A climate vulnerability assessment for Caribbean recreational fisheries

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Executive summary

Recreational fishing is a pillar of the multibillion-dollar tourism sector in the Caribbean, supporting economic development and community livelihoods. However, as climate change drives rapid shifts in habitat suitability in the tropics, key recreational target species may be vulnerable to declines. There is a critical need to project climate change impacts on recreational species and the communities that depend on them, to prioritize adaptation and mitigation efforts that can build resilience.

We conducted a comprehensive climate vulnerability assessment for recreationally important fish species in the Caribbean. We focused our assessment on three “primary” recreational tidal flats targets in Belize and The Bahamas: bonefish (*Albula vulpes*), tarpon (*Megalops atlanticus*), and permit (*Trachinotus falcatus*). The recreational fishery for these three species supported more than $200 million USD in annual revenue and 9900 jobs across the two nations prior to the COVID-19 pandemic. In addition, we assessed the climate vulnerability of a suite of twelve “secondary” recreational targets, representing pelagic and reef fishes that provide additional opportunities within the recreational sector. We assessed species’ vulnerability by coupling a desktop review of climate change impacts and species biological traits with a participatory process to elicit the local expert knowledge of recreational fishing guides, resource managers and scientists.

Based on the desktop review, bonefish, tarpon and permit each exhibit very high vulnerability to expected climate change impacts in the next 30 years. This vulnerability is largely due to their reliance on sensitive inshore habitats (e.g., seagrass, mangroves and estuaries) that are exposed to the cumulative impacts of sea level rise, rising ocean temperatures and increasing storm damage, and non-climate stressors including coastal development and pollution. Most reef species also had very high vulnerability scores due to reliance on sensitive reef ecosystems, coupled with their restricted ranges and complex reproductive strategies. Pelagic species appeared somewhat less vulnerable to climate change due to their high mobility, and low overlap with nearshore climate stressors.

The expert stakeholder group highlighted the vulnerability of their fisheries to climate change and outlined a suite of adaptation and mitigation solutions to increase resilience. Stakeholders predicted a very high magnitude of climate change impacts in the Caribbean over the coming decades but perceived some key species including tarpon and permit as being somewhat less vulnerable than they were scored in the desktop assessment. The group identified measures to enhance resilience to expected climate impacts, including mapping key fishing and nursery habitats for protection and restoration; building formal communication mechanisms between fishing guides, managers, and scientists to share knowledge about changes in stock abundance and distribution; and identifying ways to strengthen governance and management of commercial and recreational fisheries.

Our work fills gaps in our understanding of climate vulnerability in the recreational fishing sector in the Caribbean and highlights how participatory processes can build capacity and collaboration toward the goal of identifying and responding to climate change impacts on fisheries.

Background

Climate change is posing serious and accelerating threats to tropical marine ecosystems and fisheries. Many tropical species live close to their thermal limits, and a mass redistribution of marine life is predicted as water temperatures rise and suitable thermal habitat moves poleward (Morley et al., 2018; Pinsky et al., 2021). This redistribution is expected to result in declines in stock biomass available to tropical fisheries (Cheung et al., 2010; Lam et al., 2016), and the complete loss of some species from the exclusive economic zones (EEZs) of tropical nations (Oremus et al., 2020). Furthermore, threats including more intense storms, sea level rise, ocean acidification, and run-off associated with changes in patterns of precipitation degrade important habitats including coral reefs, mangroves and seagrass beds (Heogh-Gulberg et al., 2007; Waycott et al., 2009; Sippo et al., 2018) which provide food and shelter for many tropical species at key life stages. In the absence of effective mitigation and adaptation efforts, these cumulative threats layered on top of other human-induced stressors such as overfishing, coastal pollution and shoreline development point to potentially devastating losses of income, food security, and livelihoods for millions of people in coastal and island communities throughout tropical regions (Lam et al., 2020).

Recreational fisheries are vital components of the economic and social fabric of tropical nations in the Caribbean, yet their future under climate change remains unclear. Recreational fishing can create greater economic value from lower fisheries biomass due to the added value that associated tourism activities bring to communities (e.g., transport, lodging, food and other provisions; Tufts et al., 2015; Fedler, 2019). For example, in The Bahamas, the recreational tidal flats fishing sector focused on bonefish (*Albula vulpes*), tarpon (*Megalops atlanticus*), and permit (*Trachinotus falcatus*), contributes $169 million USD to the Bahamian economy and supports 7800 full-time equivalent jobs (Fedler, 2019). When managed sustainably, recreational fisheries can have a lower impact on stock health than commercial fleets if catch-and-release requirements are in place and post-release mortality rates are low (Tufts et al., 2015). Recreational fishers can be environmental stewards, lending powerful support to habitat conservation and restoration efforts (Cowx et al., 2010). For these reasons, enhancing the recreational sector may provide opportunities for communities to bolster fishing livelihoods under climate change (Uddin et al., 2021).

However, recreational fisheries rely on high quality fishing experiences. The Caribbean is home to some of the most picturesque fishing locations in the world, and opportunities to catch some of the largest and most exciting sport fish in tidal flats, blue water and reef ecosystems (Fedler, 2010). Increased scarcity of fish due to a combination of climate change and unsustainable fishing practices, or habitat degradation arising from storms, dredging and development, could lead to a decline in the quality of fishing experiences and concomitant declines in angler participation and tourism revenue (Townhill et al., 2019). Better scientific understanding and targeted mitigation and management of threats to recreational species and their ecosystems will be necessary to maintain high quality recreational opportunities into the future. Additionally, developing demand and infrastructure to support sustainable fisheries tourism within communities, strengthening management and governance to increase sustainability (Arlinghaus et al., 2016), and minimizing leakage of economic benefits via empowerment of local operators, lodges, and guides can help bolster resilience of recreational fisheries under climate change (Sandbrook et al., 2010; Wood et al., 2013).

Identifying the vulnerability of key species to climate-induced declines in availability can help prioritize adaptation and mitigation efforts. While some impacts of climate change on species distributions, productivity, and survival may be unavoidable, some of the worst effects of climate change could be buffered by mitigation strategies and sustainable fisheries management practices (Gaines et al., 2018; Free et al., 2020). To guide these efforts, it is important to understand the magnitude of climate change impacts, and the relative risks that they pose to different fishery species. Climate vulnerability assessments (CVAs) are a common tool to understand the relative vulnerability of species to climate change. These assessments do not require precise numerical inputs or detailed knowledge about ecosystem interactions to make rapid, scenario-based predictions of how climate change may impact species. Instead, they require more general knowledge about species' functional traits that are likely to increase their sensitivity to climate stressors (Pecl et al., 2014; Hare et al., 2016). This makes conducting CVAs a useful first step toward understanding climate change impacts on fisheries and planning climate-ready multi-species management (Mamauag et al., 2013; Gaichas et al., 2014; Pecl et al., 2014).

While desktop assessments of climate vulnerability can be useful, they are often hampered by an incomplete picture of local climate conditions and species' ecology. Experts with local and experiential knowledge are likely to be among the first to notice climate change impacts "on the water" (Seara et al., 2020). This knowledge can fill key gaps in data-limited systems and refine scientific understanding of climate change and its impacts on marine ecosystems at local scales (Gianelli et al., 2021). More importantly, involving local experts including the fishing community can help to build a community of practice and increase capacity for assessing and responding to climate change impacts (Samhouri et al., 2019; Bulengela et al., 2020). This encourages an inclusive management approach that allows research and conservation priorities to be co-developed by stakeholders who are at the frontline of climate change, as opposed to management strategies that are imposed externally or strictly from management authorities (Karr et al., 2017). Ultimately, communities should be empowered to design and implement their own solutions to climate change that are in line with local stewardship practices and that manage the unique suite of tradeoffs relevant to a fishery's social-ecological context (Bulengela et al., 2020).

We conducted a climate vulnerability assessment for important recreational fishery species in the Caribbean. We conducted primary assessments for bonefish, tarpon, and permit, recreational species that have enormous economic and social importance in the Caribbean (Fedler, 2014, 2019). To assess how vulnerable these flats species are relative to other recreational targets, we also assessed twelve secondary species representing both pelagic and reef species groups. We first undertook a comprehensive desktop synthesis of available information on the expected magnitude of change in key climate factors, and an assessment of each species' sensitivity to expected changes via a review of key functional traits. We then convened a workshop in March 2022 with an expert multi-stakeholder group from Belize, The Bahamas and the United States consisting of local fishing guides, fishery managers and scientists. This group discussed and refined vulnerability scores from the desktop analysis, identified socio-economic implications of vulnerability in the fishery, and outlined a series of interventions that could be undertaken by governments and communities in Belize and The Bahamas to increase resilience in the recreational sector. Our work provides a new understanding of risks posed by climate change to diverse tropical fisheries in coming decades and is a first step toward developing stronger local capacity and preparedness within the recreational fishing sector to respond to these changes.

Methods

Desktop Climate Vulnerability Assessment

To assess climate vulnerability in Caribbean recreational fisheries we first conducted an extensive desktop assessment to score a) **climate exposure** – the expected magnitude of changes in ocean climate likely to be experienced by each species over the coming 30 years, and b) **species sensitivity** – biological traits that might increase species' likelihood of responding negatively to climate exposure (Hare et al., 2016). In this framework, attributes of adaptive capacity – the ability for species to cope, reduce or recover from the effects of climate change – are incorporated into species' sensitivity scores (e.g., Hare et al., 2016; Ramos et al., 2022).

Species selection
The focus of the assessment was the recreational 'flats' fisheries in Belize and The Bahamas. This fishery is dominated by catches of three species: bonefish (*Albula vulpes*), tarpon (*Megalops atlanticus*), and permit (*Trachinotus falcatus*). These fishes inhabit coastal tidal flats ecosystems including estuaries and mangroves, often school in large numbers during pre-spawning and spawning aggregations and are caught on light tackle in shallow water by recreational anglers. This fishery represents an industry of huge economic and social importance in both Belize and The Bahamas (Fedler 2014, 2019), and species are protected in both nations by rules requiring catch-and-release to reduce fishing pressure on their populations. Understanding the vulnerability of this fishery to climate change impacts, especially alongside other stressors including coastal development, dredging, and fishing pressure, will be important to help the sector build resilience to change.

