8.5) in St. Lucia; and -3.7% (2035 under RCP 2.6) to -5.3% (2055 under RCP 8.5) in SVG.

In summary, climate-induced ecological impacts on fishery production will, all else being equal, increase domestic fish prices (in the case of Grenada, by as much as 7.7% in 2055 under the business-as-usual RCP 8.5 climate scenario), reduce domestic demand for fish and per capita consumption (by as much as 5.5% for Grenada in 2055 under the same scenario), and reduce the wealth of producers and consumers (by as much as $14.6 million in 2055 in the case of Jamaica).

Simulated economic consequences of climate-induced increases in the intensity of a sample of 111 historical tropical cyclones that affected our case study countries between 1950-2013:

- For the central case, climate change is projected to **increase production losses** from the sample of 111 tropical cyclones by 3.0 kt and 5.2 kt under RCP 2.6 and RCP 8.5, respectively, by the 2050s, and by 2.9 kt and 8.1 kt under RCP 2.6 and RCP 8.5, respectively, by the 2080s. The corresponding **reduction in revenues from landings** by the 2050s are $4.8 million and $8.3 million (2010 US dollars) under RCP 2.6 and RCP 8.5, respectively. For the 2080s, incremental lost revenue from landings amounts to $4.6 million and $12.8 million under RCP 2.6 and RCP 8.5, respectively.

- Under RCP 2.6, in no countries do projected incremental (production or landed value) losses from climate change impacts on tropical cyclone wind speeds exceed about 0.3% of historic totals. By the 2050s under RCP 8.5, projected incremental losses range from just under 0.4% of historic totals (for St. Lucia and SVG) to just over 0.5% of historic totals (for Jamaica). By the 2080s, the range of projected incremental losses has increased from just under 0.6% of historic totals (for St. Lucia and SVG) to just over 0.8% of historic totals (for Jamaica).

- For the central case, **climate change is projected to increase *total* output losses** from the sample of 111 tropical cyclones by $5.8 million and $10.1 million (2010 US dollars) under RCP 2.6 and RCP 8.5, respectively, by the 2050s, and by $5.6 million and $15.6 million under RCP 2.6 and RCP 8.5, respectively, by the 2080s. The **corresponding reduction in household incomes** by the 2050s is $1.4 million and $2.4 million under RCP 2.6 and RCP 8.5, respectively. For the 2080s, incremental household income losses amount to $1.3 million and $3.7 million under RCP 2.6 and RCP 8.5, respectively.

- By the 2050s under RCP 2.6 the incremental impact on fish supply *across the six case study countries* equates to, over average, a **reduction** of about 0.35-0.60% **in daily food supply as fish**. The corresponding range of reductions in daily food supply as fish for the 2080s under RCP 8.5 is 0.55-0.90%.

4.2 **Improvements**

The analyses and results provided in this chapter represent a first attempt to better understand the economic impacts of climate change on Caribbean fisheries. Consequently, there is plenty of scope to improve upon and refine the data and methods underpinning the results. Key potential improvements to both the data and methods are outlined below.

4.2.1 Economic Impacts of Ecological Shifts

The aggregate fish balance sheets are a critical input to the market supply-demand model and key determinant of the results. In developing the balance sheets and seeking their validation with country fisheries officers it was evident that production data and trade data are held by different departments or ministries. This hindered the validation of the balance sheets. Consideration should be given to holding all fisheries data relating to production and trade (imports and exports, weight and value) at a single source. Information on *both* production and trade flows is crucial to understanding domestic fish consumption—a key focus of socio-economic analyses.

Another key driver of the results is the assumed (supply and demand) price and income elasticities. These should be validated when time permits—this could be accomplished at a workshop with local experts. The supply elasticities are a priority for validation as they were not estimated, but rather extrapolated from values in the literature. In general, to highlight uncertainties in the analysis relating to both the aggregate fish balance sheets and assumed elasticities, formal sensitivity analysis should be performed when time and resources permit.

The market supply-demand fish model can be used to appraise climate adaptation options—as illustrated in panel (d) of Figure 1. Indeed, it already includes a place holder for (enhanced) aquaculture. Consideration should be given to formulating and simulating the economic impacts of feasible adaptation options, when resources permit.

Total economic impacts (i.e., direct plus indirect plus induced effects) were estimated using country-specific gross output and household income multipliers obtained from Dyck and Sumaila (2010). These are based on input-output data from the early-2000s, sourced from the Global Trade Analysis Project (GTAP) (https://www.gtap.agecon.purdue.edu/). To use the multipliers in this study, it is implicitly assumed that the underlying technical coefficients that characterize the structure of each economy—from which the multipliers are derived—remain unchanged over time. This assumption may not be valid. Furthermore, multipliers are designed to be applied to marginal (relatively small) changes in final demand or consumption. Direct production losses attributable to ecological impacts considered in this study are non-marginal. In these circumstances, multipliers will tend to overstate estimated total effects, since they fail to account for feedback effects and behavioural adjustments in the economy. Capturing these effects is only possible with the use of a computable general equilibrium (CGE) model.[26] In terms of practical options for improving the analyses of total economic impacts attributable to climate change, consideration should be given to updating the multipliers generated by Dyck and Sumaila, including the derivation of employment multipliers and value added or GDP multipliers.

4.2.2 Economic Impacts of Tropical Cyclones

Typologies of the economic consequences of climate change impacts, and specifically impacts arising from extreme events, often distinguish between direct and indirect effects—like the literature on natural disaster impacts (e.g., ECLAC, 2003, Hallegatte, 2013, and Kousky, 2012). Direct and indirect effects can be negative or positive, giving rise to, respectively, costs (losses or damages) or benefits (gains). Direct costs refer to the immediate negative effects that result from the exposure of harbor infrastructure, facilities, fishing gear, people, etc. to, for instance, hurricane force winds, storm surge and intense rainfall. Indirect costs stem from the direct effects. When a dock, vessel or processing facility is damaged or destroyed, this can interrupt normal use and service flows. In addition, damaged or impaired critical infrastructure may result in disruption to the supply of electricity or fuel, which may in turn interrupt the operations of fishery businesses not directly damaged by storms. Fisherfolk may also not be able to get to work for a variety of reasons. From an economic perspective, these interruptions to fishing activity result in lost output. Additionally, interactions between businesses may result in “ripple effects” (also referred to as secondary effects or multiplier effects) through the economy, leading to further loss of output.

The total economic impact of more intense tropical cyclones on the fishery sector thus comprises the sum of three components: (1) direct costs; (2) indirect output losses stemming from the direct effects; and (3) further output losses associated with ripple effects throughout the economy.[27] The incremental economic impacts of climate-enhanced tropical cyclones on fishery production presented in Section 3.5 attempt to measure (2) and part of (3); only ‘ripple effects’ associated with (2) are captured through the use of output and income multipliers. This partly explains the relatively small magnitude of the estimated impacts—withstanding the fact that they represent incremental, as opposed to absolute, impacts. Future work in this area should: first, seek to build an improved data set of relevant incremental direct costs than is currently available to allow for quantification of (1); and second, use the estimates of (1) and (2) to quantify the *full* extent of ripple effects throughout the economy. Before doing so, however, consideration should be given to updating the multipliers used in this study—as recommended above.

Furthermore, regarding the magnitude of the estimated incremental economic impacts, it is important to note that all determinants of impact size, other than wind speed, are assumed to remain unchanged—

[26] For a practical, introductory, how-to guide to CGE models see, for example, Burfisher, M., 2011: Introduction to Computable General Equilibrium Models (Cambridge University Press).

[27] If these impacts are sufficiently significant, they may impact macroeconomic indicators, such as consumer and producer price inflation, unemployment rate, Balance of Payments, and Gross Domestic Product (GDP). Macroeconomic impacts reflect aggregated effects on the economy that derive from both direct and indirect effects. Hence, macroeconomic impacts, if estimated, should not be added to estimates of direct and indirect costs as this would entail double counting.

including baseline production levels. All else being equal, if the rate of increase in baseline production levels is higher in the future, the incremental impacts of climate-enhanced tropical cyclones will be larger than they would have been otherwise. And thus, be larger than estimated in this study. At the same time, it is assumed in the analysis that there is no additional adaptation by the fishery sector to the impacts of intensifying storms. Efficient adaptation options would, of course, reduce the magnitude of estimated impacts. In addition to incorporating direct costs and ripple effects into the analysis, future work should thus also look to develop and incorporate scenarios for both growth in the fishery sector and the implementation of adaptation options. Indeed, both work extensions suggested above are needed to provide the requisite information basis for economic analyses of adaptations by the fishery sector to climate-enhanced tropical cyclones.

Furthermore, from an adaptation policy perspective, some form of disaggregation of the fishery sector is necessary to set priorities for reducing vulnerabilities and risks and prompting adaptation. The estimated models for individual fish species groupings, except for “demersal fish” and “other marine fish” performed poorly. Consequently, the results presented in Section 3.5 were for total production across all fish species groupings. Though beyond the scope of this research, future studies should develop and test separate regression models for the different fishery sectors (e.g., industrial, artisanal, subsistence, recreation), to see if they perform better than those for individual fish species groupings.

Working with annual data may also be masking shorter-duration negative impacts on production and food security. Equally, it may be masking important, shorter-duration positive impacts on production. It is important to better understand such compensatory responses in the aftermath of tropical cyclones, as adaptations could look to enhance these efforts. Adaptation is not just about managing negative consequences. Future work should thus look to collate and analyze quarterly production data; this would very likely improve the performance of the regression models, as well as provide a better information base for adaptation decisions. The results would also be improved by including all Caribbean Small Island Developing States (SIDS) in the model estimation, as opposed to only our six case study countries.

4.2.3 Other Economic Impacts of Climate Change

Consideration of the economic impacts of SLR for the fisheries sector is an important extension to the research initiated by this project. Box 3 provides estimates of the potential scale of impacts from SLR; *though not specifically for the fisheries sector*. For instance, annual costs to the agricultural sector under a +1 m SLR scenario range from US $176 million (by 2050) to US $370 million (by 2080); capital costs from damage to ports under the same scenario range from US $1.8 billion (2050) to US $4.0 billion (2080) (see Simpson *et al.*, 2010). Assessing the economic impacts of SLR was beyond the scope of this project. Such an exercise would have required the development of a coastal GIS model and corresponding data layers, including a geo-spatial inventory of fishery assets, equipment, fisherfolk and supporting infrastructure, projections of SLR, and a set of appropriate damage functions linking the data layers. Given the potentially significant impacts of SLR for the fisheries sector—either directly or indirectly by exacerbating the consequences of storms and hurricanes–this is an important area to investigate, when resources permit.

A further climate driver of economic impact on the fisheries sector not considered in this study is surface temperatures. There is an emerging field of research investing the response of economic output to increased temperatures, measured through changes in the productivity of labour when workers are exposed to thermal stress. Estimates of forgone economic output due to reductions in labour productivity under future climate scenarios have proved to be significant (see, for example, Dell *et al.*, 2012 and 2014; Burke *et al.*, 2015). In a study of 28 countries in the Caribbean and Central America, Hsiang (2010) found that *value added* from the agriculture, hunting, and fishing sector declined by 0.8% per 1°C rise in ambient temperature; equivalent to a 0.1% decline in aggregate economic output for the region.[28] Though less of a priority relative to SLR, consideration should be given to reproducing this type of analysis for the fisheries sector specifically.

Box 3: Projected Damages from SLR and storm surge in the Caribbean region

A study of the impacts of SLR and storm surge in CARICOM Member States estimated significant economic losses for 1-2 m of SLR by the end of the 21st century (see Simpson *et al.* 2010). By 2050 capital costs (i.e., the cost of repairing, replacing or relocating damaged assets) and annual costs (i.e., the ongoing costs to the region's economies) were estimated at about US $26 billion and US $4 billion, respectively, under a +1 m SLR scenario by 2100. By 2080 these costs had risen to about US $68 billion and US $14 billion under the +1 m SLR scenario; equivalent to, respectively, 8.3% and 1.6% of projected GDP for the region (Simpson et al, 2010). Projections of SLR for our six case study countries by 2100 under a 'business-as-usual' (RCP 8.5) scenario are in the range of +1 to +1.2 m (Nurse, 2017).

Separate estimates of annual costs were generated for the "agricultural sector" as a whole, while separate capital cost estimates were generated for "ports". Annual costs to the agricultural sector under the +1 m SLR scenario range from US $176 million (2050) to US $370 million (2080). Haiti is most affected, experiencing 76% to 82% of total losses across the CARICOM Member States, respectively. Capital costs from damage to ports under the +1 m SLR scenario range from US $1.8 billion (2050) to US $4.0 billion (2080). Jamaica is most affected, experiencing 70% to 80% of total losses across the CARICOM Member States, respectively.

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[28] Estimated impacts in other economic sectors were larger in magnitude; ranging from -6.1% per +1°C in "wholesale, retail restaurants and hotels" to +1.4% per +1°C in "manufacturing" (Hsiang, 2010).

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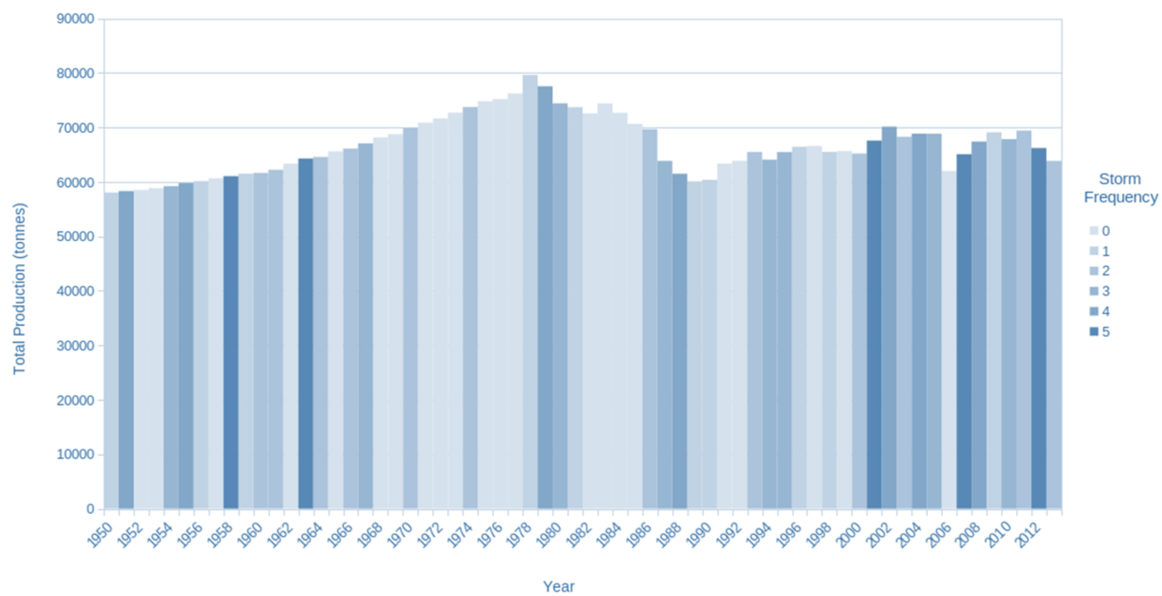
7 APPENDIX

The series of plots that follow illustrate the relationship between fishery production and occurrence of tropical cyclones. It is evident from these plots that there is no consistent pattern of sharp negative (or even positive) impacts on fishery production in the year of a tropical cyclone, or a lag effect in the following year.