In addition to these primary species, we also assessed 12 secondary recreational targets. These included six pelagic fishes: wahoo (*Acanthocybium solandri*), common dolphinfish (*Coryphaena hippurus*), yellowfin tuna (*Thunnus albacares*), king mackerel (*Scomberomorus cavalla*), white marlin (*Kajikia albida*) and blue marlin (*Maikara nigricans*), and six reef fishes: lane snapper (*Lutjanus synagris*), cubera snapper (*Lutjanus cyanopterus*), black grouper (*Mycteroperca bonaci*), Nassau grouper (*Epinephelus striatus*), blue parrotfish (*Scarus coeruleus*) and stoplight parrotfish (*Sparisoma viride*). These species were selected from a list of important or emerging recreational species identified by the expert group prior to conducting the workshop. Both parrotfish species were included due to both their ecological importance as coral grazers, and the fact that there is an emerging fishery for parrotfish in The Bahamas (Callwood, 2021). Although reef and pelagic recreational fisheries are less developed than the flats fishery in the Caribbean, these species are nonetheless both ecologically and commercially important, and are under varying degrees of both fishing pressure and regulatory protection, including in Belize's forthcoming national adaptive multi species finfish management plan (UNCTAD, 2022). Understanding their vulnerability to climate impacts alongside the flats fishery fills important knowledge gaps for this region and will ensure a more sustainable and holistic approach to management of the recreational fishing sector in the future.

Geographic scope

The geographic scope of the study was the region encompassing the Caribbean Large Marine Ecosystem (LME), extended to include the EEZs of Caribbean nations in the Atlantic, inclusive of the EEZs of The Bahamas and Belize (**Figure 1**). This regional approach was taken to encompass major oceanographic and ecological dynamics in the region. Despite this regional focus for assessing the physical and ecological impacts of climate change, the social and economic focus of the assessment was limited to Belize and The Bahamas. These two nations have different fisheries governance regimes, and these contexts are important for understanding and contrasting the ways in which species-level vulnerability to climate change may translate into outcomes for fisheries and fishery-dependent communities.

Figure 1. *Map showing the wider Caribbean region. The geographic scope of the climate vulnerability assessment was the Caribbean Sea LME (blue) plus the EEZs of Caribbean nations that extend beyond the LME into the Atlantic (red)*

Climate exposure factors

We scored 12 climate exposure factors that are likely to impact ecosystems and fisheries in the Caribbean: storm frequency, storm intensity, sea surface temperature, variability in sea surface temperature, coastal erosion, upwelling intensity, precipitation, ocean currents, sea level rise, dissolved oxygen, ocean acidification, and surface salinity. Where possible, the expected magnitude of change in these factors in the Caribbean was determined using CMIP6 ensembled global climate models (https://psl.noaa.gov/ipcc/cmip6/) forced by a “fossil fuel-based development" scenario representing about a 4.5°C change in global surface temperature by year 2100 (SSP5-8.5). The magnitude of change in each factor was calculated as a standardized anomaly value indicating their change over the coming 30 years (2020 - 2049) relative to a baseline for the previous 30 years (1990 - 2019) (see Hare et al., 2016 for threshold anomaly values used for scoring the magnitude of change). To supplement these projections and to score factors that are not represented in global climate models, we searched the literature for studies that described alternative model projections, or historical trends that we could use to infer the likely direction and rate of change over the coming 30 years. Scores were made on a scale of 1 (low magnitude of change) to 4 (very high magnitude of change).

Species sensitivity attributes
We scored 12 sensitivity attributes for each species following Hare et al. (2016): habitat specificity, adult mobility, dispersal of early life stages, early life history requirements, prey specificity, sensitivity to temperature, sensitivity to ocean acidification, reproductive complexity, spawning cycle, population growth and stock status. Attributes were scored on a scale of 1 (species trait confers low sensitivity to climate change) to 4 (species trait confers very high sensitivity to climate change) based on criteria developed in Hare et al. (2016).

Species overlap with climate exposure
To make climate exposure scores relevant to each species, we also scored spatial overlap between each species and each climate factor on a scale of 1 (low overlap) to 4 (very high overlap). We used information on species distributions and behavior to infer the degree to which a species was likely to be exposed to changes in a climate factor. For example, a species that relies on seagrass habitats for part or all of its life cycle is likely to experience a very high overlap with changes in sea level, while a pelagic species that spends its life offshore in deep water will show low overlap with the same magnitude of change in sea level. Regional exposure scores were modified by multiplying them with overlap scores, then final exposure scores for each species were rescaled from 1-4.

Participatory Climate Vulnerability Assessment Workshop

We assembled a group of 17 experts based in Belize, The Bahamas, and the United States who had expertise in recreational fishing, fisheries management, and/or fisheries and climate science in the Caribbean. This combination of "on the water" expertise and local scientific knowledge helped develop a comprehensive and complementary picture of climate change and its likely impacts on fishery species throughout the Caribbean, and of the impacts of these changes on outcomes for recreational fisheries and communities. This group was engaged in discussions around study design as well as community and capacity-building needs, before convening over the course of a two-day virtual workshop in March 2022 to exchange information on climate change impacts, contextualize and refine desktop vulnerability scores for key species, and identify challenges and opportunities for responding to climate impacts in Belize and The Bahamas.

Scoring and contextualization of climate vulnerability
We used several complementary approaches to allow workshop participants to provide their insights into climate exposure and species sensitivity during the workshop. In breakout

groups focused on capturing local scientific knowledge, we used a web-based polling tool (www.mentimeter.com) to allow participants to score 1) each regional climate exposure variable and 2) the sensitivity attributes of the three primary species (bonefish, tarpon and permit). Participants were presented with a summary of available scientific information from the desktop assessment for each factor and asked to score the factor between low (1) and very high (4), based on their interpretation of this information combined with their own personal observations or insights from other research. These scores were used to capture both the mean score and the range of uncertainty across participants for each factor. Comparisons are presented with the scores arising from desktop research to assess alignment of local knowledge and expectations with predictions from scientific literature and global climate models.

In breakout groups focused on capturing "on the water" local knowledge, we elicited qualitative narratives from guides and managers about observed climate change impacts in local areas, and descriptions of the distribution, habitat selection and behavior of primary target species (i.e., bonefish, tarpon, and permit). Participants were asked to reflect on desktop scores, with a focus on identifying which were the most concerning climate change impacts in their system, and the relative vulnerability of the three flats species. These narratives and observations are presented alongside numerical scores and provide important context for understanding perceptions of climate change impacts, particularly by recreational fishing guides.

For the 12 reef and pelagic species, workshop participants were presented with all six species from a group (i.e., reef or pelagic) visualized on a sliding scale from low to very high sensitivity for each factor (**Appendix 1**). Participants were asked to assess the sensitivity of each species along the sliding scale, and to offer additional information and recommendations that might help refine the scores. Participants were asked to focus on relative scores, i.e., making sure that the order of species along the scale seemed correct. Adjustments to scoring for secondary species made by stakeholders were directly incorporated into the final scores after a consensus had been reached.

Socio-economic implications of climate change impacts and strategies to increase resilience
Participants were divided into two groups representing Belize and The Bahamas for a structured discussion of the socio-economic implications of predicted ecological impacts and potential adaptation and mitigation measures (**Appendix 2**). As part of this discussion, participants were asked a series of questions to define what a "good day" of fishing and guiding looks like, what types of declines in the fishery would start to impact their livelihoods, and ways in which climate change has already impacted livelihoods. Each group then identified strategies to increase resilience within the recreational fishery and associated communities. This discussion included a series of questions to document immediate next steps and long-term options to mitigate the ecological and socioeconomic impacts and, where necessary, to adapt to a changing fishery (**Appendix 2**).

Results

Desktop Climate Vulnerability Assessment

Climate exposure
The desktop assessment highlighted expected changes in key climate variables in the Caribbean over the next 30 years, based on interpretation of global climate model output and a literature review. However, while there are some climate factors for which there is a relatively strong evidence base and scientific consensus (e.g., temperature, precipitation and sea level rise that are well-resolved by global climate models), much uncertainty remains regarding other dimensions of climate change (e.g., changes in ocean currents and upwelling dynamics). A summary of current knowledge regarding changes in climate exposure factors in the Caribbean is included below, and scores for each attribute are recorded in **Figure 2**.

Storm frequency and intensity
Storm damage already poses a significant threat to fisheries and communities in the Caribbean (Heck et al., 2021) and the region has been suggested as a hotspot of increasing tropical storm risk, with warming waters providing more fuel to power destructive storms. There is evidence that major tropical cyclones (i.e., Category 3 and above) have become more frequent in the Caribbean in recent decades, increasing at a rate of ~1 major storm per decade between 1980 and 2018 (Murakami et al., 2020; Vecchi et al., 2021). The probability of a storm exceeding the threshold required to designate it as a major hurricane has increased by 49% per decade between 1979 and 2017 (Kossin et al., 2020), and the probability of rapid and unpredictable intensification of individual storms has also increased (Bhatia et al., 2019). There is low certainty surrounding predictions of changes in storm activity in the future as a function of global warming (Vecchi et al., 2021), however the effects of storm damage on coastal systems are likely to be magnified by increased flood risk due to concurrent rises in sea level and changes in precipitation (Vosper et al., 2020) which will cause increasing damage to assets and infrastructure in the future (Mendelsohn et al., 2012).

Sea surface temperature
Mean sea surface temperature is predicted to undergo relatively extreme changes in the Caribbean over the next 30 years, based on the fossil fuel-based development scenario SSP5-8.5 from the CMIP6 ensemble of global climate models. Mean ocean surface temperatures are expected to rise by approximately 1^{o}C during this timeframe, relative to the mean across the historic 30-year baseline. An increase of 1^{o}C is significant relative to the range of ocean temperature variability observed in the past, representing more than four standard deviations from the 30-year mean. This continues a long-term warming trend in the Caribbean that is in line with recent increases in global sea surface temperatures (Glenn et al., 2015).

Variability in sea surface temperature
Global climate models predict that sea surface temperature will become slightly less variable over the next 30 years, exhibiting around 10% lower variability than was observed over the previous 30 years. This suggests that there is no evidence for a large, expected increase in heatwaves in this region, which can drive large changes in variability around the mean sea surface temperature.

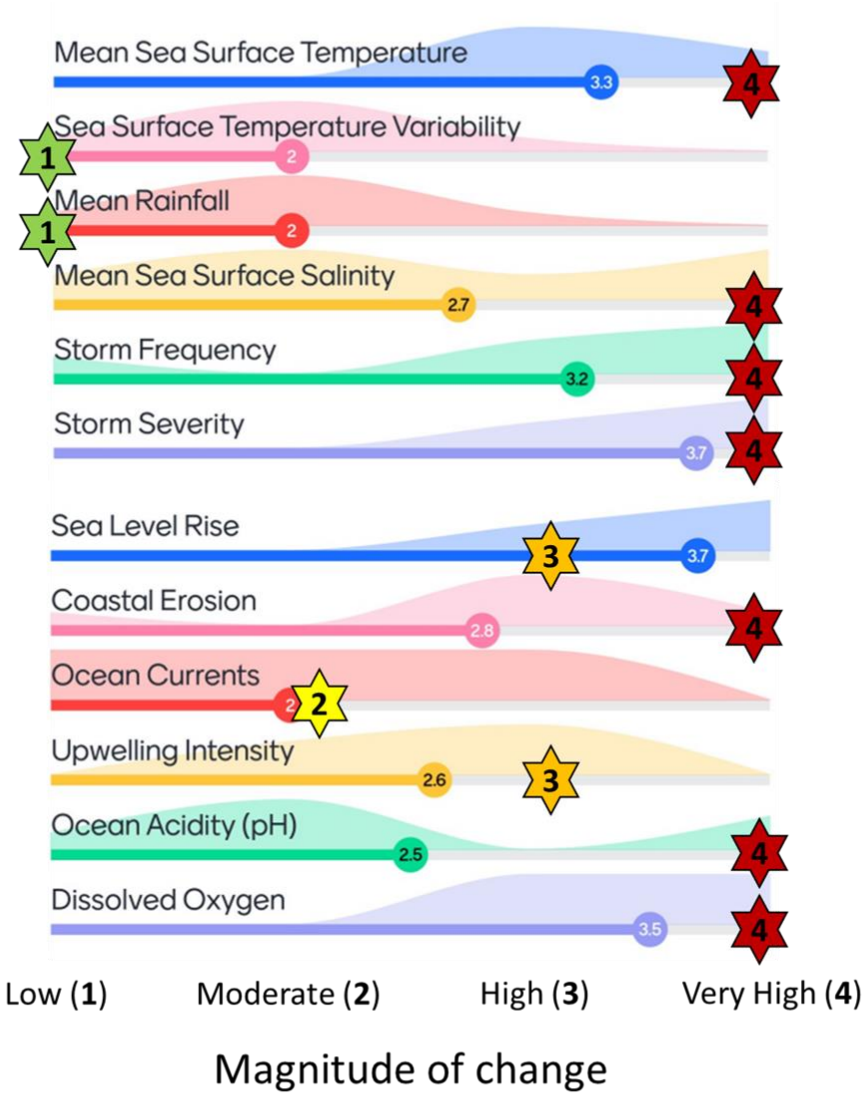

Figure 2. *Predicted magnitude of change in ocean climate factors in the Caribbean over the next 30 years compared to the past 30 years. Scores in stars represent scores made based on a desktop literature review, while scores in circles and shaded areas represent the mean and distributions of scores made by stakeholders during a participatory workshop.*

Coastal erosion

Coastal erosion can cause the destruction of nearshore habitats including tidal flats, seagrass beds and mangroves in many of the low-lying islands in the Caribbean (Gable, 1997) due, in part to the presence of soft, sandy sediments coupled with sea level rise and storm surge. For example, on the northeast coast of Cuba, beaches have retreated at 0.17m per year. At this rate, 14% of beaches will be lost completely by the end of the century, and 27% will be significantly reduced (Paneque & Finkl, 2020).

Upwelling intensity

Changes in the intensity, duration, and timing of upwelling events can have major impacts on the productivity of marine ecosystems. Upwelling intensity has decreased over recent decades in the Cariacos basin, Venezuela, apparently due to a decline in upwelling-favorable wind stress linked to large-scale climate change (Taylor et al., 2012). This has led to increased stratification and reduced delivery of nutrients to surface waters in the coastal Caribbean, resulting in lower phytoplankton bloom intensity and reduced net primary production. Declines in upwelling are likely to flow up the food web, ultimately leading to reductions in the productivity of fisheries. Evidence for changes in upwelling in other parts of the Caribbean is mixed, with some evidence for an increase in winter upwelling in La Guajira upwelling system off Colombia (Santos et al., 2016).

Precipitation

There is evidence from global climate models that the Caribbean will see spatially variable, but relatively minor changes in mean rainfall patterns. The Bahamas is predicted to see a slight increase in rainfall of approximately 20-30 mm per year, while most of the Caribbean Sea including Belize will see a slight to moderate decrease of approximately 70 mm per year. Research predicts a lengthening of seasonal dry periods and increases in the frequency of occurrence of drought conditions in the Caribbean (Cashman et al., 2010). Any changes in precipitation will have flow-on effects for river flow, turbidity, agricultural runoff, and patterns of sedimentation.

Ocean currents

There are few studies specifically looking at climate-driven changes in regional ocean currents in the Caribbean large marine ecosystem. In the broader North Atlantic region, a slow-down of the Gulf Stream has been projected under climate change, though evidence for an early signal in altimetry data or *in situ* measurements is mixed (Dong et al., 2019; Zhang et al., 2020; Chi et al., 2021). It remains unclear whether any slowdown will occur after waters have already flowed north out of the Caribbean region, or how changes might affect the Caribbean. Changes in ocean currents could have important implications for larval transport and connectivity of ecosystems in the region and have been suggested as contributing to accelerated sea level rise in the region.

Sea level rise

Moderate to severe sea-level rise of approximately 0.72-0.92 m is predicted in the Caribbean by the end of the century (Strauss & Kulp, 2018). The impacts will be most severe in regions of the Caribbean that are low-lying and sandy – nearly 1,300 km^2 of land area is predicted to be lost (e.g., 5% of The Bahamas, 2% Antigua and Barbuda). Seagrass beds and mangrove habitats that form important parts of the life cycles of key fisheries species are predicted to be severely impacted as sea levels rise, although substantial spatial heterogeneity in these responses is expected (Albert et al., 2017).

Dissolved oxygen

Deoxygenation is predicted to increase globally in association with ocean warming, and coastal, tropical reef systems such as those in the Caribbean are expected to be hotspots of decreased oxygen levels (Hughes et al., 2020). Evidence indicates that significant hypoxic events associated with high ocean temperatures in parts of the Caribbean caused mass mortality of reef-building corals and an associated loss of reef biodiversity (Altieri et al., 2017)

Ocean acidification (pH)
The Caribbean Sea has already experienced increasing ocean acidity (Friedrich et al., 2012). This is alarming considering that increased acidity and resulting reductions in aragonite saturation reduce the ability of organisms such as corals and shellfish to reproduce, settle, and build skeletons (Albright et al., 2010). Acidification is expected to increase as new carbon dioxide is added to the ocean, suggesting that the same trajectory can be expected to continue, possibly at an accelerating rate, into the future.

Sea surface salinity
Global climate models predict an increase in surface salinity of ~0.3- 0.4 psu in the Caribbean over the next 30 years. This increase is more than double the normal range of variability seen in the past 30 years and these values resemble values characterized as an extreme salinity value during the historical period.

Species sensitivity
Bonefish, tarpon and permit were all found to have a high to very high sensitivity to climate exposure based on their biological traits. A brief description of some of the dimensions contributing to sensitivity are included below (Hare et al., 2016), and scores for each attribute are recorded in **Figure 3**.

Bonefish
Bonefish inhabit shallow tidal flat ecosystems including those comprising seagrasses, mangroves, sandy bottoms and tidal creeks (Perez et al., 2018). This is likely to make them sensitive to broadscale reductions in the availability or quality of critical nearshore habitats under climate change. Due to their use of extremely shallow (< 2m) nearshore habitats, bonefish are exposed to large temperature fluctuations (> 12^{o}C) across daily tidal cycles, which may give them a physiological buffer to cope with the effects of ocean warming. However, upper critical thermal limits for bonefish have been determined to be 37^{o}C, and under worst-case IPCC projections, waters in their preferred feeding habitat are likely to exceed this critical threshold 18% of the time by the year 2100 (Murchie et al., 2011).

Adult bonefish demonstrate high site fidelity to particular areas throughout their life cycle, with daily foraging ranges of approximately 2km (Murchie et al., 2013). However, bonefish are highly mobile and capable of traveling large distances (>100km) during seasonal migrations to spawning grounds (Larkin et al., 2008; Murchie et al., 2013). Thus, healthy bonefish stocks rely on a mosaic of different interconnected habitats and corridors. Larvae appear capable of dispersing distances of 100-1000s of km from spawning sites (Zeng et al., 2018). Mobility characteristics of both adults and early life stages indicate the potential for bonefish to colonize suitable new areas if conditions on ‘home’ flats deteriorate (Boucek et al., 2019). However, new potential home flats may not be easily discovered by bonefish if the habitat mosaic needed for bonefish throughout its lifecycle is insufficient. It is likely that spawning is optimized to environmental conditions, with adult bonefish being observed to test properties of the water column prior to releasing gametes (Lombardo et al., 2020). This may increase their sensitivity to changes in oceanographic conditions during spawning windows but may also indicate some adaptive capacity to respond to shifting conditions.

Bonefish have demographic characteristics that confer a moderate to high sensitivity to disturbance. For example, they have lifespans of approximately 20 years, and relatively fast growth rates to their maximum size of 80 cm (Larkin, 2011). Natural mortality is variable by age but relatively low for large adults (Larkin 2011). Bonefish stocks are listed as Near Threatened by the IUCN (Adams et al., 2012), with a 42% reduction in catch and large declines in catch-per-unit-effort in South Florida observed since 1980 (Santos et al., 2017; Klarenberg et al., 2019). No stock assessments or estimates of abundance are available for bonefish in Caribbean waters.

<u>Tarpon climate sensitivity</u>

Tarpon occupy many habitats, requiring marshy mangrove or anoxic freshwater swamp habitats as juveniles (Ault, 2010; Elmo et al., 2021) and moving to coastal or up-river habitats as adults (Kurth et al., 2019; Ault, 2010; Griffin et al., 2018). Despite this use of diverse habitat types, tarpon distribution may ultimately be limited by their requirements for suitable wetland habitat for juvenile nursery grounds (Elmo et al., 2021). Although adult tarpon have fidelity to specific locations, they are capable of migrating large distances to warm oceanic waters where they release gametes in aggregations (Griffin et al., 2018). Tracked tarpon experienced an ambient temperature range of 20 - 32^{o}C and migrations appear to follow the 26^{o}C isotherm, which may represent the optimal temperature for gonad development (Luo & Ault, 2012).

Tarpon have population growth characteristics that may make their populations sensitive to climate disturbance. They are long-lived, with a maximum age of at least 55 years, mature at 6-7 years old, and grow slowly to a maximum length of 250 cm. Although there is no current estimate of stock size, there have been global declines of at least 30%, including major declines in previously famous fishing areas, which are now almost devoid of tarpon (Ault, 2010). These declines in tarpon stocks have led to a listing of Vulnerable by the IUCN (Adams et al., 2019).