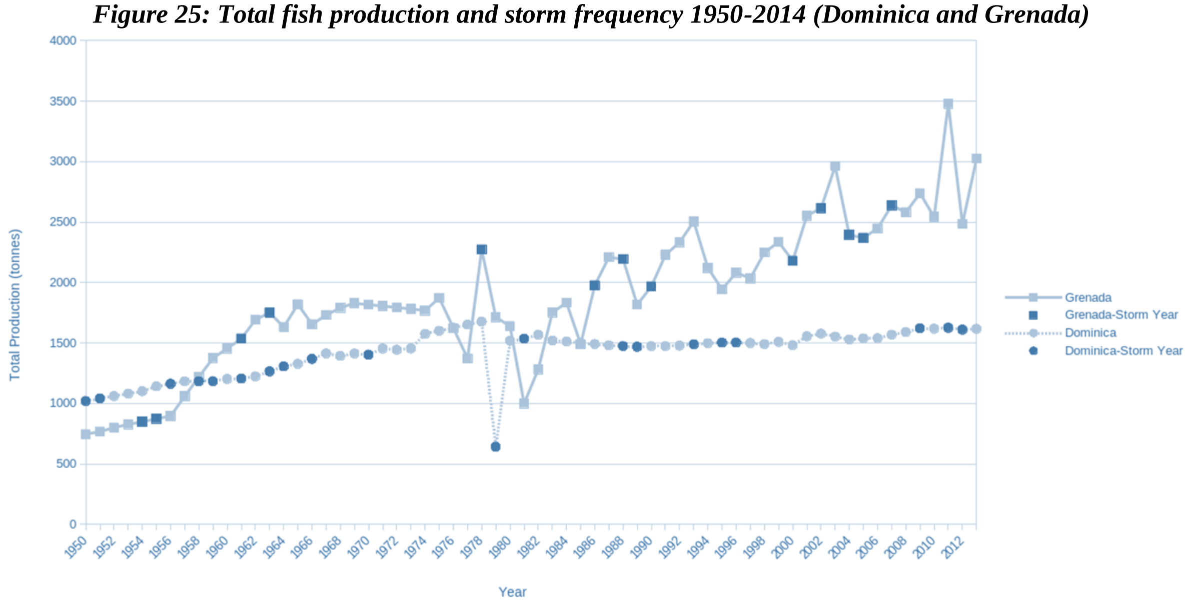
7.1 Tropical Cyclone and Fishery Production Plots

Figure 24: Total fish production and storm frequency 1950-2014 (pooled)



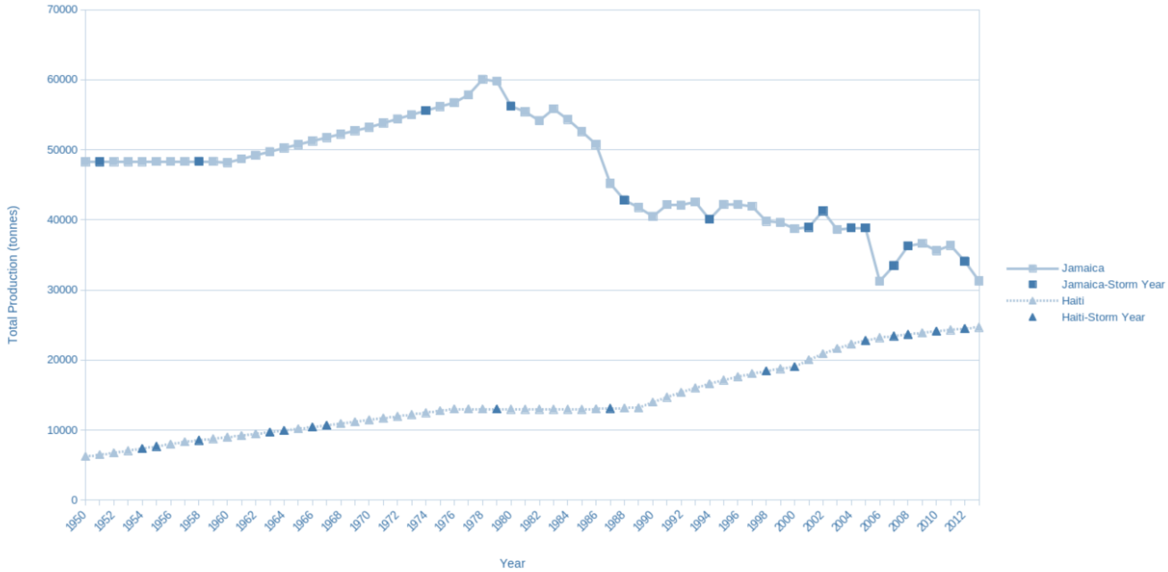
Source: Seas Around Us, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib

Figure 25: Total fish production and storm frequency 1950-2014 (Dominica and Grenada)



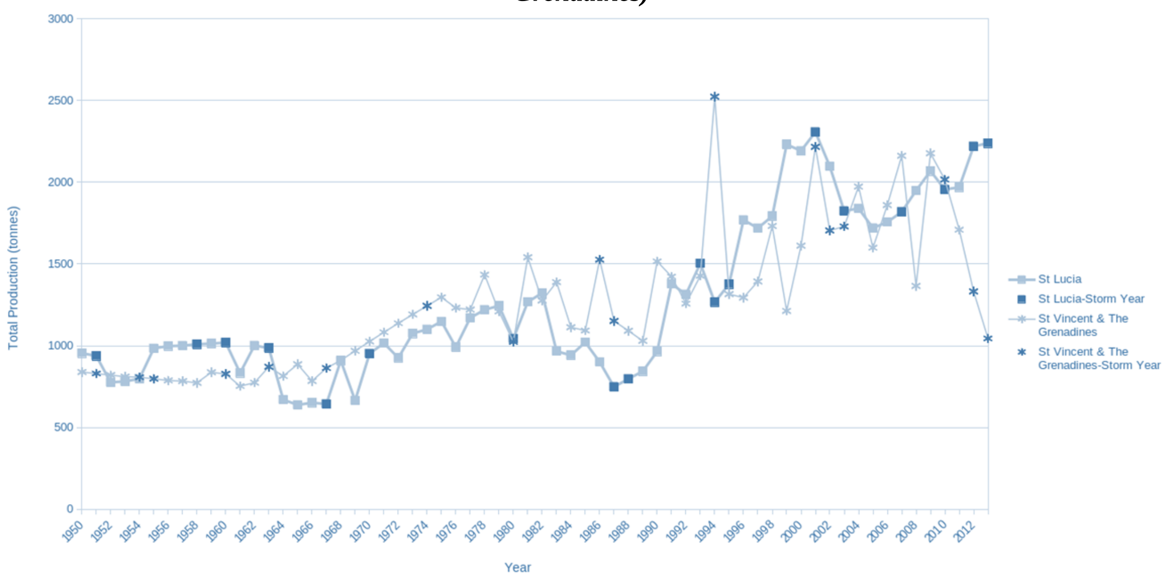
Source: Seas Around Us, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib.

Figure 26: Total fish production and storm frequency 1950-2014 (Jamaica and Haiti)



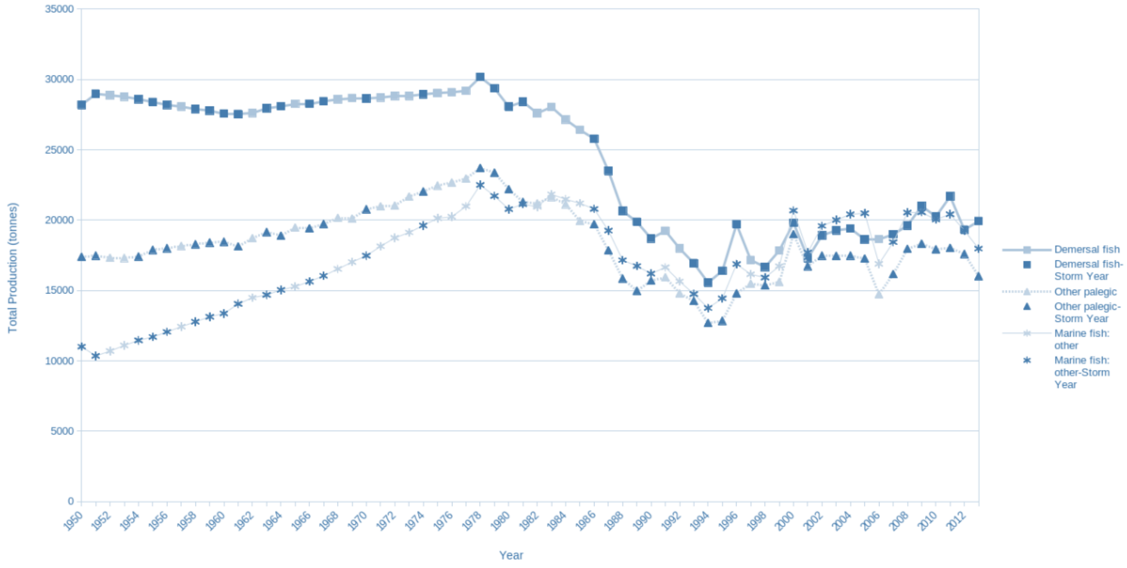
Source: Seas Around Us, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib.

Figure 27: Total fish production and storm frequency 1950-2014 (Saint Lucia and Saint Vincent and the Grenadines)



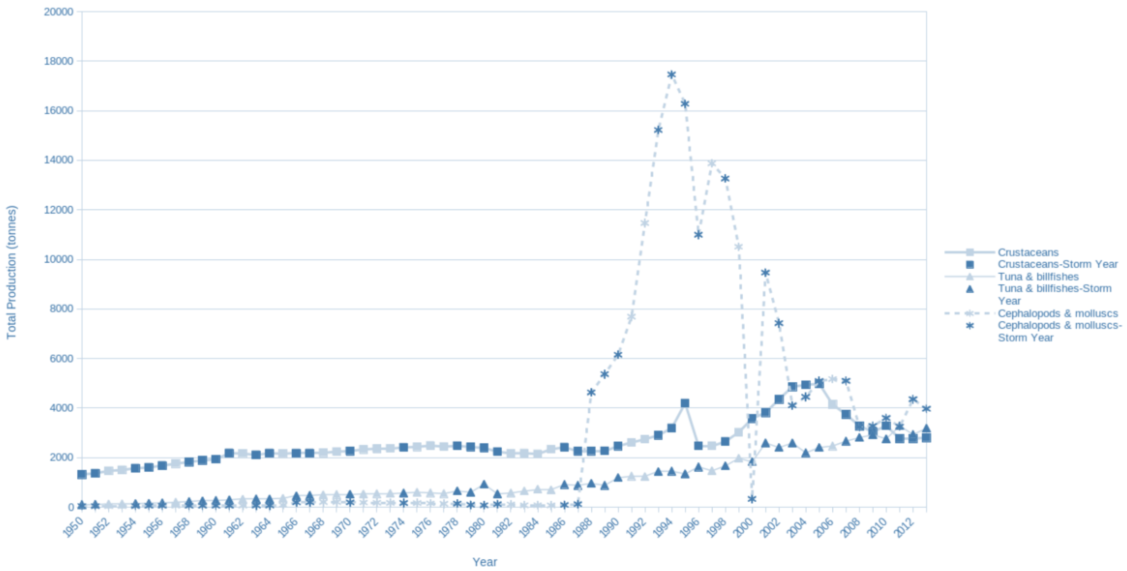
Source: Seas Around Us, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib.

Figure 28: Total fish production and storm frequency 1950-2014 (pooled demersal fishes, other pelagic fishes, other marine fishes)



Source: Seas Around Us, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib

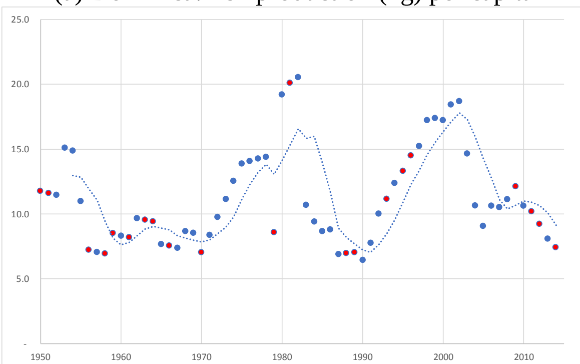
Figure 29: Total fish production and storm frequency 1950-2014 (pooled crustaceans, tuna & billfishes, cephalopods & molluscs)



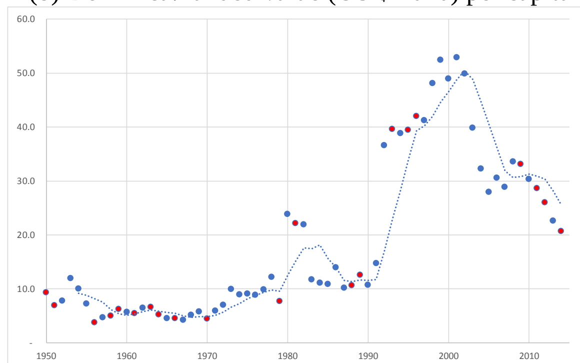
Source: Seas Around Us, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib

Figure30: Per capita fish production, landed value and storm frequency 1950-2014 (Dominica, Grenada and Haiti) (officially reported catch only) (dashed line is 5-year moving average)

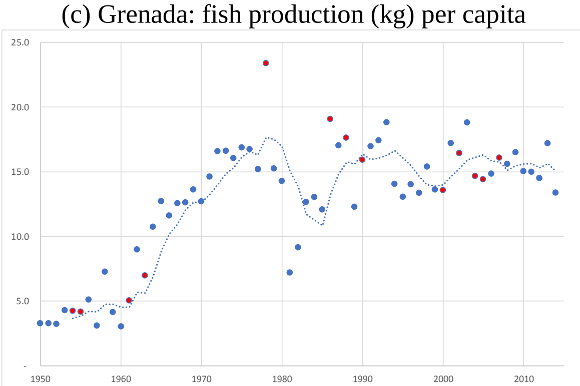
(a) Dominica: fish production (kg) per capita