<u>Permit climate sensitivity</u>

Juvenile permit are found in both estuary and open coastal sandy beach habitats (Adams & Blewett, 2004; Andrades et al., 2012); adults move between shallow flat sandy areas (< 3m) for feeding, and deeper reef areas (15-40 m) for spawning (Brownscombe et al., 2020). Stable isotope analyses indicate that permit may rely heavily on seagrass beds for foraging (Brownscombe et al., 2022). Permit remain within a home range of up to hundreds of km but move frequently among distinct habitat types within this area (Brownscombe et al., 2022), indicating some potential for redistribution by adults under unfavorable climate conditions.

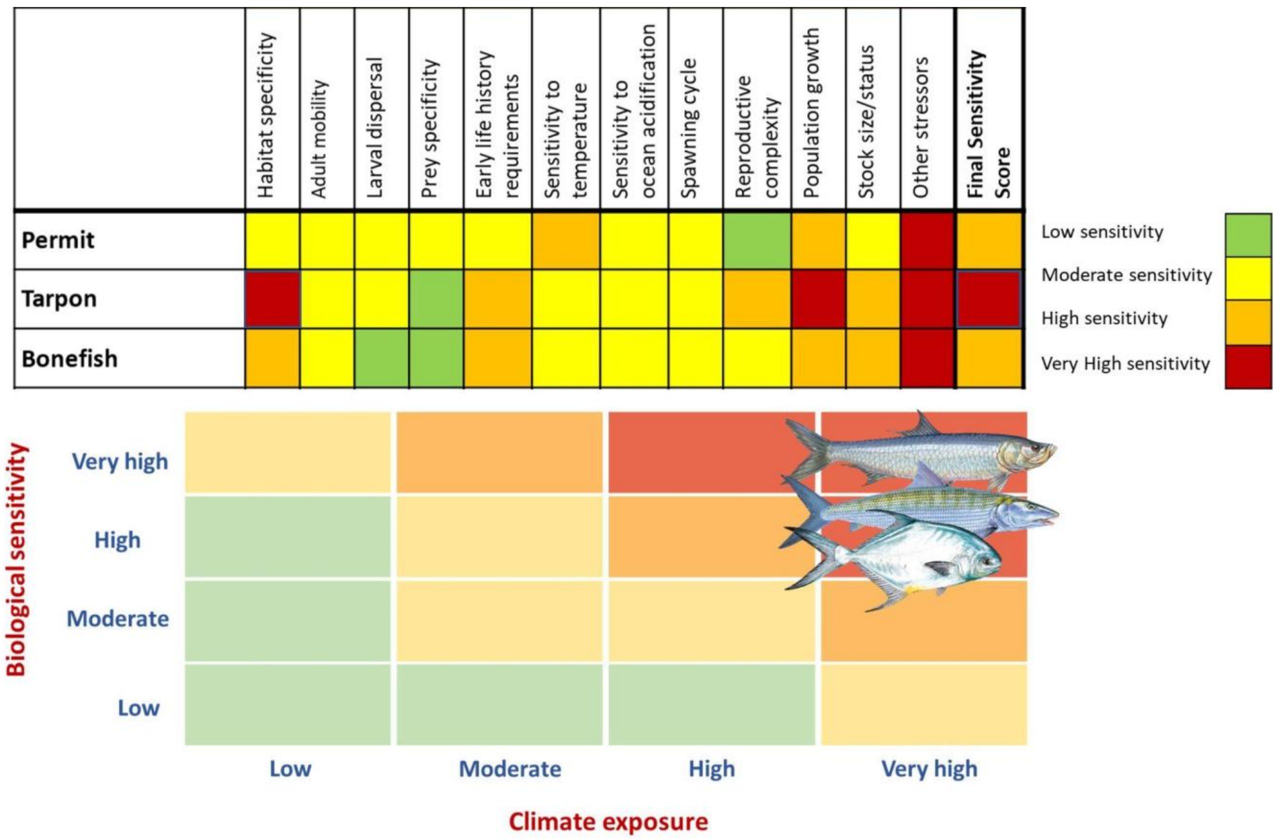

Figure 3. *Sensitivity (top) and overall vulnerability (bottom) scores for bonefish, tarpon and permit, three primary recreational targets in The Caribbean. These scores were based on a desktop literature review of species' ecology.*

Permit spawn from February to October depending on location, forming large aggregations with thousands of fish gathering on natural and artificial offshore structures where they swim in a spiral pattern while releasing gametes. The larvae produced by permit populations in Belize and Cuba have high local larval retention to specific spawning sites (Bryan et al., 2015), which may result in ecological 'traps' if conditions in these areas become less favorable under climate change. Permit live to be at least 23 years, mature at 2-3 years and reach a maximum size of 120cm (Crabtree, 2001). There is no evidence that regional populations are in decline, and the species is listed as Least Concern by the IUCN (Smith-Vaniz, 2015).

Additional stressors for flats fishes

All three flats fishes are also exposed to additional stressors that could decrease their resilience to climate impacts. These additional stressors include threats from coastal development including dredging, limestone mining, and reclamation of tidal flats for hotel and marina development. These impacts will degrade or destroy important nursery, spawning and feeding habitat. Environmental degradation may also result in decreased connectivity between habitats, including impacts to corridors between juvenile and adult habitats. Although all three species are catch-and-release only in Belize and commercial harvest for these species is not allowed in The Bahamas, the species are commercially harvested in other parts of the Caribbean including Cuba (bonefish, tarpon and permit), and South Florida (permit). Illegal fishing also occurs, and there is no recreational catch limit for any of these species in The Bahamas. In the recreational sector, post-release mortality is also a threat, with significant predation by lemon sharks on newly released bonefish (Danylchuk et al., 2007).

Species' spatial overlap with climate exposure

Bonefish, tarpon and permit were determined to experience very high spatial overlap with the magnitude of change expected in climate factors, due in great part to their coastal distributions throughout the Caribbean which bring them into contact with nearshore climate change impacts (e.g., storm damage, sea level rise and coastal erosion). Their use of shallow, inshore areas gives them a very high overlap with changes in surface ocean properties including sea surface temperature, sea surface temperature variability, and surface salinity. Additionally, tarpon use upriver habitats, and may overlap to a greater degree with changes in precipitation which in turn affects patterns of river flow, erosion, and turbidity.

<u>Reef fishes</u>

Reef fishes had high to very high sensitivity scores (**Figure 4**) and high to very high exposure to climate change, resulting in very high climate vulnerability scores (**Figure 5**). The main dimensions of vulnerability for this group were their reliance on specific habitats including coral, seagrass and mangroves, which are themselves sensitive to the effects of climate impacts (e.g., storm damage, sea level rise, ocean acidification, and coral bleaching during extreme heat events). Additionally, the recent proliferation of stony coral tissue loss disease, a novel plague that is decimating coral reefs in the Caribbean, threatens the persistence of reef assemblages (Heres et al., 2021). The restricted geographic ranges and shallow depth distributions of many reef fishes also mean that their thermal tolerances are extremely narrow (< 5^{o}C), increasing the probability that waters within their current range will exceed optimal temperatures under ocean warming scenarios. Many reef species also have complex reproductive strategies including forming large spawning aggregations. These aggregations can increase their vulnerability to climate impacts, particularly in cases where there is a very narrow spawning window, and high fidelity to 'home' spawning sites (e.g., Nassau grouper). The predictability of the timing and location of these aggregations also make reef fish more vulnerable to overfishing, and many reef fish stocks are under high fishing pressure and have experienced large declines in the Caribbean. The long-lived, slow-growing life history strategies of some of the snapper and grouper species (e.g., Nassau grouper, black grouper and cubera snapper) also make them less resilient to disturbances from fishing and environmental perturbations and may decrease their resilience to long-term climate change.

<u>Pelagic fishes</u>

Pelagic fishes had moderate to high sensitivity to climate change (**Figure 4**) and high exposure to climate change, giving them high vulnerability scores (**Figure 5**) making them slightly less vulnerable to climate change overall than the flats or reef fish assemblages. Pelagic fish are generally highly mobile with very little evidence for site fidelity, granting adults the ability to redistribute in response to changes in ocean climate conditions. Pelagic species also have much simpler reproductive behavior than reef species, including spawning cycles that occur over longer periods. Larval transport distances and early life history requirements are generally unknown for most pelagic species, but it is likely that recruitment variability is not dependent on a specific set of environmental conditions. Two pelagic species, common dolphinfish and wahoo, have exceptionally fast growth rates despite their large sizes. These traits make their populations more resilient to threats including fishing, however their populations are harvested intensively and there is evidence of population declines, including age and size truncations in parts of their range, including in the Atlantic. Furthermore, the transboundary nature of these stocks and offshore distribution of pelagic fishes also exposes them to other stressors such as overfishing in neighboring countries and international waters, and exposure to remote perturbations such as those associated with oil spills (e.g., the Deepwater Horizon spill in 2010) which may have large impacts on larval survival and development of species.

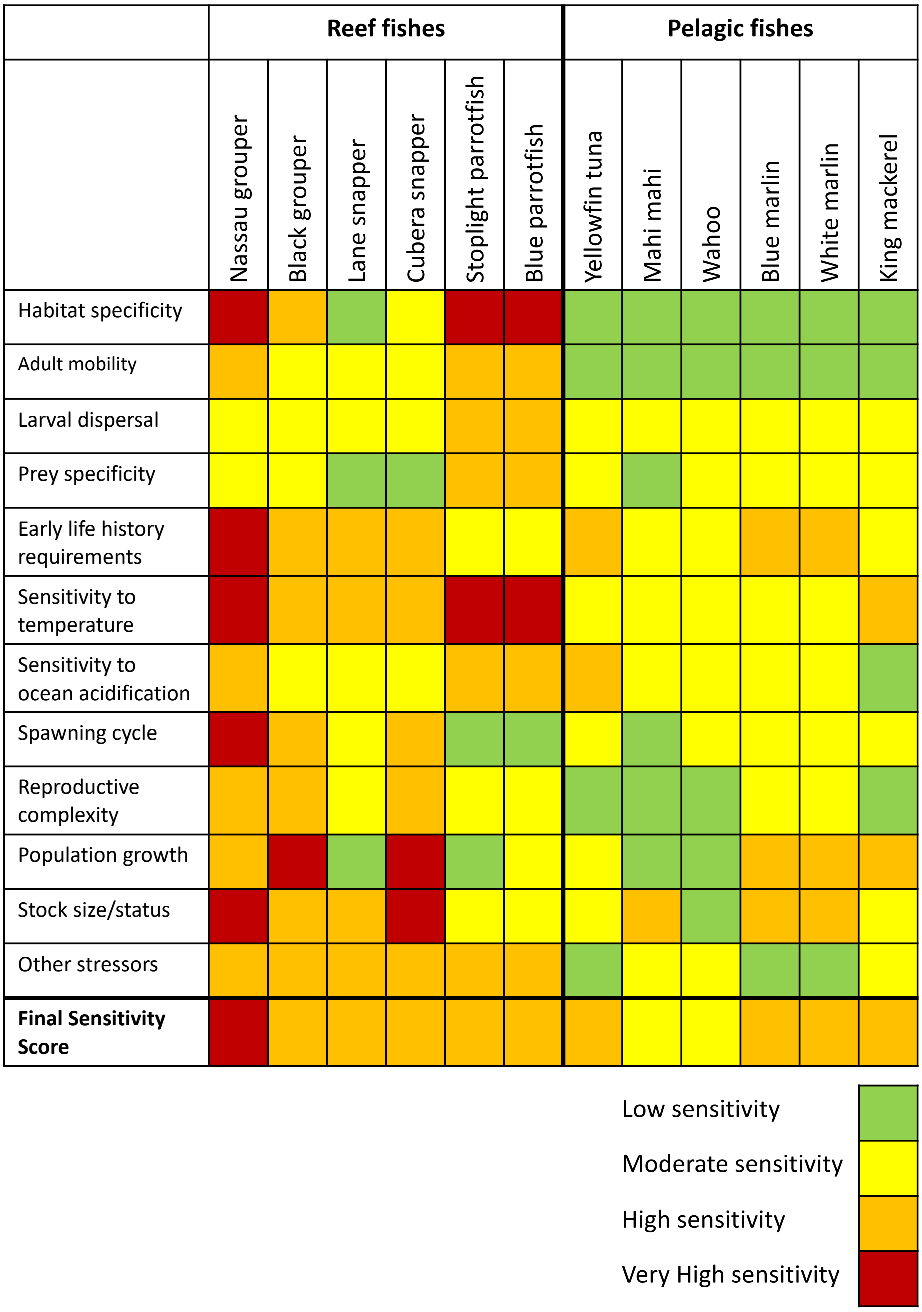

Figure 4. *Climate sensitivity scores across 12 biological traits for 12 secondary recreational target species in the Caribbean representing reef (cubera snapper, lane snapper, black grouper, Nassau grouper, blue parrotfish, stoplight parrotfish) and pelagic (common dolphinfish, wahoo, white marlin, blue marlin, yellowfin tuna, king mackerel) taxa*

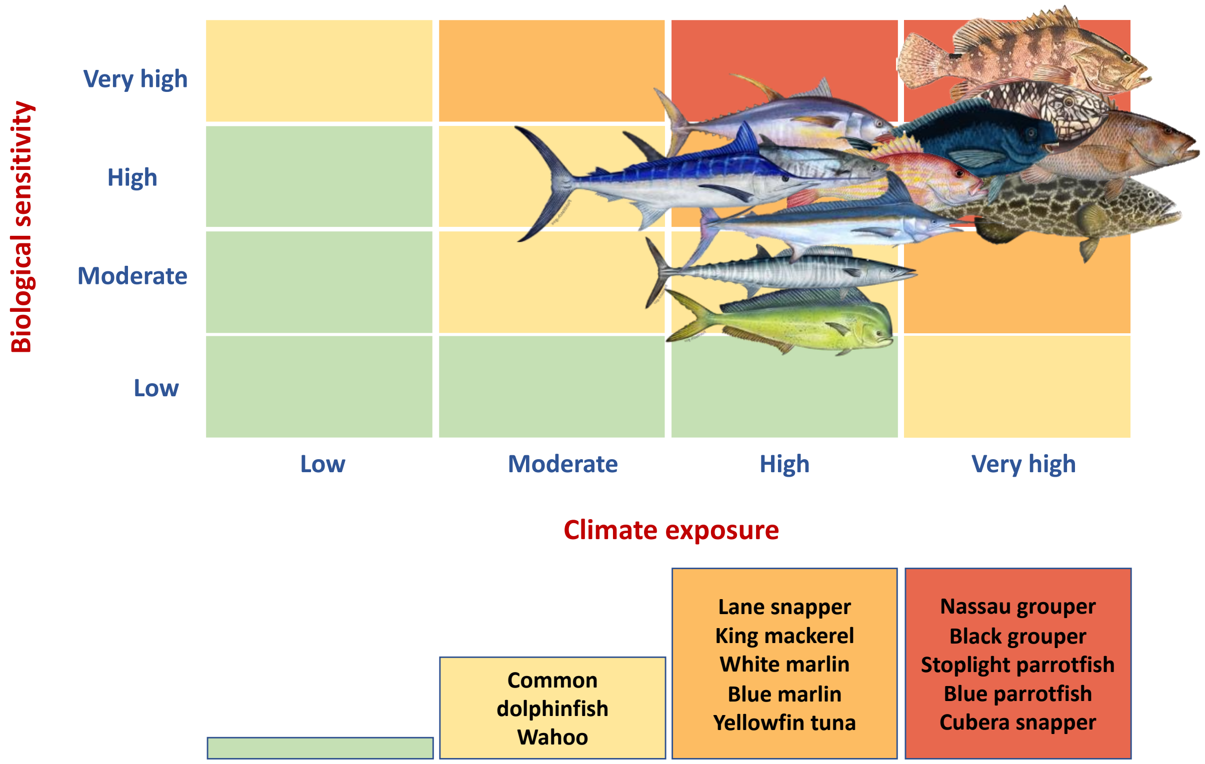

Figure 5. *Final vulnerability scores for a suite of 12 secondary recreational target species in the Caribbean, representing reef (cubera snapper, lane snapper, black grouper, Nassau grouper, blue parrotfish, stoplight parrotfish) and pelagic (common dolphinfish, wahoo, white marlin, blue marlin, yellowfin tuna, king mackerel) taxa*

Participatory Climate Vulnerability Assessment Workshop

Climate exposure

The expert stakeholder group including fishing guides from Belize and The Bahamas highlighted several climate factors that they perceived as likely to cause major and increasing threats to fisheries in the Caribbean in the future. Participants agreed that storm activity was one of the most concerning climate change factors in their region (**Figure 2**). Results from the Mentimeter polling software indicated a perception that storm severity and storm frequency will show high to very high magnitudes of change over the next 30 years (mean scores of 3.7 and 3.2 out of 4 respectively). Participants from The Bahamas highlighted their recent experience of Hurricane Dorian in 2019, a category 5 storm that was one of the strongest Atlantic hurricanes on record and the strongest hurricane ever to hit The Bahamas. Hurricane Dorian reshaped the flats fishery around the islands of Abaco and Grand Bahama, with devastating impacts for important mangrove habitats. Although there remains some uncertainty surrounding the trajectory of storm intensity under future climate change, there was a perception by stakeholders that any increase in the severity of the average storm, or the frequency of severe storms, could have strong, negative consequences for the recreational flats fishery.

Sea level rise was another factor that stakeholders agreed was a pressing issue in the Caribbean, with a very high expected magnitude of change over the coming 30 years (mean score of 3.7 out of 4). In addition to sea level rise, coastal erosion was identified as a significant concern by participants from both countries (mean score of 2.8 out of 4). Several experts in the workshop noted that natural erosion is being compounded by erosion from coastal and inland development. Participants from Belize were especially concerned with dredging upstream in rivers leading to increased erosion and sedimentation on the coast. Concerns surrounding sea level rise and coastal erosion, in combination with storm activity, highlight the reliance of the recreational flats fishery on sensitive inshore ecosystems on sandy, low-lying islands which are especially vulnerable to these climate impacts.

Participants also noted that mean sea surface temperature was changing (mean score = 3.3), with stakeholders from The Bahamas citing personal observations that waters have already warmed. One guide highlighted that in Grand Bahama, particularly in the summer, bonefish are increasingly seeking refuge in cooler waters in the shade of mangroves. Dissolved oxygen was also predicted to show a high to very high magnitude of change in the region (mean score = 3.5). In both countries, participants noted that while mean rainfall appeared to have a low projected magnitude of change based on global climate models (mean score of 2 out of 4), their experiences of rain events are becoming very different from the past. These observations included longer periods without rain and then more intense rain events when they occur. In Belize, it was noted that yearly weather patterns seem to have changed, with dry spells during the rainy season and increased precipitation during the dry season. This suggests that variability in precipitation may be a more important consideration for shaping the experiences of locals in the Caribbean than average trends, and highlights potential impacts on coastal systems via runoff, erosion, salinity, sediment deposition, and turbidity.

Stakeholders did not expect any climate factors to show a low magnitude of change (mean score < 2 out of 4). However, there was considerably less consensus regarding the direction and magnitude of change in some ocean climate factors. For example, ocean currents (mean score = 2) and upwelling intensity (mean score = 2.6) both had very wide distributions around the mean, suggesting that changes in these factors were less well understood by participants, in line with the paucity of scientific data that was available for these factors.

Flats species sensitivity

Expert stakeholders noted that the major threats to bonefish, tarpon, and permit result from their specificity to inshore habitats at various life stages, including seagrass and mangroves associated with tidal flats. Participants scored habitat specificity as moderate to high for all three species (mean score for bonefish and tarpon = 3, permit = 2.4). Participants from Belize further highlighted that the sensitivity of all three flats species to changes in habitat corridors from both climate change and human activity was a primary concern in their country. There is also a strong need to better understand habitat use and connectivity and manage threats to habitats of recreational fishes on the flats.

For bonefish, the other main traits that stakeholders identified as likely to confer high sensitivity to climate change were reproductive complexity due to the formation of large pre-spawning and spawning aggregations (mean score = 2.8), and spawning cycle which occurs seasonally and appears to correspond to specific oceanographic conditions (mean score =

2.6). Although participants scored bonefish stock size and population growth rates as conferring moderate sensitivity (mean scores for each = 2.2), there was a high degree of uncertainty surrounding scores for these factors. Several participants from The Bahamas indicated concerns about bonefish stock declines following Hurricane Dorian in 2019, which destroyed important tidal habitats. One guide noted that bonefish populations seem to be rebounding in fishing grounds three years after this disturbance, especially where mangroves had been re-planted as part of restoration efforts. This provides some hope for the resilience of stocks and ecosystems to occasional extreme events in this system. Participants highlighted a high sensitivity for bonefish resulting from additional stressors on top of recreational fishing and climate change (mean score = 2.8), highlighting habitat degradation, catch-and-eat practices in parts of The Bahamas, and release mortality due to predation or poor handling protocols by inexperienced guides as potential stressors for bonefish populations. While bonefish has legal protection in Belize, it is still caught and kept for consumption as bycatch from other fishing activities or during illegal and unreported fishing activities.