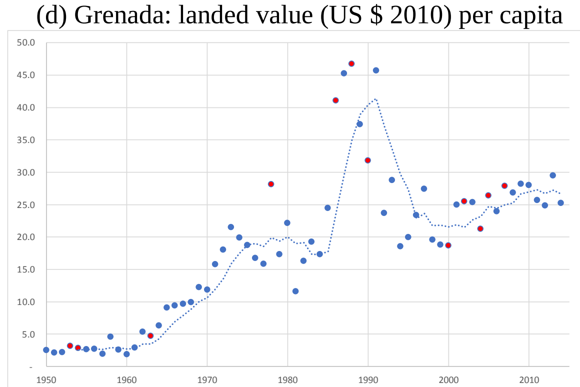
(b) Dominica: landed value (US $ 2010) per capita



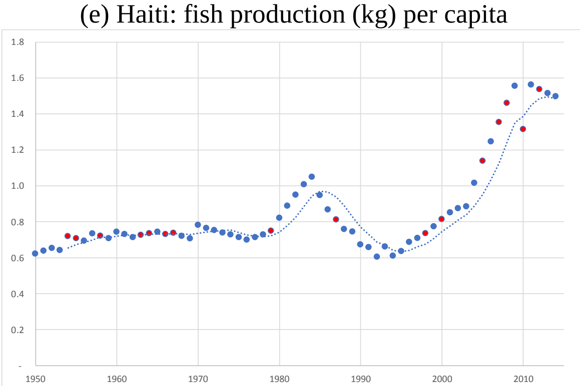
(c) Grenada: fish production (kg) per capita



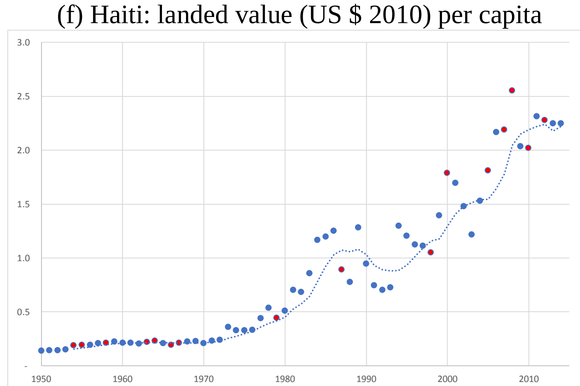
(d) Grenada: landed value (US $ 2010) per capita



(e) Haiti: fish production (kg) per capita



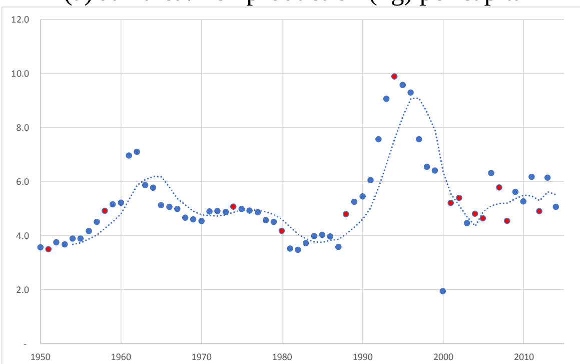
(f) Haiti: landed value (US $ 2010) per capita



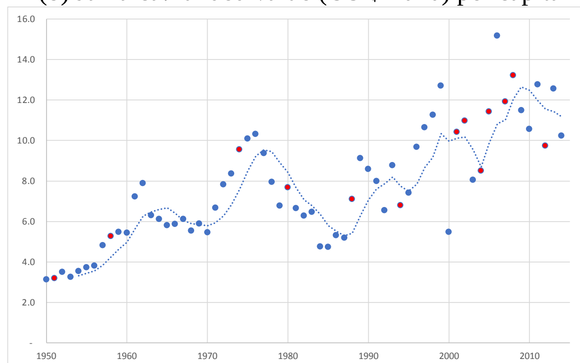
Source: Seas Around Us, U.N. World Urbanization Prospects, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib.
Note: The blue dots are years without a storm event; the red dots are years with storm events.

Figure 31: Per capita fish production, landed value and storm frequency 1950-2014 (Jamaica, St. Lucia and SVG) (officially reported catch only) (dashed line is 5-year moving average)

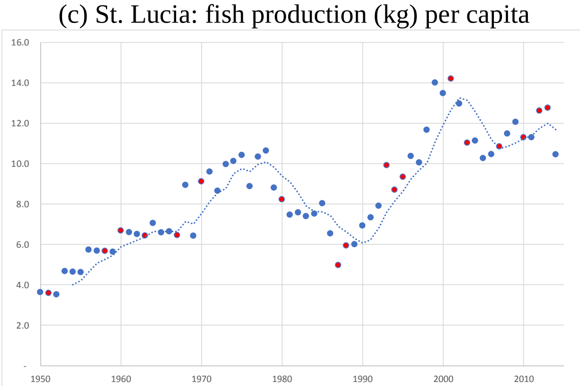
(a) Jamaica: fish production (kg) per capita



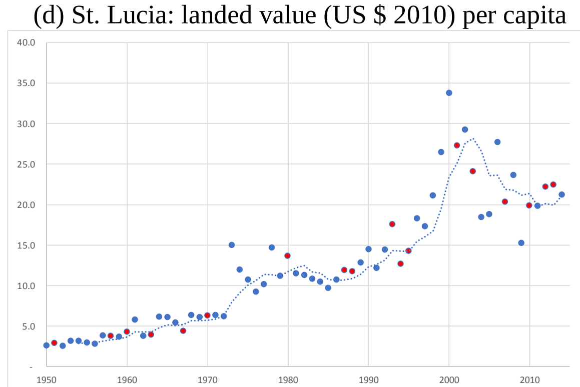
(b) Jamaica: landed value (US $ 2010) per capita



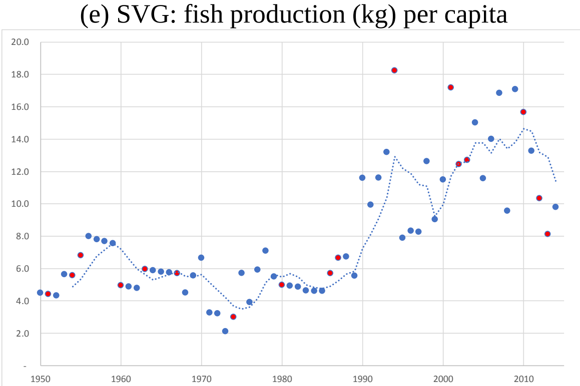
(c) St. Lucia: fish production (kg) per capita



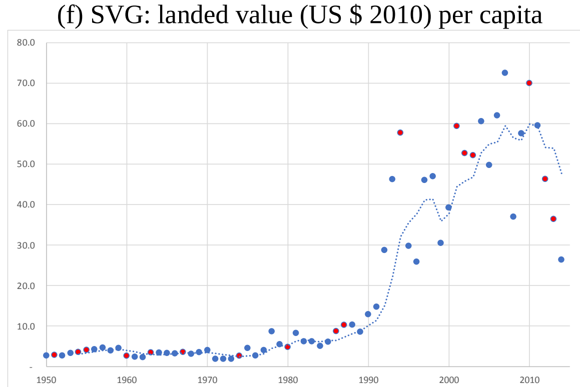
(d) St. Lucia: landed value (US $ 2010) per capita



(e) SVG: fish production (kg) per capita



(f) SVG: landed value (US $ 2010) per capita



Source: Seas Around Us, U.N. World Urbanization Prospects, NOAA Historical Hurricane Tracks Tool and the Caribbean Hurricane Network StormCarib

Note: The blue dots are years without a storm event; the red dots are years with storm events.

D. TOWARD CLIMATE-SMART VALUE CHAINS IN CARIBBEAN FISHERIES

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Abstract

Value chains are unique analytical tools to assess the viability of fisheries and their resilience to global change. As climate change impacts intensify, how resilient can seafood value chains be, and what mechanisms and measures are necessary to build local adaptive capacity? Through literature review, key-informant interviews and focus-group sessions, three policy entry points were identified and examined along the fish production chain, in pursuit of conservation targets, food and livelihood security and a viable seafood trade. Analysis and recommendations focus on two highly climate-vulnerable nations, Jamaica and Saint Vincent and the Grenadines (SVG), as case studies to understand the broader Caribbean context. Findings show that there is a cascading effect of climatic impacts on fish species' productivity and raw material supply, to volume and value, consumer preferences and value-addition opportunities. The co-benefits of adaptation planning and fisheries management are, thus, crucial to make fisheries sustainable and viable through various policy instruments and governing arrangements. These may include institutional reforms and cross-sectoral planning for synergistic effects, self-organization of resource users in building local adaptive capacity, promoting seafood product differentiation and identifying enablers for governance effectiveness. Various adaptation pathways are discussed in meeting the needs of vulnerable coastal communities, including developing National Adaptation Plans and negotiating regional governance mechanisms for migratory stocks. Despite the many challenges, opportunities do arise for both resource users and regulators to adopt and promote enabling conditions for climate-smart approaches and to employ a responsive indicator system along the seafood chain for monitoring and evaluating future climate risks.

1 INTRODUCTION

This report is part of the deliverables under Work Package 1 for the project *Fishery-Related Ecological and Socio-economic Impact Assessments and Monitoring System*. Specifically, this report contributes to the following objectives of Work Package 1:

- Assess the socio-economic impacts of climate change and variability on the fisheries resources and sector

This report uses mixed methods that integrate secondary and primary data to identify and assess enabling conditions for inclusive and responsive governing institutions across the seafood value chain. Analysis and recommendations focus on two highly climate-vulnerable nations, Jamaica and Saint Vincent and the Grenadines (SVG), as case studies to understand the broader Caribbean context.

1.1 Climate Change as a Cross-cutting Governance Challenge for Fisheries

Managing and adapting to climate change impacts in the Caribbean is high on the region's policy and economic agendas (CARICOM, 2009; CCCCC, 2009; CCCCC, 2012; CRFM 2013a, b; CARICOM 2014a, b; CRFM, in press), with an updated regional framework for climate resilient development soon to be released (K. Nichols, *pers comm*). The increasing frequency and intensity of extreme events and related loss and damage to coastal infrastructure and maritime industries have increased regional awareness of what climate change could bring. This is of special importance to the blue-economy sectors (fisheries, coastal tourism, ports, and maritime transport), as climate change impacts will have dire consequences in multi-faceted ways. Increasing sea surface temperatures and ocean acidification within marine ecosystems are affecting fish productivity; dependence on fish commodity for food and export earnings heightens the region's sensitivity to ecosystem changes. Similarly, loss and damage of fishing infrastructure and other assets such as wharves and fishing vessels have implications toward viability and disruption of supply chains, which in turn disrupt marketing and distribution networks.

Understanding and responding to these multi-faceted challenges demand novel policy instruments. Current policy instruments generally ignore network effects or unintended consequences across domains or sectors. The value chain is central to a systematic response strategy to climate resilience as it exemplifies interaction across social-ecological systems, and cross-scale linkages from local wharves to global markets. New research now demonstrates how governance across social and ecological systems can lead to enhanced revenues from the fishery, better nutritional wellbeing and ecological stewardship (Smith *et al.*, 2010; Miller *et al.*, 2012; Steenbergen *et al.*, 2019).

1.2 Conceptual Framework for Value Chains

Value chains (Box 1) have emerged as a research topic to address socio-economic and livelihood vulnerabilities and make markets work better for a greater proportion of the world's coastal communities (Gudmunsson *et al*., 2006; Gereffi *et al.*, 2005; M4P, 2008). In fisheries, value chain analysis has a unique niche, as seafood is highly perishable, with higher percentages of post-harvest spoilage compared to other agri-commodities (FAO, 2016). This is often due to high ambient temperatures and bacterial and microbial infestation, which places high demand for refrigeration and primary and secondary processing. Seafood value chains are also unique in that they are renewable resources and highly coupled within social and ecological systems. Unlike agriculture and to some extent aquaculture, seafood value chains are one of the last wild capture food systems subject to environmental variability and global change.

The value chain is a useful lens to understand the level of exposure, sensitivity and adaptive capacity to both climatic and non-climatic stressors (or drivers of change) and to identify management measures that are complementary to adaptation and resilience building (Timmers, 2012). Warming waters and changing climate means range contraction for some species as well as migration of tropical species to temperate regions due to habitat characteristics (Cheung *et al*., 2013; Cheung *et al.*, 2019 - studies in this Collection). This would not only affect catch levels and access rights but also exacerbate the cost of fishing, particularly operational costs (e.g., fuel use), but also port state measures and compliance with chain of custody rules.

Box 1: What do we mean by "fish value chains"?

Notable applications of the "chain" metaphor include "global commodity chains", "global value chains" and "supply chain management", among others. In this context, chains can refer to consumer goods (Gereffi, 2008), food industries (Bernstein *et al*., 2006; Kaplinsky & Morris, 2001), as well as agri-commodities. In the context of this study, the seafood or "fish chain" focuses on understanding fishery systems. It looks at the interaction between fishery ecosystems and seafood through the production chain from "oceans to plate", spanning from the ecological to social systems, with the goal of identifying entry points for the greater benefit of society (e.g., enhanced profitability, greater market share, enhanced food security). The **value chain** (denoting additional benefits of increasing shelf life, product differentiation options, quality, and revenue) provides an analytical framework to understand seafood production starting from capture (harvest stage) to post-harvest (processing and marketing) and the interlinkages with ecosystem changes as shown in Figure 1.