For tarpon, participants from both countries highlighted that despite their very slow growth rates (mean score = 3.6) and diminished stock size (mean score = 3), there is some anecdotal evidence that populations may be rebounding from fishing pressure in some parts of the Caribbean. Participants credited the perceived upward trajectory of these tarpon stocks to net bans (which have been in place in Belize since 2020) and prohibiting commercial take of tarpon (which has been in place in Belize since 2010 and in The Bahamas since 2017). While gill nets are banned in Belize’s marine waters, they can still be used in rivers which may lead to capture of tarpon within rivers as by-catch or targeted illegal fishing activities. There was less consensus surrounding habitat specificity scores for tarpon. Stakeholders scored habitat specificity as high (mean score = 3), but with a wide distribution in responses. Stakeholders noted that despite the very high specificity of tarpon to marshy wetlands in the early juvenile phase, the wide range of habitats in which adult tarpon are caught in the Caribbean (i.e., from freshwater to estuarine to coastal environments) may ultimately make them more resilient to disturbances. In general guides were not highly concerned about climate change impacts to tarpon stocks based on their on-the-water experience and stakeholder-informed scores suggested reducing biological sensitivity from very high to high (**Figure 6**).

For permit, there was agreement from stakeholders that ecological information was relatively limited, but that the species may be less sensitive to climate change than bonefish or tarpon, based on their more moderate sensitivities associated with habitat specificity (2.4), sensitivity to temperature (2.4); adult mobility (2.2) and larval dispersal (2.2). Little is known about permit stocks in the Caribbean, and participants scored the species as moderately sensitive based on population size (2) and population growth (2.2). Stakeholder suggested reducing biological sensitivity from high to moderate, leading to a reduction in overall vulnerability from very high to high (**Figure 6**).

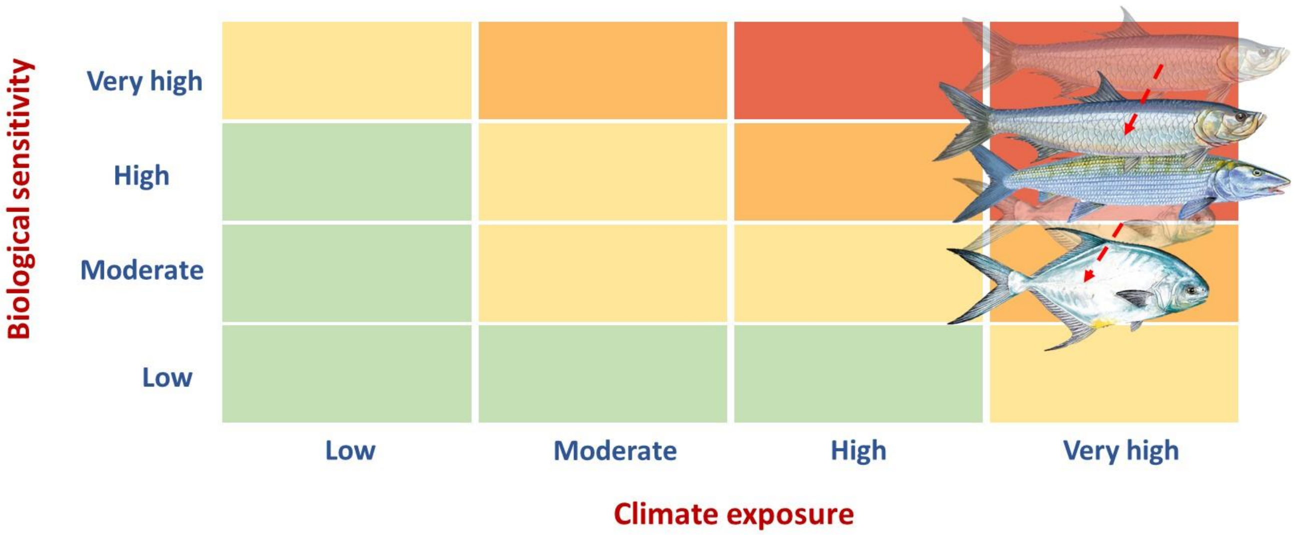

Figure 6. *Climate vulnerability scores for bonefish, tarpon, and permit integrating the local ecological and scientific knowledge of expert stakeholders.*

Discussion

Climate change will have large impacts on tropical marine ecosystems (Doney et al., 2012). Outcomes for individual fish species under climate change will be diverse, depending on their inherent vulnerabilities and the degree to which they are subject to additional stressors including unsustainable fishing practices and habitat degradation. Assessing the relative climate vulnerability of a suite of species with different distributions and functional traits can be a useful first step toward prioritizing species for additional protection (Gaichas et al., 2014; Reece et al., 2018) and preparing industries and communities to adapt to projected changes in stock availability or species assemblage (Ojea et al., 2020).

Climate vulnerability of flats species in the Caribbean

Based on a desktop analysis and participatory stakeholder workshop, we found that a very high magnitude of ocean climate change is expected in the Caribbean in the coming 30 years, with anticipated increases in ocean temperatures, rising sea levels, coastal erosion, ocean acidification, and storm damage (Friedrich et al., 2012; Mendelsohn et al., 2012; Peneque & Finkl, 2020; Vosper et al., 2020). Important recreational target species in the Caribbean exhibit high vulnerability to these changes, which puts fishing livelihoods and the multibillion-dollar tourism industry in jeopardy in this region (Fedler, 2013, 2014). Bonefish, tarpon and permit each exhibit several characteristics that confer high to very high vulnerability, including specificity to sensitive coastal ecosystems, slow population growth rates, and high fishing pressure (Crabtree, 2001; Adams et al., 2019).

Stakeholder perceptions of both the magnitude of climate change in the Caribbean and the sensitivity of key recreational species to these changes were generally slightly lower than scores determined via the desktop review (**Figure 2, Figure 6**). Differences in exposure scores for physical climate change factors may reflect local knowledge that provides more nuance than 'big picture' synthetic studies of climate change impacts in the scientific literature (Reyes-Garcia et al., 2016) or may simply reflect difficulties calibrating a scoring framework based on scientific literature and statistical thresholds with human perceptions of change. Regardless, the stakeholder group clearly identified that significant changes are occurring and are expected to continue across a suite of climate variables, in line with many previous studies investigating perceptions and understanding of climate risk by fishery participants (e.g., Tiller et al., 2016; Sarkar et al., 2022).

Stakeholder-adjusted species' sensitivity scores resulted in a down-weighting of sensitivity for both tarpon and permit from very high to high, and high to moderate, respectively. This resulted in a suggested shift in the overall vulnerability of permit from very high to high after incorporating climate exposure scores (**Figure 6**). The difference in stakeholder perceptions and the desktop review scores for species' sensitivity may reflect differences between the ecology and status of Caribbean stocks compared with stocks in the southeast United States, where much of the published information for tarpon and permit were available. During discussions, stakeholders also tended to weigh some sensitivity factors as being more important than others for determining outcomes for species in the Caribbean which may have influenced overall perceptions of climate vulnerability. For example, stakeholders noted that the broad suite of habitats occupied by tarpon during adult life stages is likely to confer a relatively low vulnerability to climate change impacts and recommended adjusting the score lower to reflect a moderate sensitivity based on the occurrence of tarpon in diverse environmental conditions.

Importantly, stakeholders emphasized that climate change is likely to amplify existing threats to flats species and their ecosystems in Belize and The Bahamas. These include unsustainable coastal development including shoreline hardening, dredging and limestone mining (Suchley & Alvarez-Filip, 2018); recreational fishing pressure including catch-and-release mortality in both countries and catch-and-eat practices for bonefish in The Bahamas; and illegal, unreported and unregulated fishing including netting of tarpon in inland freshwater habitats in Belize (Steinberg, 2015). In many cases, these local, non-climate threats may be more immediate than climate change, as well as more tractable in the short term. Identifying strategies to mitigate threats to this fishery is a priority, and there is a strong need to find integrated solutions that account for potential climate change impacts in the context of other stressors.

Socio-economic implications of climate vulnerability in the recreational sector

The recreational fishing sector in the Caribbean relies on high-quality fishing opportunities to entice visiting anglers to spend money on premium experiences. It is therefore important to consider how much buffer there might be in target stocks to withstand any declines under climate change without degrading the fishing experience. Stock assessments and monitoring programs for recreational stocks are not undertaken in the Caribbean, so there is a high degree of uncertainty surrounding the status of stocks under current climate conditions. In Belize, some stakeholders felt that any future declines in stocks would negatively impact their business, particularly in the north of the country where fishing pressure is already high.

Participants suggested that any decline in permit stocks might have more noticeable effects on catch, because this species is already more difficult to catch than bonefish or tarpon.

In The Bahamas, one guide shared that a good day of guiding sees guests landing 10-12 bonefish, and 1-2 permit or tarpon. To achieve that high quality fishing experience, guides need to target several different flats areas, which each hold different numbers of fish at different times of the day and year. One guide mentioned they don't like to "exhaust" a flat with too much fishing pressure, so if their client catches a few fish on one flat, they will move on to another, and it is common for guides to let flats "rest" with no fishing pressure for a day or two between visits. This suggests both the importance of good stewardship to sustain recreational stocks in flats ecosystems, and the necessity of having multiple high-quality flats accessible within a short distance from one another, thus further highlighting the need to maintain functional environmental corridors between flats. Under climate change, if fewer flats areas are available due to the impacts of storms or sea level rise, finding sufficient fish to satisfy anglers may be a challenge. For example, after Hurricane Dorian, miles of mangrove shorelines were decimated on eastern Grand Bahama and the number of flats holding bonefish became limited (pers. comm.). The impacts of this were felt most strongly by inexperienced guides who have knowledge of only a few (~5) flats, and therefore have less buffer to adapt to declines of bonefish stocks in any given site.

Strategies to build resilience against climate vulnerability in the Caribbean

Ecological strategies

Despite a sobering outlook for recreationally fished species in the Caribbean over the next 30 years, the expert working group identified several strategies to increase resilience in recreational fisheries in their communities (**Table 1**). As the main threats to flats fisheries are degradation of key habitats, primarily from coastal development, coastal erosion, rising sea levels and storm damage (Steinberg, 2015), protection and restoration of these habitats is a critical strategy to build resilience. In Belize, participants identified the need to undertake a comprehensive mapping exercise to understand important areas for recreational flats fishing and important pre-spawning aggregation and nursery grounds. Such mapping exercises, in combination with assessments of major impacts on critical ecosystems would fill a key knowledge gap regarding habitat use of bonefish, tarpon, and permit in this region, and identify areas that are experiencing greater impacts. This type of mapping should be achieved via collaborations between local scientists and fishing guides to ensure that local guides' expert knowledge regarding fish distribution and behavior is accounted for. Maps of essential fish habitat for flats species could be used by management agencies to formally identify and proactively protect sensitive, ecologically and recreationally important areas from development.