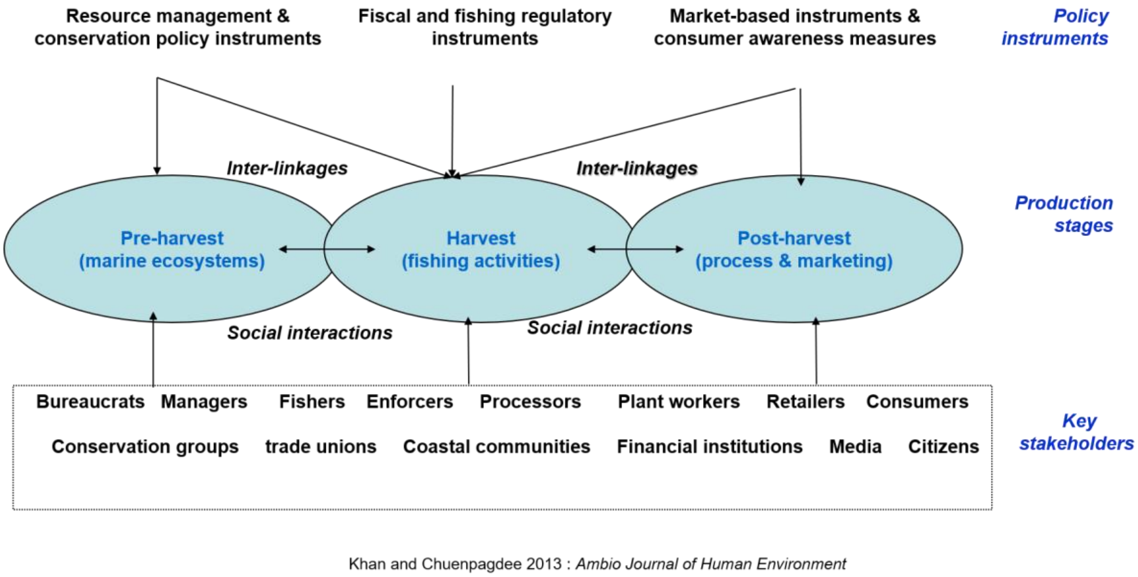

Figure 1: Value chain framework showing various production stages, policy instruments and actors

Analyses across the value chain can be quantitative in terms of predictive modeling and stock assessment under extreme conditions (Sumaila *et al.*, 2011); to assessing viability through indicators such as fishing revenue, cost allocation, and profit margins (Gudmunsson et al. 2006); to estimating fishing revenues and price mark-up across various seafood actors (Purcell et al. 2017), to mapping flows of products and distribution networks in the event of stock collapse (Khan 2010). Analyses can also be qualitative, prescriptive, and value laden with human right concerns and environmental and social safeguards.

Focus on the fish value chain highlights key complementarities with strategies for climate change adaptation and resilience building. These include the following:

- The backward bending supply nature of wild captures fisheries as shown in Figure 2(Copes 1970), where increasing demand from D_1 to D_2 can lead to increasing quantity and production from Q_1 to Q_2 and in the absence of good management measures lead to overfishing and stock collapse beyond the Maximum Sustainable Yield (MSY);
- Management and innovative harvesting strategies with attention to habitat suitability, ocean acidification and stock migration patterns;
- Livelihood opportunities and social resilience for both fishers and processors;
- Coastal infrastructure protection and an ecosystem-based approach to adaptation;
- Governance as a catalyst and enabler for institutional innovation, multi-level arrangements and cross-scale linkages.

Figure 2: Limits to seafood production as shown by the backward bending supply curve (Khan, 2010)

Market forces are non-climatic stressors of particular importance; they interact simultaneously with climate stressors to impact and exacerbate human well-being and their dependence on fishery resources. The value chain analysis targets both commercial and subsistence species for international and local markets, which intersects with export earnings and local seafood security. Exploring these dimensions is essential for understanding economic viability and adaptive capacity and issues around insolvency, savings and capital assets and safety nets. The value chain methodology, as applied to seafood, starts with an examination of trophic dynamics and species abundance, which provides a starting point to understand the policy and governing implications across the post-harvest stage. Trust and communication are very important to such governing interactions amongst stakeholder groups as institutional mechanisms build adaptive capacity and promote both ecological and social resilience at multiple scales.

Since governing fisheries for value addition requires coordination among the various actors and stakeholders (Bavinck, 2007), participatory processes are key to value chain analysis. For example, "fish" has different meanings and this needs to be accounted for in setting governance and management goals and objectives across the value chain. Some see fishes in terms of their intrinsic value as species and part of biodiversity that needs to be sustained and regulated; others see fish as a natural resource and a commodity that needs to be harvested for wealth creation and prosperity. Fish is also food and feeds more than a billion people around the world. Seafood contributes to major animal protein globally and consumption can be as high as 28kg per capita in the Caribbean. Fish is also a commodity. Seafood is the most tradable commodity in the world, with global exports and imports reaching up to 140 billion dollars; as such, there is recognition that attention to product quality, processing methods and health standards and product differentiation can enhance revenues and build social resilience (Jaffry *et al.*, 2004; Smith *et al.*, 2010).

2 METHODS

The research design follows a multi-level approach within a social-ecological system perspective drawing on Ostrom (2007) and within a fisheries context (Khan, 2010; Khan *et al*., 2016; Khan *et al.*, 2018). Primary and secondary data were sourced and analyzed to highlight community-based vulnerability and adaptive responses and to explore leverage points for climate resilience. The *socio-economic adaptive capacity and response* of the fishing sector is based on socio-economic survey data from previous studies and historical management data available through academic articles and government reports. Next, new data was collected as part of this project derived from a stakeholder workshop, focus group discussions and key informant interviews. To be systematic, we employed a diagnostic tool to elucidate ecological and social vulnerabilities relating to the fisheries sector and examine responses to vulnerability and governance mechanisms to enhance adaptive capacities. The tool consists of a matrix of system attributes modified to the fisheries value chain framework (see Table 1) and can have a suite of metrics and indicator systems for monitoring and evaluation especially under climate change (Appendix 1). The inherent assumption is that the more diverse, complex, dynamic and multi-scale the systems are, the greater the need for building adaptive and promoting effective governance mechanisms (Khan & Amelie, 2014; Khan & Cundill, 2018).

Table 1: A diagnostic tool for probing vulnerabilities and adaptive capacity (Source: Khan and Amelie 2015 as adapted from Chuenpagdee 2011)

Attributes	(1) Pre-harvest stage (marine ecosystems)	(2) Harvest and post-harvest (resource- and market-based activities)	(3) Governing systems (policy instrument tool kit)
Diversity	What are the types of species, and their biomass within the ecosystem?	What are the main ecosystem goods and services and beneficiaries?	What are the various institutional mandates and policy frameworks?
	How do species interact: competition, mutualism, compensatory / depensatory processes?	How do property rights and access influence compliance, stewardship, and adaptation response?	Who are the various organizations that influence policy design and implementation?
Complexity	What is the composition of the species and their richness? Endangered, endemic or keystone?	How do adaptation measures influence various groups: power, equity, and conflicts	What types of policy instruments are found within the ICZM and in adaptation toolkits?
	How do non-climatic factors such as currents, upwelling, dispersal, etc. affect ecological resilience?	Do the fisheries policy instruments have a spill-over effect to other sectors or regions?	Are there feedback mechanisms for policy re-formulation toward diversification or alternative livelihoods?
Dynamics	What are the trends in resources appraisal and critical habitats during anomalies?	How do changes in macro- or micro-economic policies affect cost and earnings and the ability to cope/adapt?	What structures or steering mechanism affect viable economies and resilience infrastructure?
	What short-term and long term (cyclical and non - cyclical) changes have been taking place?	How could interventions affect power brokerage, interest groups and social networks?	How do changes in management vision or priorities affect adaptive capacity?
Attention to scale	Are Large Marine Ecosystem (LME) considerations given for spatial processes and interactions across geo-political boundaries?	Do economic boundaries or cross-sectoral approaches limit or enhance adaptive capacity?	How do multi- governance structures affect the design and implementation of adaptation strategies?
	Are these ecosystems and biophysical attributes unique, or representative: corals, eddy mixing, hotspots, etc.?	Does mobility of people and other resources affect ecosystems services and adaptive capacity?	How does the spatial scale of management influence institutional arrangements?
Sensitivity	What are natural or human-induced stresses, drivers, and threats that can be identified for ecosystem health?	What economic activities and livelihoods are most susceptible to interventions being considered?	What precautionary and adaptive governing capacities are in place for various stakeholder groups?

2.1 Field Research

In assessing socio-economic factors at the local and community scale, a questionnaire was designed that explored questions across the three production stages of the fish chain, focusing on climatic risk and viability options. The thematic content of the questionnaire was informed by the diagnostic tool. The questionnaire comprised three sections:

Coastal & marine governance (managers, planners and public administrators)

- Organizational and institutional vision on synergies between fisheries management, coastal disaster risk reduction, and climate adaptation planning
- Cross sectoral linkages on adaptation and fisheries co-benefits and spatial planning
- Mainstreaming adaptation into fisheries management
- Policy networks and brokerage across the fish chain

- Partnerships (public and private, public and university, etc.)

Resource users and fishing households (fishers, cooperatives and others)
- Resource use and fishing activities
- Livelihood vulnerability to climate stressors
- Cost and earnings of fishing fleets and techno-economic performance under climatic and non-climatic scenarios
- Individual, private and public adaptation responses to climate stressors

Post-harvest activities (processors, buyers, exporters, retailers, hotels, etc.)
- Product differentiation (fresh, whole, fillet, frozen, canned, smoked, etc.)
- Value addition and up-scaling initiatives (eco-labels, branding, traceability, etc.)
- Supply chain dynamics amongst stakeholders and risk assessments
- Market destinations and consumer preferences
- Insurance and risk mitigation

To respect cultural diversity and develop ethical procedures, survey and interview protocols were provided to local partners and members of the project Working Group (consent notes are in Appendix 2). Members of the project Working Group (including a member of the Caribbean Regional Fisheries Mechanism Secretariat and national fisheries officers in Saint Vincent and the Grenadines and Jamaica) also assisted in determining appropriate points of contact with stakeholders at pilot sites (e.g., the president of a local fishing cooperative) and arranging interviews or meeting appointments with other members of the fishing community and government officials. Such an approach provided: a) assurance that appropriate steps were taken to protect the rights and welfare of humans participating as subjects in our study; b) assesses the ethics of the research and its methods; c) promote informed participation; and d) allow ESSA and the project team to use the data collected by the team for future work.

Primary data collection in wild captured coastal and marine fisheries took place in two pilot study sites between April and June 2018: Kingstown (Saint Vincent and the Grenadines) and Montego Bay (Jamaica). Although recreational fisheries and aquaculture ventures can play important roles in resource economies and for food security, these segments were excluded from the socio-economic assessment, due to time and resource constraints for fieldwork. Appendix 3 describes the process undertaken to select pilot study sites and where data collection activities were undertaken at the local level.

Field work was stratified at two levels: i) stratification across key coastal and marine ecosystems and ii) for the key fisheries within each ecosystem, stratification across value-chain actors (e.g., fishers, vessel owners, processors, local vendors, and exporters among others), to ensure a diversity of perspectives within ecosystem and value-chain analyses.

About 50 key informant interviews in total were conducted in Jamaica and Saint Vincent and the Grenadines (Appendix 4). These included 24 fishers (inshore and offshore), individually or in focus groups. For the post-harvest stage, about 12 key informants interviewed in the processing, marketing, and retail activities. This included fish processors in public and private facilities, vendors and traders, retailers, restaurants and hotels. The objective was to document concerns about climate risks and seek ideas on how to resolve them in capturing the gains from seafood trade and the resilience of the fishing industry. For the pre-harvest marine ecosystems, the questionnaires targeted public officials and conservation groups, comprising 14 individuals with roles in fisheries and marine resource management, economic planning, tourism development and recreational fisheries, environmental planning and climate change adaptation. Government officials had expertise on a wide range of subjects, including stock assessment, fisheries extension, marketing and quality, disaster risk reduction, integrated management, parks and wildlife, and adaptation planning.

3 FINDINGS

The following sections present key findings organized by the three stages along the fish chain, from pre-harvest marine ecosystems, to the harvesting and fishing stage and finally to the post-harvest and processing stage. These stages are not independent from each other, but rather interact through raw material supply and consumer demand and are influenced by various actors, policy instruments and global change drivers as shown in Figure 1.

Overall, field research allowed us to identify two major types of fish chains in Saint Vincent and the Grenadines and Jamaica: small-scale artisanal and small-scale industrial fisheries. These two chains have three features in common: (1) low fishing capacity, (2) limited value addition and (3) low skills and infrastructure support toward product differentiation and up-scaling opportunities. The small-scale artisanal fish chain mostly targets species such as snappers, parrotfish, wahoo, conch, tuna and barracuda for the local market. The small-scale industrial fish chain includes all species in the artisanal category in addition to shrimps, conch and lobsters, but targets regional and global markets. A third category was identified although not fully studied: the large-scale industrial fish chains. This includes offshore fleet operations, trans-oceanic shipments and on-board processing, and export markets. This is more capital intensive and presents different types of risks and management interventions beyond jurisdictional mandates.

3.1 **Pre-Harvest Stage**

In the Caribbean, as in many parts of the world, fisheries are governed as public goods, with rights of access and delegation of management authority to a central fisheries agency. In Saint Vincent and the Grenadines, the Fisheries Division oversees fisheries policy through various input and output control measures, support to fisherfolk regarding compliance and stewardship, protected areas as marine conservation tools and by-catch rules. Various legislative and policy frameworks support fisheries and coastal governance, e.g. the Fisheries Act (1986), Fisheries Regulations (1987), the High Seas Fishing Act (2001), High Seas Regulations 2006, Illegal, Unreported and Unregulated Fishing Regulations 2017, the Maritime Areas Act (1983), and the Town and Country Act. These frameworks work synergistically and are part of integrated coastal zone management and fisheries management objectives in an ecosystem approach. Similarly, in Jamaica the Fisheries Division, under the Ministry of Industry, Commerce, Agriculture and Fisheries, overseas all activities in the seafood industry. This includes creating fishing harvest strategies, national export standards and management measures. In Jamaica, some key supporting legislative and policy frameworks are the Fisheries Policy (2008) and the Fisheries Act (to replace the Jamaica Fishing Industry Act of 1975).

Regional surveys on important fish stocks include large and small pelagics, demersal species, shellfisheries, snapper, and dolphin fish as crucial to the Caribbean economies (Figure 3). Although stock health of these species are within reasonable levels of exploitation within the context of viability and sustainability, some stocks have been prioritized by regional and national management entities for continuous assessment and monitoring. These include the spiny lobster (*Panulirus argus*), queen conch (*Strombus gigas*), dolphinfish (*Coryphaena hippurus*), marlin (*Makaira nigricans*), wahoo (*Acanthocybium solandri*), yellowfin tuna (*Thunnus albacares*) and snapper (*Lutjanus sp; Etilis sp*).

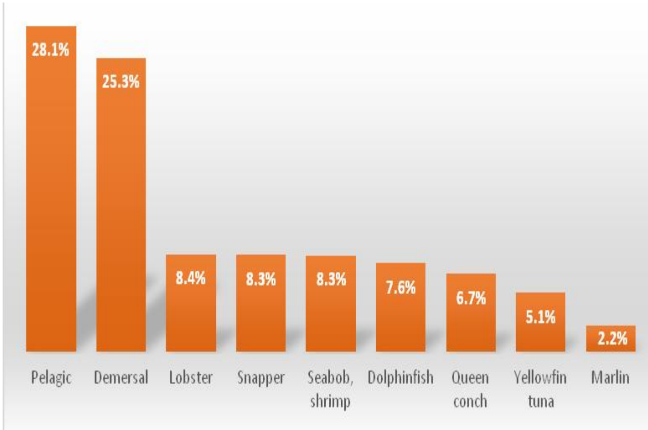

Figure 3: Major fisheries resources base from regional assessment and proportion of regional landings (FAO & CRFM 2017)

In meeting resource sustainability objectives, various conservation measures have been initiated in the Caribbean such as marine protected areas or marine conservation areas. For instance in Saint Vincent and the Grenadines, 33 marine conservation areas have been established in ten regions (St. Vincent, Bequia, Isle a Quatre, Mustique, Canouan, Mayreau, Tobago Cays, Union Island, Palm Island and Petit St. Vincent). These marine protected regions were instituted under the Fisheries Act of 1986 and Regulations of 1987 and prohibit specific fishing activities such as spear fishing, protect critical habitats, and limit human impacts such as pollution. Likewise, in Jamaica, there are several conservation initiatives including special fishery conservation areas and marine parks instituted through partnerships such as the Montego Bay Marine Park Trust. This non-profit agency promotes sustainability measures for critical fish habitats such as mangroves and coral reefs and raises awareness about biodiversity and marine resource management.

In addition to these, there are various fisheries regulations informed by other regulations in the Caribbean, notably opening and closing seasons, gear use restrictions, harvesting measures (fish size and length), by-catch rules, and entry and trip limits through licenses and number of days or months to fish. In Saint Vincent and the Grenadines, there are several rules and regulations for specific fisheries, such as the Caribbean spiny lobster industry. Closed seasons for lobsters are from May 1st to August 31st with prohibition on taking moulting and female lobsters carrying eggs. There are also restrictions for lobsters with body length less than 9 inches (= 228.6 mm), weight less than a pound or carapace length of less than 3 inches (= 76.2 mm). In Jamaica, closed seasons run from April 1st to June 30th, with other restrictions including minimum-size limits (carapace > 89 mm or 3.5 inches) and prohibition on taking berried females, tar-spotted females (with a sperm packet), or molting individuals.

Compliance and surveillance measures are weak owning to the nature of the landing sites, as well as monitoring capacity. However, punitive measures have always been a strong part of management to deter unsustainable fisheries practices although enforcement is a challenge considering meagre control and surveillance capacity in the region. New amendments to the Jamaican Fishing Industry Act of 2015 highlights fines and prison terms for infringements on fishing regulations especially toward unlicensed boat use, poaching, unauthorized gear use, illegal, unreported and unregulated fishing (IUU) and failure to adhere to other fishing measures.

Climate change compounds the task of managing marine resources in the Caribbean. Changing environmental conditions such as ocean acidification that affects growth rates, habitat suitability and fish migration patterns will test the management measures mentioned above, requiring adaptive approaches to offset the social and economic ripple effects of a decreased or uncertain resource base. With climate change and raw material supply constraints, new tools and multi-level governance arrangements are needed for social and ecological resilience. This brings the harvest stage of the fish chain into sharp focus. The harvest stage bridges resource availability and raw material supply on one hand and enhancing the socio-economic benefits in terms of resource utilization on the other. It comprises a number of inter-connecting levers for resilience building and adaptation, as it underscores the importance of processing and value addition, protection of coastal infrastructure, risks mitigation through social kinship ties and early warning systems.

3.2 **Harvest Stage**

Fish landings (wild stocks) are dependent on the health and sustainability of marine ecosystems (pre-harvest stage) and the effectiveness of management measures put in place. Findings indicate that seasonal stock migration patterns are affected by the influx of Sargassum, bad weather, increasing operational costs –especially fuel – and other market drivers that affect the volume and value of fish landings.

Fish diversity. Fishers rely on the seafood resource base as a commodity for their livelihood, for food and as a way of life and culture. Because fishing is seasonal and regulated to different degrees, what species are caught and how much are caught influences processing requirements, infrastructure needs, and consumer demand. For instance in Saint Vincent and the Grenadines, snapper (Red, Queen and Blackfin), parrotfish and butterfish are available and can be fished all year round, but more fishing occurs in spring, summer and autumn months compared to tuna (Blackfin, Yellowfin and Skipjack), which are fished in summer and autumn only. Conch is harvested only in the summer months, hence its price and seasonal implications. Whilst some species are mostly sold alive (lobsters) or fresh (snappers), others might require ice and refrigeration (conch), or beheading and filleting (barracuda). These options reduce on post-harvest loss, increase product differentiation, and thus enhance revenue generation along the fish chain. Conch was identified as one of the national iconic species in Jamaica and deserves branding and protection, especially as it is under the watchful eyes of Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). The conch fishery is under gear restrictions (using the Florida trap model) and a management plan is underway.

Fishing activities. Fishing operations can be daily or every other day involving a couple of hours in the case where Fish Aggregating Devices (FADs) are available, or longer up to 12 hours. Normally, a daylong trip to unplanned fishing grounds is expected especially for demersal species and overnight trips from two to five nights searching for migratory stocks such as tuna. For such longer trips, fuel accounts for 20 to 50% of the operational cost, next to ice and bait. For some species that are demand-driven or consumed as staples such as snappers, wahoo and parrotfish, there is less need for on-board preservation as consumer preference is often for fresh fish (catch of the day). For these, landings can be as low as 5 barracuda, 5 wahoo and 40 tunas per day trip. Various types of boats are employed, ranging from relatively small to medium and large with crew size ranging from two to three, three to five and three to fifteen with various gear types including lines, nets and seines targeting multitude of fish species (as shown in Figure 4 and Figure 5). Interviews with fishers also demonstrate the centrality of the 'collective' and the community dimension to crew composition that involves family, relatives and friends, and reflects on wage-sharing mechanisms.

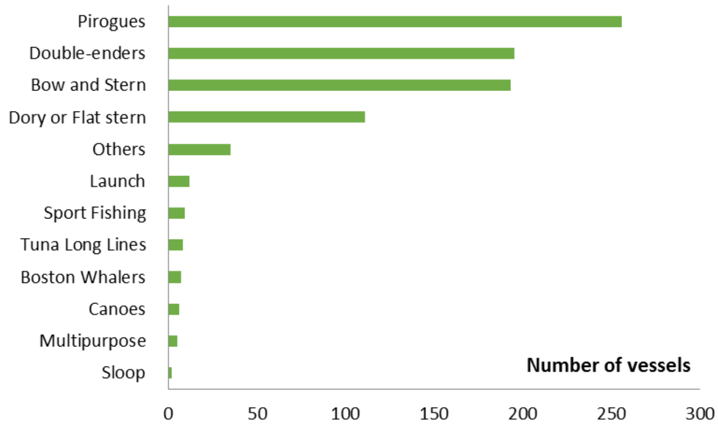

Figure 4: Composition of fishing fleet in SVG, unique features of SSF in the region (Source: FAO & CRFM 2017)

Figure 5: Array of fishing boats and gears as seen in Saint Vincent and the Grenadines and Jamaican wharves, representative of the Caribbean region. Vessels range from locally-made small pirogues and canoes to larger imported motorized vessels, bows and sterns, to sport and tuna-fishing vessels.

Cost and earnings: For most full-time fishers, fishing contributes 100% to their monthly household income and can range from $500 EC on bad days to $7000 EC per day during a good harvest season. Almost all of the fishers interviewed are full-time occupants in the industry except for few younger crew members especially in Saint Vincent and the Grenadines who used to work as mechanic or were high school or middle-school drop-outs. Some fishers started in other occupations (service industry or agriculture) but switched to fishing, mostly due to the independence and daily wage as compared to salaried occupation.

be high especially for the cost of buying a small boat of about 26 ft (7.9 m) ($ 25,000 EC) in SVG, 25 HP engine ($ 15,000 EC) and nets, as well as daily operational cost including food, bait, gas, and repairs. Similarly, for a 33 ft (10 m) (4 stroke) fishing boat in Jamaica, this will cost about $5.4 million Jamaican and a 40hp outboard engine about $ 500,000 Jamaican dollars. Most fishers finance their fishing operations through family and relatives (mostly young fishers) whilst others have had loans from cooperatives and community banks such as the Teachers and Police Co-operative Credit Unions in Saint Vincent and the Grenadines. Cost and earnings for major species is given in Table 2 for Saint Vincent and the Grenadines, showing the relative returns per trip for captain, boat owner and crew member. These survey results for various trip amounts were consistent with information gleaned from interviews with fishers in Jamaica with respect to income streams, benefit-sharing mechanisms with crew members and the increasing operation costs of fishing operations (fuel, bait and ice), for which secondary data was unavailable.

Livelihood security: The interviews in both Jamaica and Saint Vincent and the Grenadines revealed that most of the fishers are content with their monthly and annual returns and for no reason want to change occupation nor be retrained to other professions. This reveals the potential for high vulnerability, in the event of stock migration and lower total allowable catch if fishers are not integrated into other economic sectors in the event of climate shocks. They may be jobless and face serious hardship especially in the absence of welfare and unemployment insurance. According to fishers in Jamaica, the fisheries can be viable in most seasons although recently there is dwindling of raw material supply through poor catch, frequency of killer whales that limits fishing trips, loss and damage from extreme events such as hurricanes, piracy, and the incidence of Sargassum that affects fishing operations. To be viable, fishers are taking extended trips out at sea for days, often incurring higher operational costs due to fuel costs, and safety at sea.

In the event of loss of income, most fishers rely on their meagre savings, kinship ties, as well as cooperative schemes. Government support through social security / insurance is an option some young fishers are exploring. Unlike older and senior fishers who were never part of any national social insurance scheme that targets the fishing industry, younger fishers have the option through new legislature and are "thrilled" to contribute to monthly insurance subscriptions. Most of the older fishers interviewed feel that they are too old to contribute to such a program and rather prefer to invest in their children's post-secondary education. With increasing climate change impacts, CRFM has played a pivotal role in supporting the formulation of the Caribbean Ocean Assets Sustainability FaciliTy (COAST)to support insurance programs for fishers in collaboration with fisher folk organizations and other regional economic and disaster risk reduction (DRR) organizations.[29]

Adaptation and resilience options: Demographics influence the type of social safety nets available to fishers. Demographics are important considerations in efforts to build social resilience as age, sex, race, ethnicity, and educational attributes will influence outcomes. For instance, there is no exit to other industries for older fishers, as their skill sets are often not transferrable and many are not literate. As such, older fishers have been adaptive towards recreational fisheries or other blue-economy sectors like eco-tourism. Younger fishers, on the other hand, tend to be more educated and have social skills to formulate self-organizing entities such as cooperatives that use information and communications technologies (ICTs) in their business development, marketing campaigns and towards hazard early warning programs using SMS. Fisheries are not the last resort for employment anymore (as land used to be unavailable for farming), but rather as a premier opportunity to develop business and marketing models that link up with the global seafood trade. This has been the motivation for the development of cooperatives in other Caribbean island countries such as Saint Lucia and Grenada. Incentives that target inner city youths through vocational training programs to highlight fisheries as a key formal occupation with curriculum development can help advance the "professionalization" of small-scale fisheries. According to respondents in the fishing industry, financial literacy programs and support to start-ups can influence a new generation of fishers who are not only marine stewards but also social entrepreneurs.

[29] COAST. https://www.unisdr.org/files/globalplatform/5930912268d82COAST_one-page_handout_final.pdf

Table 2: Survey results on cost and earning estimates for some major fish species in Saint Vincent and the Grenadines. Values are in Eastern Caribbean $ (Source: FAO and CRFM 2017)

Types of costs and earnings	Group A Trips per month (x14)	Group B Trips per month (x16)	Group C Trips per month (x22)	Group D Trips per month (x4)
Direct cost per trip	$ 161.85	$ 82.30	$ 272.87	$ 407.94
Deferred maintenance and repairs	$ 25.93	$ 8.07	$ 12.63	$ 64.81
Deferred payments to State & others	$ 206.37	$ 30.20	$ 165.13	$ 315.65
Deferred depreciation boat & engine	$ 24.14	$ 8.20	$ 15.60	$ 69.87
Total cost per trip	**$ 418.29**	**$ 128.78**	**$ 466.23**	**$ 858.27**
Incomes per trip of lobster	**$ 800.00**		**$ 1,451.59**	
Incomes per trip of conch			**$ 2,003.44**	
Incomes per trip of demersal fish	**$ 2,148.15**	**$ 431.48**	**$ 1,096.04**	**$ 5,183.89**
Net revenue per lobster trip	$ 381.71		$ 985.37	
Net revenue per conch trip			$ 1,537.22	
Net revenue per fish trip	$ 1,729.86	$ 302.70	$ 629.81	$ 4,325.62
Profit margin	**71.62%**	**70.15%**	**69.27%**	**83.44%**
Income for owner – lobster trip	$ 609.14		$ 958.91	
Income for captain – lobster trip			$ 197.07	
Income for crew – lobster trip	$ 95.43		$ 73.90	
Income for owner – conch trip			$ 1,234.84	
Income for captain – conch trip			$ 307.44	
Income for crew – conch trip			$ 115.29	
Income for owner – fish trip	**$ 1,283.22**	**$ 328.56**	**$ 781.13**	**$ 3,021.08**
Income for captain – fish trip		Is the owner	$ 125.96	$ 865.12
Income for crew – fish trip	**$ 432.46**	**$ 51.46**	**$ 47.24**	**$ 648.84**
Average monthly income owner	**$ 13,246.54**	**$ 5,257.00**	**$ 21,815.76**	**$ 12,084.32**
Average monthly income captain			$ 4,623.51	$ 3,460.50
Average monthly income crew member	$ 3,695.25	$ 823.35	$ 1,733.82	$ 2,595.37

Another resilience option identified in focus groups was the importance of kinship ties and fishing associations such as cooperatives that use a collective-action model to support safety nets to fishers when in need. However, not all fishers are part of cooperatives because of the associated leadership and administrative challenges, such as regional representation, financial accountability and (need for) broad-based participation. Interviewed fishers who were part of a cooperative (e.g., Goodwill Coop in Saint Vincent and the Grenadines) showed optimism about partnership opportunities with vendors, where their dues can be used to secure markets, get political representation and explore collective bargaining options. Due to the high operational cost of chasing fish during their migration season, fishers identified FADs as one of the best ways to adapt to changing climate. FADs, when well designed and monitored, attract various stocks thereby having a good catch, less time at sea, and low operational cost especially fuel consumption. Fishers and other value-chain actors like vendors identified opportunities for coordination and collective action especially through vertical integration – through harvesting, processing and marketing infrastructure. The new Fisheries Fleet Policy in Saint Vincent and the Grenadines provides a suitable platform for self-organization of fishers and processors to work within cooperative frameworks or national associations with public-private support. Cooperative frameworks such as these could help address power asymmetries and fairness along the fish chain through policy brokerage and negotiation on key issues such as price setting, seasonality, storage facilities, and access to finance and insurance (FAO 2018).