Habitat protection and restoration are key strategies that can build ecological resilience of flats species to climate change impacts. Following Hurricane Dorian, Bonefish & Tarpon Trust undertook an extensive mangrove restoration project in The Bahamas, and guides noted that they are already seeing bonefish return to some replanted mangrove areas. Additionally, coral restoration projects have been a focus of conservation efforts in Belize and The Bahamas, and major efforts are currently underway to combat stony coral tissue loss disease, which is decimating reefs (Dahlgren et al., 2021; Heres et al., 2021) and further eroding the resilience of many coral reef specialists, including parrotfish, snappers and groupers. Habitat restoration should be guided by the best available science and should include planning for future conditions. Better protection of spawning aggregation sites via seasonal, spatial closures can also help reduce fishing mortality, particularly for reef species that do not have catch-and-release measures in place. However, more detailed information is needed to understand precisely when and where to implement these protections to make them as dynamic and effective as possible.

Capacity building strategies

Enhanced education and training programs can build resilience and provide investments in the long-term viability of the recreational fishing industry. In the Caribbean, many experienced guides are reaching retirement age, and there are fewer younger guides entering the industry. Young guides who are entering the industry, often from the commercial sector, require training in understanding key habitats and fish distributions, and best practice protocols for catching and releasing fish which may help to reduce post-release mortality for recreational species (Adams, 2016).

Increasing the financial resources available for stakeholders to respond to climate change can also build necessary capacity. For example, one guide mentioned that after Hurricane Dorian, guiding opportunities were limited by a lack of fishing tourism infrastructure like lodges, boat ramps, and docks to regain access to the water and bring back fishing tourists. Establishing sources of government or climate insurance funds to rebuild important infrastructure and help get guides back to work after natural disasters would be a potential avenue to increase economic resilience to climate impacts and may be a necessary investment given the expected magnitude of climate change in the region.

Fisheries management strategies

Bolstering fisheries management is an important step toward buffering fishery species and their ecosystems from the effects of climate change. In some systems, many climate-induced declines can be forestalled by strong and effective management measures (Gaines et al., 2018; Free et al., 2020). In both Belize and The Bahamas, fisheries management measures are in place to protect recreational stocks, including requirements for catch-and-release in both countries (Sherman et al., 2018), and the banning of gill and lobster nets in marine waters in Belize that incidentally catch flats species including permit in the coastal zone. However, regulations need to be systematically reviewed to ensure they are meeting their goals, and regulations must be more evenly enforced. Illegal and unregulated fishing remains a concern, including where transboundary fishing occurs by vessels entering Belizean and Bahamian waters from other parts of the Caribbean region. Furthermore, existing fisheries management measures may not be well understood by fishers and their communities, and there is a need to improve communication of existing laws and their importance for protecting key stocks via targeted public outreach campaigns.

Table 1. *Strategies identified by the country specific breakout groups to increase resilience within the flats fishery and associated guiding communities.*

What would you like to see be done by…			
	Government entities	**Your community**	**Individuals**
The Bahamas	-Support research and conservation through permitting and policies -Enhance onshore protection of critical habitats (e.g., wetlands, mangroves) -Eliminate consumption of bonefish, tarpon, & permit -Protect flats from destructive behaviors of developers -Apply environmental impact assessments and include impact on rec fisheries when coastal construction or development is proposed	-Increase awareness of potential threats through improved communications between researchers, managers, fishers, etc. -Increase education of the public that uses the marine environment, emphasizing areas that are ecologically important (i.e., flats, creek areas) -Assess vulnerability of these species to different climate threats; ID which species and ecosystems are resilient; use to inform management -Restore important ecosystems and monitoring of management strategies to understand effectiveness of the restoration -Increase willingness to share information across organizations and sectors	-Through education, help others understand the impacts of their actions in fishing and habitat protection -Participate in restoration and monitoring
Belize	-Update and enforce dredging regulations -Improve coordination between forestry and fishery departments for mangrove protection -Reduce impact from development projects through better planning	-Support existing and future mangrove and coral restoration projects by community and NGO groups -Coral restoration to deal with stony coral tissues loss disease -Sport fishing associations advocate for protection of sandy bottom flats from development and dredging -Educate and train newer guides -Research and map the flats fishery to understand key habitats and corridors for protection -Increase research to fill important fishery information gaps for flats species, working with guides to document the situation and gather data	-Improve release mortality with better guide training to help improve stock health

Better coordination between government agencies was suggested by stakeholders as a way to improve management and enforcement of existing measures. In the case of illegal transboundary fishing, lack of coordination among coastguard, immigration and fisheries departments was cited as a cause of decreased enforcement efficacy. This same lack of coordination between government agencies has been observed to hamper protection efforts, with important coastal habitats like mangroves falling between the jurisdictions of fisheries management and forestry agencies. Creation of working groups and a national strategy to coordinate between agencies in service of protecting key stocks and strengthening fisheries governance could be an important step in improving resilience in the system.

A key recommendation from workshop participants was to institute a managed access program to ensure long-term sustainability of recreational fisheries. One guide raised concerns about the increased number of guides targeting the same sites and proposed a managed access program for specific flats areas to reduce fishing pressure. Additionally, the guide mentioned that when the weather is bad, most guides can't get to outer cays and usually require other places near the coastline to fish. This tends to concentrate pressure on nearshore locations closer to population centers, and may be exacerbated under future climate scenarios where the number of flats is reduced periodically and over the longer term by storm damage, sea level rise, and coastal erosion.

Participants also highlighted the need for international governance structures that are sufficiently robust. This includes examining and modifying, when necessary, enforceable treaties that address transboundary issues related to recreational fisheries, where stocks are thought to be impacted by illegal fishing from vessels originating in neighboring countries. Enforcement also needs to be coordinated among nations.

Expansion of alternative livelihood opportunities

Recreational fisheries and guiding provide one strategy for commercial and small-scale fishers to diversify livelihoods, while leveraging their in-depth knowledge of the marine environment and maintaining their cultural ties to fishing activities. One consideration in planning for potential climate-induced declines in fisheries is to assess the feasibility of shifting fishing effort toward less vulnerable stocks, or away from vulnerable fisheries into other sectors (e.g., guided fisheries and/or catch and release recreational fisheries). Although reef and pelagic species may provide alternative recreational targets in the Caribbean, many of these species are experiencing high fishing pressure from the commercial sector, and reef species are experiencing threats to multiple key habitats including seagrass, corals and mangroves. Any increase in targeting of reef species should carefully consider sustainable catch limits and the potential for catch-and-release using appropriate handling protocols to reduce mortality.

Many pelagic species are data-deficient throughout their range, and particularly in the Caribbean, making it difficult to assess the potential impacts of any increase in fishing pressure from an expansion of the recreational sector to focus on blue water ecosystems. In Belize, one guide mentioned that in some areas of Belize there are few guides that offer blue water sportfishing, and this is an opportunity to grow those fisheries which can also help take pressure off the flats. However, the group also highlighted the need to manage risks of shifting too much pressure to any one fishery, recognizing that the transition of livelihoods needs to be sustainable and well planned out in the context of the entire sector. Licensing or managed access to new fisheries for pelagic species may be an option to increase their sustainability. In The Bahamas, licenses are not required for Bahamian recreational anglers to catch pelagic fish, but they are required for visiting sportfishing anglers; licenses are required for fishing guides in the flats. Overall, any consideration of interventions to assist with diversifying livelihoods from one fishing sector into another should consider the carrying capacity of the number of operators in the fishery.

The major barriers to expanding livelihood options in Caribbean fisheries are the availability of economic and social resources to make transitions (**Table 2**). For example, targeting flats species requires a much smaller vessel than targeting pelagic or reef species, and guides and other local community members often do not have access to the capital needed for larger vessels. Stakeholders from The Bahamas identified that guides could work together to form a co-op and share the higher costs associated with larger boats (e.g., initial purchase and insurance). Participants from both countries highlighted access to financing as an important strategy to diversify livelihoods in their country and across the Caribbean. Training programs - such as the national flats fishing guide training program at the Bahamas Agriculture and Marine Science Institute (BAMSI) - can also help sustainably expand economic opportunities in the guiding sector while minimizing economic leakage. In Belize, the Ministry of Tourism requires that all nature and tourism guides are certified through a national program and expanding that program to include flats fishing and offshore fishing guiding training may provide a strategy to sustainably expand guiding opportunities. Another key consideration in expanding livelihoods tied to recreational fisheries is to better understand the role of other members in the value chain – including women and family members – and emplace solutions for their economic and social empowerment in the community.

Table 2. Barriers and opportunities identified by the country specific breakout groups to switching or improving livelihoods:

Barriers and opportunities to switching or improving livelihoods:		
	Barriers to Switching to Blue Water or Reef Species	**Resources or Opportunities to Help Fishers and Guides Switch**
The Bahamas	-Larger vessels are needed to access reef fish and pelagic species -Training and experience are needed to safely operate a larger boat	-Partner with resorts and lodges to acquire larger boats -Form a guide co-operative to share costs and benefits of a larger boat (e.g., Spanish Wells community lobster boats) -Provide training to promote nature and tour guiding, business acumen, entrepreneurship, and other skills (e.g., grant writing, community organizing)
Belize	-Lack of access to capital to transition to new livelihoods and industries (e.g., new vessels and gear) -Lack of capitol for basic business needs (marketing, staff support, transportation, etc.) to support new tourism industries and opportunities -Lack of understanding and fear of unintended effects that switching livelihoods may have on the guiding industry and the ecosystem (e.g., risks of over-fishing or low return on investment, failure of businesses)	-Explore options to utilize managed access for emerging recreational blue water fisheries -Create education and training programs around recreational fishing opportunities -Broaden collaborations with University of Belize and NGOs. Help to access funds and create proposals for funding through grant opportunities -Provide micro-financing for women and other community members to help support them in their vital role in families and communities -Provide micro-financing to support emerging guiding and other businesses in the recreational fishery -Incentivize public sector to invest in markets for alternative livelihoods (holistic approach across sectors, make sure investment split across sectors)

Key Recommendations

Based on the tactics that we identified above, we offer a list of key recommendations to increase the resilience of recreational fisheries and dependent communities to climate change in the Caribbean. These recommendations should be considered as part of a suite of broad, integrated solutions across sectors that consider recreational fishing as one component of complex social-ecological systems.