Access to key inputs and services such as engines, bait, repairs and gas affect fishing operations as well as operational costs and profit margins (FAO 2018). Some fishers identified bigger boats and access to finance as catalysts to improve productivity and the viability of fishing enterprises. Although there are no national association of fishers or processors to address financial inclusion and access to inputs, there are cooperatives and community associations borne out of stewardship initiatives and capacity-building efforts to address post-harvest loss as well as safety nets, micro-insurance and risk-averse programs. The Montego Bay Fisher Cooperative is one such example, created more than fifty years ago through a union and as a non-profit with a community-based approach and co-management model. Rotating savings funds through micro-credits to fishing associations have been paramount in addressing risks, since commercial insurance is too expensive for boats and personal insurance is usually accessed through community ventures such as credit unions. Insurance is not the only option for risk reduction. Fishers identified community initiatives to deal with climate risks such as blowing community horns as warning signals as well as docking boats in mangrove forests during hurricane season. For larger and more semi-industrial trawler boats in Jamaica, fishers usually sail to Uruguay, where they dock till the end of the hurricane season. According to interviewees in the industrial export sector, docking fees in Jamaica are expensive and the dock is getting shallow due to poor management and financing options.

3.3 **Post-Harvest Stage**

Raw material supply and sustainable harvesting are two key links in the fish chain that directly supports post-harvest activities such as value addition, up-scaling and trade. Seafood export is an important source of foreign earnings for many Caribbean countries (2 to 4% GDP in countries like Grenada and Haiti). However, most Caribbean nations are net seafood importers, exporting high-value products and importing cheap and affordable seafood products and to some extent some luxury products (e.g., salmon) for the hospitality industry. Seafood trade is mostly within regional markets as well as with the United States and Canada (mostly for imports), owing to tariffs, phyto-sanitary measures and Hazard Analysis and Critical Control Point (HCCAP) measures. For instance, Saint Vincent and the Grenadines lost its export license to the European Union due to poor health and environmental standards as well as traceability and chain of custody rules. Below we look at both short and long value chains and the dynamics of product type and differentiation.

Value chains with limited product differentiation. The post-harvest stage of the fish chain in Saint Vincent and the Grenadines is short, with limited value addition opportunities and product differentiation. With about 36 landing sites and about half of that on Saint Vincent, most of the catch is taken to Kingstown due to limited storage and processing infrastructure at other landing sites. The Kingstown Fish

Market is a hub for landing fish, reporting catch statistics, as well as processing and having weekly seafood displays and vendors. Since the chain is consumer or demand-driven as opposed producer or supply-driven, catch mostly fulfills local needs, relying on short trips without need for frozen fish or primary processing.

Value-chain actors for local staples such as snappers with limited opportunities for processing usually comprise of fisher and direct consumer; or through intermediaries to include vendors, primary processors and consumers. The chain is not necessarily linear, as some seafood is directly sold from fishers to hotels or restaurants especially for shellfisheries such as lobsters and conch. In this circumstance, Skipjack tuna can fetch $6 to 7 EC / pound from a vendor who will clean it, fillet it and sell it to local consumers for $9 EC per pound. Dolphin fish is sold for $8 EC to a vendor but if cleaned and filleted by fisher can fetch from $10-12 EC from hotels and restaurants.

At high-end restaurants, grilled fish can compete with steak and lobster at the $40 to $50 EC range. About 80 to 90% of the local catch harvested goes through vendors with limited value addition and high level of post-harvest spoilage (Figure 6). The 10 to 20% that goes through the Fish Market is sold frozen, often filleted according to retail needs and in the form of weekly supplies to supermarket chains focusing on larger pelagics such as swordfish, barracuda, skipjack tuna and snapper.

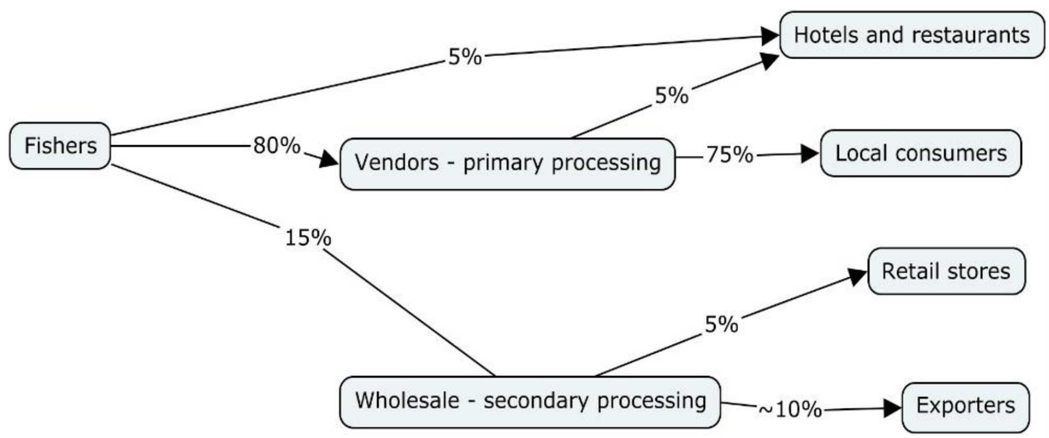

Figure 6: Schema of seafood flows by volume across the value chain in Kingstown, Saint Vincent and the Grenadines

Vendors who also do primary processing do better in terms of total revenue than vendors who sub-contract the cleaning and filleting. After expenses (e.g., stall fees), monthly earnings can range from $1,000 to 6,000 EC. The value chain in Kingstown (Saint Vincent and the Grenadines) was described by respondents as highly disconnected and fragmented with high level of operational and market risk as well as post-harvest loss. The level of risk and investment costs for fishers and vendors differ as the operational cost varies greatly for fish-chain actors. For fishers, the operational expense of fuel for longer trips is often not matched by an increase in landed value. Similarly, processing requirements and warehouse needs for vendors require additional inputs especially under supply-glut seasons. Most times, after processing into fillet, about half of the fish are discarded, as reported by vendors (see Figure 7), creating loss but also an opportunity to process these into fishmeal for aquaculture, use as bait or pet food.

Figure 7: Photos depicting 'oceans to plate' for fresh fillet in Kingston, SVG: boat at sea (top-row left), multi-species catch (top-row middle), processors and workers at their stalls cleaning and sorting (top-row right), post-processing waste suitable for cat feed or fish meal (lower-row left), fish fillet for sale (lower-row middle) and finally the dinner plate (lower-row right)

Value chains with multiple actors and mechanization: In Jamaica, the fish chain is multi-faceted depending on the fish species, ecosystems in which fishing takes place, targeted markets and enabling policy environment for local consumption or export markets (see Figure 8). Currently, fishers are interested in a wide variety of commercial species of importance including snappers, parrotfish, conch, kingfish, dolphinfish, lobster and, to some extent, sea cucumbers. The value chain can be very short involving direct sales to households, such as for snappers or lobsters to the hospitality industry. For other commercial species destined for export markets such as conch, the value chain can be longer including brokers, processors, retailers, traders and/or exporters and with mechanized infrastructure. Most of the catch is traded fresh or, as in the case for crustaceans, sold on ice to improve product quality and freshness. Per trip, for instance, snapper can be sold locally for $600 Jamaican per pound (about 40 pieces average), yielding about 10 to 25% profit margin. Similarly, on average, conch will go for $500 Jamaican per pound from fisher to vendor, with similar profit margin. Lobsters are the most expensive, fetching $800 Jamaican per pound locally, next to Marlin and Skip Jack tuna at $600 Jamaican per pound. Parrotfish and snappers have the highest local value, often sold fresh and directly to consumers/households or to restauranteurs (ranging from $500 to 600 Jamaican per pound). These are local prices; market price varies for exports, depending on destination and the level of processing and value addition, and price or product substitution.

Fisheries in Jamaica is very important to coastal residents as it provides multiple livelihood opportunities in the harvesting, processing, marketing, transportation, food catering, restaurants and hotels and allied hospitality industries. A key feature in Jamaica's fish chain is the location and operations of one of the largest seafood processor and retailer in the Caribbean: Rainforest Seafoods. Rainforest Foods also has major processing infrastructure and operations in Saint Lucia, Belize and Barbados, with planned operations in Saint Vincent and the Grenadines.

In contrast, limited opportunities exist for small-scale processing and value addition, with no option toward fillet or beheaded products, frozen or salted or smoked seafoods. The biggest challenge raised was financing small-scale ventures in local processing and marketing. This can be facilitated by the use of cold storage trucks and the creation of local brands with sustainability standards such as seen with hook and line fishers in Seychelles (Khan and Amelie, 2015). Such a model can increase product differentiation, adding value to the minimal catch, and exploring market access to the European Union and North America.

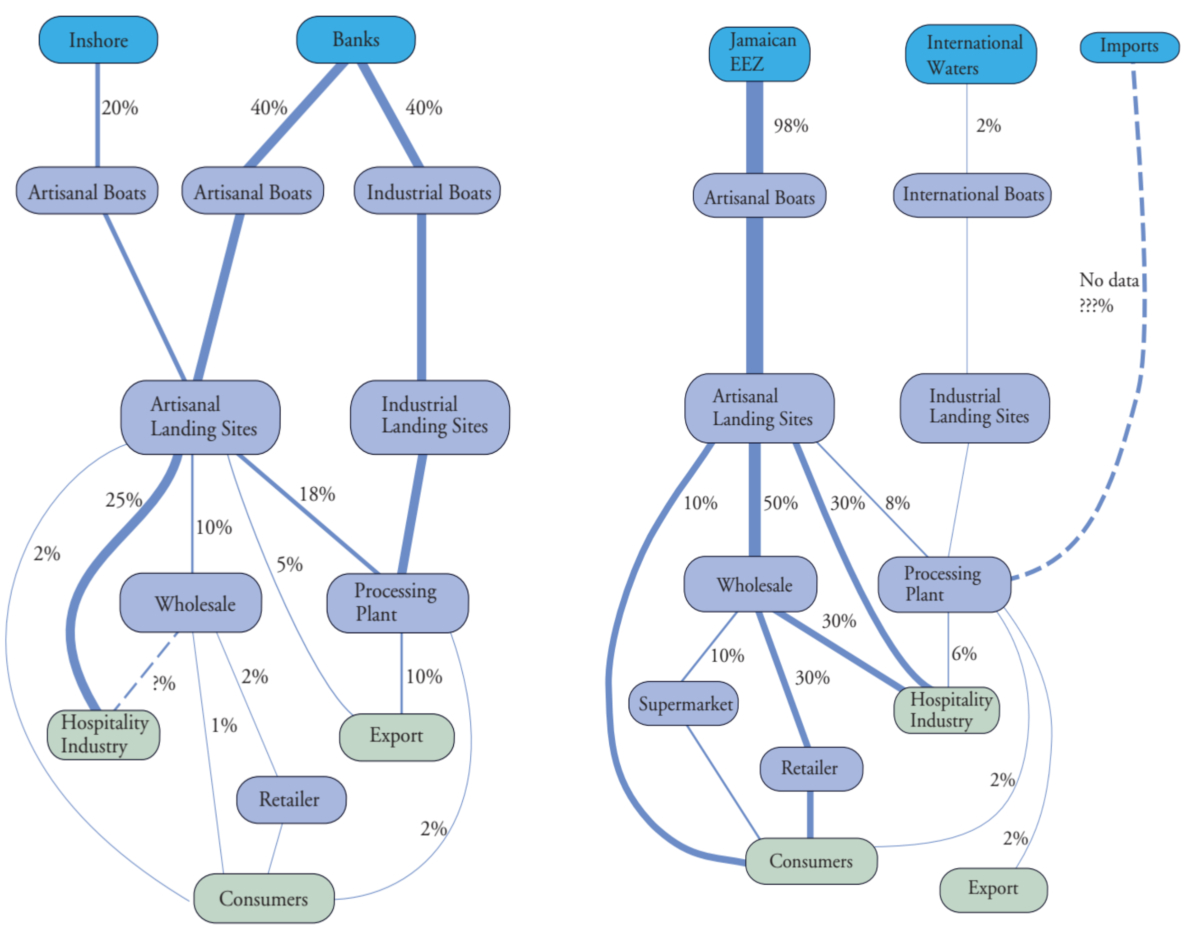

Figure 8: Value chain dynamics and linkages for offshore pelagics (Left) and lobsters (Right) in Jamaica (Source: CFRAMP 2000)

Self-organization through cooperatives could help address resource-supply issues and the financing of the development of fish value chains. The Whitehouse Fisher Cooperative (in Jamaica), for instance, is one of several cooperatives seeking support for processing infrastructure at the community level as well as leadership training to assist in livelihood diversification and building of local supply chains. Interviews with restauranteurs and representatives of the hospitality industry underscored the importance of these cooperatives and the seafood industry to their business operations and for locally-sourced fish product. Seafood is presented in many culinary forms with various price premiums for specific species. Menus can include one or all of the following seafood preparations: pan-fried, brown stew, roasted, steam with okra (local delicacy), escovitched, and curried. There are also prospects for 100% utilization and "zero waste" approach through primary and secondary processing (fillet, smoking, adding flavors such as curry and tobacco sauce) and making pet foods or fish feeds for aquaculture farms.

For the semi-industrial sector in Jamaica, reliance is on high-value commercial species including crustaceans (conch, lobsters, and scallops), as well as snappers. Product innovation is part of corporate strategies, as bigger companies have more resources to attend seafood expos (e.g., the Boston and Brussels seafood expos) and seek brokers to assist in financing and market access. This creates a vast marketing opportunity to enhance product differentiation via seafood imports and repackaging, export of live products, locally cooked and dried products, as well as canning. For instance, blast frozen and vacuum-sealed products are now common Jamaican exports targeting specific market niches, such as for sea cucumbers. This is made possible through government support in meeting European Union standards through accredited laboratories to test and develop traceability and chain of custody rules through Vessel Monitoring Systems as well as to ascertain the absence of tick-borne diseases. Interviews with government officials and industry stakeholders highlight the need to up-scale operations and develop the human resources and skills for eco-certification schemes such as the Marine Stewardship Council (MSC) certification. Although training is available, other concerns include market access post Brexit, and the sustainability of the public-private-partnership between the Conch Export Savings Scheme (CESS) and the Ministry, which has financed most of these value chain innovations.

4 ANALYSIS AND DISCUSSION

Resilient fisheries require climate change consideration in management measures as well as improvements in disaster risk reduction of essential coastal infrastructure. The value chain approach for social-ecological resilience highlights how raw material supply can be affected by changing environmental conditions and stock migration, which will have domino effects on stakeholder interactions, product differentiation, seafood security and markets. Moreover, increasingly severe storm events have impacts on coastal fisheries aquaculture. Thus, the analysis and discussion focuses on three major themes of consequence to livelihood security and the viability of the sector: i) governance along the fish chain, ii) enabling conditions to promote policy integration of adaptation and fisheries management and iii) locally-based capacity for adaptability and resilience.

4.1 **Governing Resilience along the Fish Chain**

Integrated approaches such as coastal zone management (ICZM) are imperative for complementarity between conservation and well-being. There is a need to develop synergistic interventions for fisheries to intersect with adaptation planning and other sector planning such as tourism, watershed management, and disaster risk reduction. Although knowledge about the impact of climate change on fisheries and seafood production is growing, integrating multi-level and cross-sectoral synergies can often take time and require technical and financial resources. Efforts to make linkages between ecological productivity and climate risk in the Caribbean have been initiated at the regional level, through CARICOM and its advisory units such as the Caribbean Regional Fisheries Mechanism (CRFM). There have been various scientific assessments and policy inputs into climate variability and fisheries impacts (McConney *et al.*, 2016), as well as projects and programs implemented in various countries. The United Nations Development Program /Global Environmental Facility project on the Caribbean large marine ecosystems (CLME+[30]), for instance, is uniquely poised to support climate resilience as well as leverage policy support toward regional fisheries organizations. Moreover, regional and national initiatives with the University of the West Indies regarding climate information services and early warning have been helpful in developing emergency response tools (e.g., FEWER App that was commissioned by the CRFM-led marine sub-component of the PPCR Project) and crowdsourcing data and citizen science for community resilience. New initiatives are underway to respond to socio-economic vulnerabilities through training on seafood standards and quality, exploring insurance and disaster readiness (CRFM, 2018, CCRIF, 2011).

[30] CLME+ https://www.clmeproject.org/

Mainstreaming adaptation into fisheries management is a challenge owing to sectoral silos as well as the demanding requirements for National Adaptation Plans (NAPs) under the UN Framework Convention on Climate Change (UNFCCC). In Saint Vincent and the Grenadines the fisheries sector and coastal resources are two of twelve priority sectors for NAP integration. Given that more extreme events will affect major coastal sectors such as fisheries and eco-tourism, this provide a rationale to address employment and livelihood opportunities and to contribute significantly to the country's regional economic development. As such, the traditional Precautionary Approach, Ecosystem-based Management, and Adaptive Management approaches in fisheries for dealing with risks as espoused in Code of Conduct for Responsible Fisheries should be complemented within the NAPs. Cross-sectoral collaboration with the Department of Sustainable Development under the Ministry Finance, Economic Planning, Sustainable Development, and Information Technology is, thus, crucial for policy integration of fisheries management with adaptation planning and disaster risk reduction.

Critical infrastructure, such as ports, wharves and bridges, are already subject to damage and destruction from storms and coastal flooding, which can cripple the economic fabric of society; identifying levers to address these collateral impacts is essential. Disconnects between place-based adaptation planning and sector-based fisheries management necessitate appropriate entry points for integrated adaptation responses and monitoring. These can be achieved through evaluating stock health and critical habitats in the pre-harvest ecosystem stage, protecting essential infrastructure in the harvest stage and securing livelihoods in the post-harvest stage (Figure 9). These entry points provide the necessary enabling platform to (a) engage in citizen science and co-management with fishers for protected areas; (b) achieve product differentiation and processing infrastructure; (c) develop and enforce zoning by-laws for vulnerable coastal regions (e.g., at the Parish level in Jamaica); (d) expand protection and insurance to manage risk related to coastal infrastructure, and (e) facilitate the functioning of cross-sectoral working groups at multiple levels, as in Jamaica.

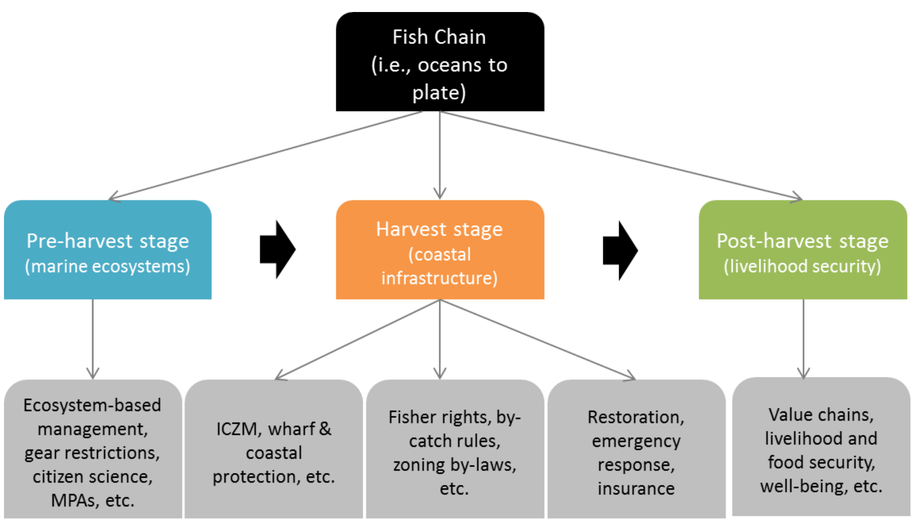

Figure 9: Climate policy integration with fisheries management for resilience building (Khan et al. 2016)

Regional Fisheries Organizations (RFOs) and other complementary regional cooperation entities are institutions with the potential to enable sustainable management of regional stocks in the face of fish-stock migration due to climate stressors. However, addressing the migration of straddling stocks across Areas Beyond National Jurisdiction (ABNJ) under climate change impacts could present new challenges due to illegal, unregulated and unreported (IUU) fishing. New governance models such as the Parties to the Nauru Agreement might present opportunities for collection action and joint management approach recognizing common interests and sovereign access rights. A resilient outcome to attain is policy integration between fisheries management and climate adaptation as well as meaningful regional collaboration on ecological conservation, sustainable economic development and livelihood security.

4.2 **Enabling Environment**

Creating the right enabling environment for stakeholders to self-organize through policy reforms and incentives is necessary for building social and ecological resilience. Fishers and processors are highly attuned to the need to create sanctuaries and marine reserves to protect critical habitat and to augment raw material supply. However, changing environments due to warming oceans are likely to affect habitat suitability and stock-migration patterns. In this dynamic context, what types of access rights and harvesting strategies within and beyond national jurisdiction might work for highly migratory species? Moreover, for sedentary stocks like crustaceans, how can citizen science and joint management measures protect stocks and secure rights of fishers?

To date, synergies and complementarities achieved between National Adaptation Plans, multispecies fisheries management plans, and integrated management appears promising. The Working Group on climate change and fisheries in Jamaica is an exemplar of creating complementarities in National Adaptation Plans as well as in Fisheries Management Plans. The institutional silos and top-down approach to fisheries management and climate adaptation makes cross-sectoral partnership challenging and daunting. Because fisheries are often associated with poverty (Bene, 2003), as in the case of small-scale fisheries, social safety nets and secured rights of access are important in promoting stewardship and community-based adaptation approaches. As the importance of small-scale fisheries becomes topical in terms of societal contribution and policy formulation (Svein and Chuenpagdee, 2015) so too does the need to identify adaptation co-benefits with fisheries through various fiscal instruments such as small loans, value addition, access to markets and insurance schemes (CCRIF, 2011). Such incentive-based approaches create legitimacy and empowerment for conservation efforts and citizen science and foster initiatives such as beach nourishment, mangroves restoration and reforestation, as well as ownership of protected areas. National and regional efforts toward insurance schemes and micro-credits through cooperatives and co-management arrangements could further strengthen the resilience of fisheries systems. In 2015, a risk insurance initiative for fishers, the Caribbean Ocean Assets Sustainability FaciliTy (COAST) was launched to support incentive-based insurance schemes that would promote climate-smart food security practices within the fisheries sector of Caribbean countries. This has supported the development of both a parametric insurance product for Caribbean governments and also a livelihood security protection product for individual fishers that are to be launched in the near future (CRFM, 2019).

Resource users and government officials agree that the effective use of fiscal incentives and inclusive policy instruments can act as enablers to promote socio-ecological resilience. In many instances, these policy spaces and brokerage involve non-governmental organizations (NGOs) who foster stewardship and branding opportunities for key actors along the chain (e.g., MSC, Blue Ventures, WWF, etc.). Self-organization by resource users such as in cooperatives and fisher associations are instrumental for creating co-governance schemes that can help strengthen the adaptive capacity for vertical and horizontal integration. From Alaska salmon coops, to Seychelles Hook and Line fishery, to Maldives Pole and Line tuna fishery, all demonstrate the role of policy brokerage in securing market access, eco-certification and enhanced revenue for their seafood products.

The sale price of fish by pound is fixed in many Caribbean countries (as noted in Jamaica and Saint Vincent and the Grenadines), irrespective of the quality and nature of operational and variable costs. These conditions affect the operational costs for various stakeholders especially regarding fuel hikes or the need for storage or cold rooms or refrigerated trucks. Exploring price-setting options that act as incentives for quality standards and market risks are necessary. Options can be explored through a marketing board, price-setting panel, or a joint association of fishers and processors that can negotiate price floor or ceilings with some criteria on standards as incentives for upscaling. Technical working groups and taskforces have also been influential in creating the space for cross-sectoral initiatives relating to fiscal incentives and insurance, multi-user spatial planning and protected areas, as well as training and capacity building. The new international airport and the processing capacity at the Kingstown Fish Market provide a unique opportunity for Saint Vincent as a regional hub for seafood value addition. Moreover, a zero approach to post-harvest waste could include product differentiation (breading, dried fish, canning, blast freezing, fish balls, fish oil, etc.) as well as the production of fish feeds for aquaculture or pet feeds to reduce underutilization.

For ABNJ and tuna stocks that migrate or straddle under climate change impacts, regional institutions such as the International Commission for the Conservation of Atlantic Tuna (ICCAT) have better mandate and capacity to address governance challenges of allocation and harvest rules. The Parties to the Nauru Agreement (PNA) model is uniquely interesting to the Caribbean small-island developing states (SIDS) context as it is MSC certified and generates enough revenue for the countries involved in Oceania. The PNA model uses vessels at sea schemes with a total allowable catch that is allocated to participating countries and tradable rights using purse seines and long liners. Through a spirit of cooperation and value addition for canning and tuna processing, this eight-member state model maintains interests in increasing revenue through innovation. The purse seine tuna fishery for skipjack tuna alone has increased its revenue base from US$ 60 million to close to half a billion in the past seven years. Although the Caribbean is not as productive as the Pacific island nations in terms of tuna stock biomass, the joint management model can be instrumental towards collective action and regional cooperation towards resource sustainability.

For stocks that straddle two jurisdictional boundaries, bilateral agreements such as the International Pacific Halibut Commission model is ideal, which involved an international treaty between Canada and the US for transboundary stock management. However, the biggest challenge in transboundary stock agreement under climate uncertainties is negotiating the value-laden questions about access rights, transferability, durability, and common property (Bromley, 2002; McKay, 1987).

4.3 **Local Adaptability and Resilience**

Coping, adapting and being resilient are all responses to vulnerability reduction. In Jamaica and Saint Vincent and the Grenadines, there is a strong sense of community spirit to cope with and adapt to shocks through formal and informal mechanisms and institutions. Through self-organization of fishers and community members, local cooperatives have been instrumental in creating a sense of community and adaptive response to issues around loss and damage of boats, gear repairs, localized early warning signals through horns to storm surges, and weekly contributions toward insurance schemes. The Half Moon Bay cooperatives in Hellshire (Jamaica) are a unique venture with 40 years of fisheries and tourism-related operations and have contributed to multiple initiatives including building breakwaters for disaster risk reduction and coastal resilience. The funds were raised from community members to build the groyne; create artificial reef and construct another breakwater to reduce on potential coastal disasters.

Potential interventions through government or private-sector assistance could include developing multi-user coastal plans and training in support of community enterprise development. Strong social cohesion and kinship ties have, in the past, spurred action toward management of coastal erosion, fisheries management and habitat protection, improvements to human settlements and urban planning. Kinship ties and personal savings still present the best option to deal with risks. Various community and stewardship initiatives were identified by fishers in Clare Valley, Saint Vincent and the Grenadines, involving marine parks as well as taking part in emergency rescue and safety through radio communication programs.

The experiences of fisher cooperatives in Grenada and Saint Lucia illustrate a new era for fishers, where fishing does not equate to poverty nor is the job of last resort; instead, fishers are competitive and educated, take informed risks, can broker co-governing arrangements and can link to global industries. The Soufriere Marine Management Area initiative is an excellent spatial planning initiative brokered by community members that meet multiple goals from fishing, to marine conservation and eco-tourism (Pittman and Armitage, 2017). Similarly, community support and self-organization involving youth turning challenges with Sargassum mats as market opportunities speaks to institutional norms to address broader regional environment change.

4.4 **Conclusion**

Building resilience in fisheries requires attention to both ecological (including stock health and migration patterns) and socio-economic dimensions, including livelihoods and contributions to the economy. The value chain is a conceptual and analytical approach to assess production and productivity from raw material supply in the marine ecosystems to harvesting strategies, fishing activities, processing and marketing. The production chain is not static but complex and dynamic with various actors, multi-species, and markets that require coordination and synergy with external threats such as climate change. To assess risk and the effectiveness of responses, sustained monitoring of the state of key indicators across the fish chain is important (see Appendix 4), although investments in monitoring beyond project-based work can be difficult to justify in the face of urgent demands. Synergies and complementarities between fisheries management and climate adaptation planning is crucial within integrated management approaches in coastal and marine spatial planning. Various enabling conditions are required to achieve effective integration, including fiscal incentives and inclusive governance mechanisms that foster community-based action. This is of crucial policy significance as marine ecosystems and coral reef fisheries provide tremendous socio-economic benefits, including access to seafood, employment to over 20,000 fishers and livelihoods in a country like Jamaica, and export earnings.

Fostering collaborative ties among fishers and processors through cooperatives for value addition and marine stewardship is necessary for traceability and eco-labeling as well as for market access and price premiums. Moreover, multi-level arrangements and directives toward critical habitats and essential infrastructure are important for building policy networks and self-organization for social change, insurance toward loss and damage, and governance arrangements for stocks beyond national jurisdiction. The findings in this study and others that adopt systems approaches have implications for setting harvest rules, developing cross-sectoral partnerships and empowering resource users to be adaptive and resilient in the face of climate change.