1. Advance scientific understanding of important recreational fisheries and their habitats, including the impacts of climate change:
    a. Prioritize research that improves understanding of species vulnerability (building on the results of this study) and the health of important stocks, including regional coordination between countries on stock assessments
    b. Improve data collection including collaborations between guides and scientists to identify important habitats used by recreational species as nursery ground, feeding, pre-spawning and spawning sites that could benefit from formal protection
    c. Increase efforts to predict short and long-term climate impacts on fish populations and ecosystems
    d. Improve understanding of the full suite of ecological, economic and social benefits that marine ecosystems and fisheries provide in the Caribbean (e.g. carbon sequestration, nutrition etc.) to elevate the case for restorative, protective and sustainable management
2. Strengthen coordination across government ministries and departments to identify, protect and restore key habitats from coastal development:
    a. Facilitate coordination between ministries or departments of tourism, fisheries and forestry, immigration, and coastal zone management
    b. Elevate the importance of local and international scientific research within and across borders and ensure that research permitting processes support scientific needs
    c. Establish and/or strengthen national frameworks for addressing the economic and environmental impact of coastal development on habitat that supports recreational and commercial fisheries
3. Bolster national policy and strengthen management institutions to improve key aspects of recreational fisheries management including:
    a. Data collection
    b. Science-based adaptive management
    c. Managing access, carrying capacity, and effort
    d. Habitat protection and restoration
    e. Enforcement of existing regulations including net bans (where applicable), harvest restrictions, and license requirements
    f. Education and training of current and new guides and anglers to reduce post-release mortality
    g. Education within local communities focused on the importance of key habitats and why community support in conservation of these areas is critical in helping to build coastal resilience
    h. Engaging a formal or informal working group of recreational fisheries stakeholders to identify the greatest conservation and management needs.

Conclusion

Climate change will continue to cause major threats to recreational fisheries in the Caribbean over the next 30 years, compounding a host of other anthropogenic stressors affecting species, habitats and ecosystems. However, there are many reasons to remain hopeful. The opportunities outlined in this report can build upon a strong foundation of policies and scientific research. Fishery managers, guides, scientists, and NGOs working in the Caribbean have already advanced policies, regulations, and research that create pathways for strengthening recreational fisheries management that can boost resilience to climate impacts. Additionally, the challenges and successes that Belize and The Bahamas have navigated can help chart a route for other countries in the Caribbean to address similar issues. With collaboration, optimism and the necessary level of resources across the region, the recommendations outlined in this report can be advanced to help sustain the natural resources and livelihoods that are tied so closely together in this biologically and culturally rich region.

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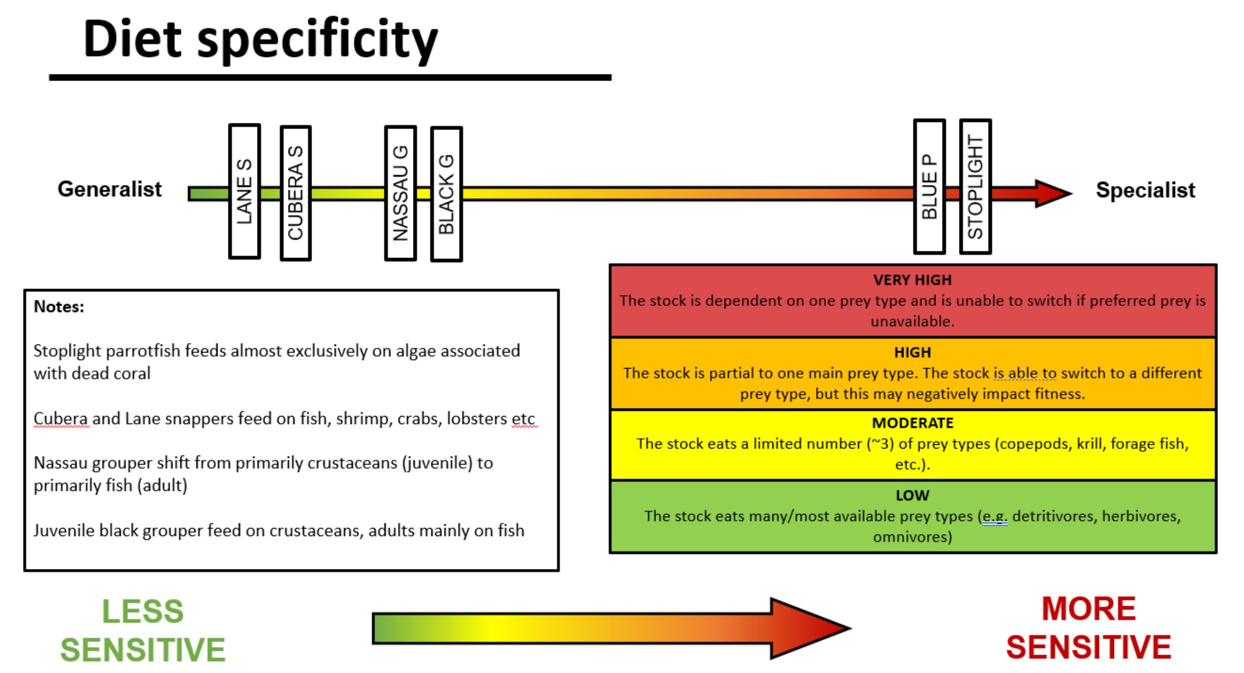
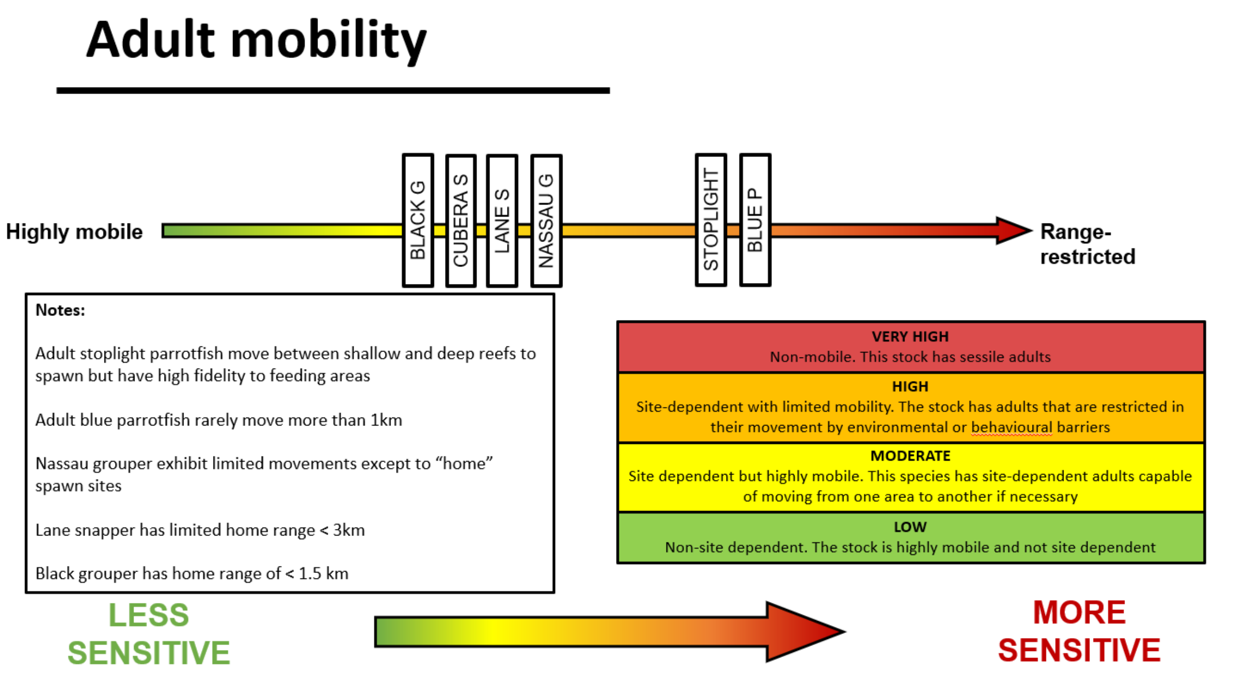
Appendices

Appendix 1. *Examples of information presented to stakeholders during a participatory workshop to score the relative climate vulnerability of secondary recreational targets (reef and pelagic taxa) across a range of 12 climate sensitivity traits.*





Appendix 2. *Questions used in each group to identify the socio-economic implications of climate change impacts and strategies to improve resilience*

Current state of the fishery, potential declines, and strategies to improve resilience:

- How many fish do you need to catch to have a "successful" trip in terms of customer experience and satisfaction?
- On what proportion of trips do you catch this number of fish?
- At what point would declining fish stocks start to impact businesses?
    - For example, will a 20% decline affect catch rates and customer satisfaction? How about a 50% decline?
- Have you known people whose guiding business has been impacted in this way?
- Have you? Does it worry you personally? Why?
- What research gaps could scientists and managers help to fill?
- What are some strategies to reduce declines in flats species?
- What do you think your *government* can do to increase ecological resilience of the ecosystems and the communities that depend on flats species?
- What can local *communities* do?
- What can *individual guides* and fishers do?
- Which three have the most impact or ripeness?
- What would we suggest as immediate next steps?
- What could we do in the next 6 months that could be a good first step to taking action on these?

Alternative livelihoods: barriers and opportunities

- To what extent do local communities rely on revenue from fishing flats species?
- How diverse are the fishing portfolios of fishing guides and operators now?
- Do people who engage in the flats fishery target other species besides bonefish, tarpon, and permit? (consider all the different parts of the year)
- For households that earn some of their income from guiding in the flats, what are the main other industries that the household is also engaged in?
- Have you or people you know had to switch industries?
- What barriers are there to recreational fishing guides and operators moving from fishing flats species to other livelihoods? What about switching to fishing blue water or reef species?
    - Are these the same for both commercial and recreational opportunities (gear/infrastructure investment costs, permits, regulations, training)?
- What resources or opportunities are available to support fishers and guides to diversify from fishing flats species to fishing blue water or reef species (investment, grants, training opportunities)? What additional resources and strategies would help?

Cultural importance of the fishery

- How important is fishing the three flats species to the social and cultural identity of the fishing community?
- Are these particular species important to communities beyond their economic value?
- Are there family traditions related to the practice of fishing these species (do guides learn from their fathers or grandfathers)?
- And ask participants if they know of other places in their country where these species have additional cultural value.