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7 APPENDICES

7.1 Appendix 1: Examples of Indicators and Metrics for Monitoring Sustainability, Risks and Resilience using Baseline and Targets

	Indicators and metrics
Pre-harvest stage (Marine ecosystems)	Maximum catch potential
	Habitat suitability indices
	Ocean acidity or pH
	Stock migration range
	Fish stock index
	Marine Trophic index
	Area of Marine Protected Area (MPA)
	Patchiness
	Sea Surface Temperature (SST), etc.
Harvest (fishing activities)	Fishing effort (days at sea, fuel use, etc.)
	Fleet types and characteristics
	Total Allowable Catch (TAC)
	Landings
	Seafood consumption
	Net production
	Export and import
	Fishing as % household income
	Asset loss and damage
Post -harvest (processing and marketing)	Landed value
	Ex vessel price
	Viability (economic/profitability/etc.)
	Changes in operational cost
	Return on Investment (ROI)
	% value addition
	Market destinations, etc.
	Consumer preferences

7.2 Appendix 2: Consent Form

Dear interview respondent:

Thank you for your participation in this project relating to seafood value chains and socio-economic impact of climate change. This research project aims to improve availability and use of information for "climate-smart" planning and management in the fisheries and aquaculture sector in the Caribbean. The project is funded by the Inter-American Development Bank and undertaken by **ESSA Technologies** in collaboration with the **University of West Indies** and the **Caribbean Regional Fisheries Mechanism (CFRM)**.

The seafood industry is highly vulnerable to global change with ecological and socio-economic concerns that requires collective action from stakeholders in government, private sector and civil society. Through the *"Fishery-Related Ecological and Socio-Economic Impact Assessments and Monitoring System"* project, we hope to provide the evidence base on impacts and policy responses for resilient development in the Caribbean region recognizing the contribution of fisheries to nation and local economies. Specifically, we are interviewing stakeholders at the community level across the "fish chain" on how best to integrate seafood vulnerabilities into fisheries resource management and national adaptation planning processes. The purpose of these stakeholder interviews is to monitor and develop climate response strategies at the community and national levels on ecosystem-based and resilient development outcomes.
We are contacting you today to see if you are willing to be an interview participant. Your knowledge and experience on these issues is valuable in contributing to our research objectives. The list of people we are calling upon for these interviews is based on background research we have conducted as well as suggestions from participants and community stakeholders. **If you agree to participate, the interview will take about 45- 60 minutes. You are free to participate or not participate, you may decline to answer any question put to you, and you are under no obligation to explain or justify your decision**.

There are individual and collective risks and benefits about this kind of applied policy research. Participants' real name or views gathered in the interviews will not be used except if they wish to do so and with their permission. Furthermore, all the individual responses will be destroyed at the end of the research. The potential benefits are the opportunities you will have to influence the findings from this research and contribute to securing livelihoods and sustaining economic development under climate change impacts in the Caribbean. There are potential collective benefits associated with documenting multiple perspectives on seafood vulnerabilities and adaptation planning. These pluralistic views are useful in exploring adaptation options and conservation incentives for stock migration and climate change impacts. Collective benefits lie in improving stewardship and value-addition opportunities through governance mechanisms.

We are very grateful that you are willing to participate and share with us your experience and invaluable knowledge. Together with our project partners, we intend to present preliminary results from this research at community events. This will give people like you an opportunity to comment on the research and to identify any gaps or incorrect information. **Stakeholders who participate in the study will receive a copy of the final report and will have the opportunity to influence such regional and national engagement processes on how best to monitor and manage fisheries under climate uncertainties.**
If you have any questions or would like further information about this study, please contact:

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7.3 Appendix 3: Selection of Pilot Study Sites

The Terms of Reference for the Fishery-Related Ecological and Socio-Economic Impact Assessments and Monitoring System project ("the project") called for the selection of and focus on "pilot study sites". Based on Project Team discussions with the CRFM Secretariat and budgetary considerations, we propose to undertake localized project activities at up to three pilot sites. This memo describes the purpose of pilot study sites, selection criteria, evaluation of the potential sites, and recommendations for site selection. Based on the selection criteria and evaluation, the three proposed sites are (1) Montego Bay (Jamaica); (2) Kingstown (St Vincent and the Grenadines) and (3) Roseau (Dominica).

7.3.1 Purpose

Pilot study sites within the six countries with Pilot Program on Climate Resilience initiatives serve three purposes. First, they are areas on which to test the implementation of the eventual monitoring system. Second, the focus on pilot study sites provides a practical bounding for project activities pertaining to assessment (data collection for the value chain analysis) and communications (target audiences for the Knowledge-Attitudes-Practice study). As discussed in the Inception Report, layering project activities in the same three pilot study sites provides efficiencies, continuity, and greater potential to usefully integrate project components and promote sustainability of project results. Third, although the scope for primary data collection within the project parameters is limited, strategic data collection at the site level will yield valuable information on climate-related risks and appropriate policy responses from the local to national levels.

7.3.2 Criteria

In selecting pilot project sites "country make up" was a first consideration. St Vincent and the Grenadines, Saint Lucia, Dominica and Grenada are in the Lesser Antilles / Eastern Caribbean and are a part of the Organization of Eastern Caribbean States (OECS). These countries share a number of similarities that can be attributed to their geographic proximity, and socio-political, historical and linguistic background. Jamaica and Haiti are larger islands in the Western Caribbean, with Jamaica sharing some of the socio-political, historical and linguistic background of the OECS countries and Haiti presenting language differences (French/ Creole) and known deficiencies in official data. Given that we are limited to three pilot study sites to be selected from two countries in the Western sub-region and four countries in the Eastern Caribbean, it is reasonable to select one site in the Western Caribbean and two in the Eastern Caribbean.

Further to this first consideration, we used the following selection criteria to help us identify sites with the potential to maximize learning:

1. Representativeness (critical habitats - mangrove/seagrass ecosystems, reliance on fishing, etc.);
2. Strong coupling of ecological and social systems to understand feedbacks;
3. Ecological connectivity (stocks, habitats, inshore and/or offshore migration, etc.);
4. High contribution of / reliance on fisheries to food security, commodity trade, livelihoods, etc.;
5. Vulnerable of coastal infrastructure and assets (e.g. port, fishing wharf, processing plant);
6. Level of stakeholder interest in climate resilience;
7. An environment that is conducive to undertaking field research / engagement in a way that is socially inclusive and supportive by the state and local authorities;
8. Potential access to a wide range of knowledge holders for interview / focus group (fisher folk, fishing cooperatives, fish vendors, fish processors, fisheries officers, policy makers);
9. Data availability for assessment purposes; and,
10. Accessibility for field work (transportation, safety and security, cost effective, etc.).

7.3.3 Options

The following table gives a score for the various criteria (high, medium and low), based on the Food and Agriculture Organization (FAO) country profiles[31] and a preliminary review of the literature.[32] (Table 1).

Country and site location		**Selection criteria**										**Total score**
		Representation	**Coupling**	**Connectivity**	**Reliance**	**Vulnerability**	**Interests**	**Conducive**	**Knowledge**	**Data**	**Access**	
Jamaica	Montego Bay	3	3	3	3	3	3	3	3	2	1	**27**
	Portland Bight	2	2	3	2	3	3	3	2	2	2	25
Haiti	Port-au-Prince	2	2	2	3	3	2	1	2	1	1	19
Saint Vincent and the Grenadines	Kingstown	3	3	3	3	3	3	3	3	2	3	**28**
Saint Lucia	Soufriere	3	3	3	2	2	2	2	2	2	3	24
Dominica	Roseau	2	3	2	3	3	3	2	2	2	3	**25**
Grenada	Carriacou	3	2	1	3	2	2	2	3	2	2	22

Table 1: Candidate pilot study sites and scores against 10 criteria (where 1 is low and 3 is high)

Two summary charts are also provided, one with some biophysical features and the other with socio-economic attributes.

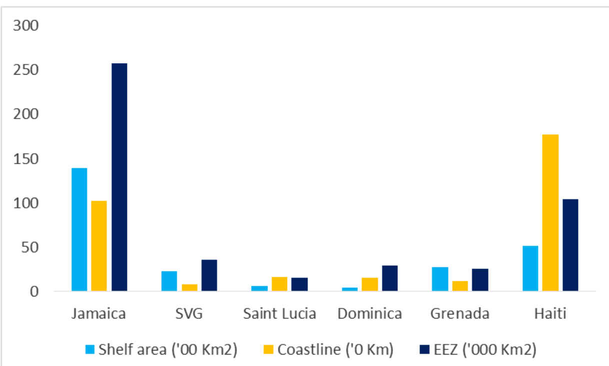

Figure 1: Non-variable geophysical features of participating countries (Source: FAO)

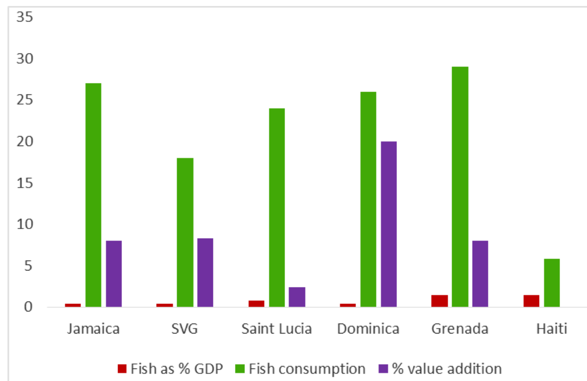

Figure 2: Varying socio-economic attributes of participating countries (Source: FAO)

Jamaica has the largest shelf area and economic exclusion zone of the six countries, whereas Haiti has the longest coastline. Among Eastern Caribbean states Saint Vincent and the Grenadines and Grenada present similar characteristics in terms of shelf area, areal extent of the economic exclusion zone and coastline length. With regards to socio-economic attributes, the fisheries sector is a greater contributor to gross domestic product in Haiti than in Jamaica. However, levels of fish consumption and value addition are

[31] http://www.fao.org/fishery/countryprofiles/search/en

[32] This includes: CMEP (2017) Caribbean Marine Climate Change Report Card 2017. (Eds. Paul Buckley, Bryony Townhill, Ulric Trotz, Keith Nichols, Peter A. Murray, Chantalle Clarke-Samuels, Ann Gordon, Michael Taylor). Commonwealth Marine Economies Programme, 12pp.

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significantly greater in Jamaica than in Haiti. Within the Eastern Caribbean, fish consumption and sectoral contribution to GDP are highest in Grenada, with value addition being most significant in Dominica.

7.3.4 Recommendations

As shown in Table 1, the top-ranked sites of interest are **Montego Bay** in Jamaica; **Kingstown** in SVG; and **Roseau** in Dominica. Montego Bay in Jamaica is the top-ranked site in the Western Caribbean and we recommend undertaking project activities in that site for the following reasons:

- Montego Bay is highly coupled, with Marine Protected Area (MPA) and mangrove ecosystem linkages and reliance of seafood for both local consumption and export markets. Sufficient secondary data exist. There is strong stakeholder interest in climate change, not to mention the availability of sea-level rise and loss and damage estimates for coastal infrastructure. In addition, the Project Team has access to institutional and logistical support in Jamaica, since two team members are based there (including a professor at the University of West Indies, Mona Campus), as is the Project's executing agency (the Mona Office for Research and Innovation at the University of West Indies).
- In Haiti, reliance on fishery resources is high, owing to the strong connectivity to the reefs and vulnerability of the sector's infrastructure assets is also high. However, most of the management measures are not operational, due to capacity constraints and declining health of the reefs. There is also a growing aquaculture industry, which decouples marine social-ecological connectivity and places more reliance of fish farming mostly tilapia. Data availability is a known constraint.

Within the Eastern Caribbean, we recommend Kingstown and Roseau as the pilot study sites in which to undertake project activities for the following reasons:

- Kingstown (St Vincent and the Grenadines) is a good starting point for the socio-economic assessment as more than 50% of the national catch is marketed through the Kingstown Market Complex, a modern facility and processing hub for regional exports and global trade. There is also a strong inter-regional fish trade with most of the catch exported fresh to Martinique. This site scores highly against selection criteria of representativeness, connectivity and coupling, as does Soufriere in Saint Lucia. In Kingstown, however, the Project Team can count on additional institutional support from the CRFM Secretariat.
- Roseau (Dominica) is a favoured candidate site due to the processing and trade dimensions and the potential to explore livelihood synergies within that context. The key marine ecological reserves, such as Scott's Head, require travel by car but the travel distances are manageable and do not present challenges to conducting the work. Taking a closer look at Dominica in general has the potential to yield important lessons on assessment needs, data and monitoring requirements to enable the sector's preparedness for, response and recovery from major hurricane devastation. Dominica has also committed to becoming the world's first climate resilient nation, which means that interest among stakeholders is high, especially in the aftermath of the serious damage caused by Hurricane Maria.

7.4 Appendix 4: Breakdown of Interviews and Focus Group Discussions

Jamaica

1. White House Cooperative Fishers, Montego Bay Jamaica
    a. Omar Dickson
    b. Davis Boysie
    c. Kenneth Gibbs
    d. Errol Brown
    e. Upton Gordon
    f. Harold Austin
    g. Allan Austin
    h. Kemar Gibbs
    i. Lenford Blake
    j. Ian Reid
    k. Norman Turner
    l. Clifford Maxwell
    m. Rowan Williams
    n. Lascelles Samuels
    o. Donald Williams
    p. Joe Samuel
2. River Bay Fishers Cooperative
3. Government officials
    a. Mrs. Avery Smikle, Director, Aquaculture Branch
    b. Mrs. Kimberlee-Cooke Panton, Fisheries Officer
    c. Shaun Baugh, Principal Director, Planning Policy and Development
    d. Dr Kevin Walker, Veterinary Services Division
4. Seafood industry
    a. Seafood One Limited
    b. Rainforest Seafoods Limited
    c. Hellshire Vendors
    d. Ton-Rick Enterprises Ltd.

Saint Vincent and the Grenadines

5. Government officials
    a. Hayden Billingy, climate change and disaster risk scientist, FAO
    b. Trelsom Mapp, Central Planning
    c. Shermine Glynn-Johnson, Division of Fisheries
    d. Kris Isaacs, Division of Fisheries
    e. Dunstan Johnson, New Kingstown Fish Market (Former Manager)
    f. Keith Howard, Owner of KP Marine (Fish Supplies shop)
    g. Winfield Tannis, Former Chairperson, Fisherman's Day Committee
    h. Alrack Rauggette
    i. Joy Johnson
    j. Mark Lall
    k. Joseph Cruickshank
    l. Alisa Martin, Fisheries Officer, Quality Assurance Unit, Division of Fisheries
    m. Carlina Laborde Edwards, Fisheries Officer, Quality Assurance Unit, Division of Fisheries

6. Fishers, restauranteurs, and vendors
    a. Phillon Joseph, fisher, Clare Valley
    b. Winston Charles, fisher, Calliaqua

   c. Maclean Bruce, fisher, Clare Valley
   d. Samuel George, crew member, Calliaqua
   e. Cornelious Bristol, restauranteur and chef, Kingstown
7. Kingstown Fish Market
   a. Ferique Shortte, Manager, New Kingstown Fish Market, Agriculture Input Warehouse Ltd
   b. Kevin Lewis, processor, Kingstown
   c. Eocen Victory, Fisher cooperative lead, Kingstown
   d. Samuel Francis, fisher, Kingstown
   e. Williams Laverne, vendor, Kingstown