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A climate vulnerability assessment for U.S. highly migratory fishes in the Atlantic Ocean

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Abstract

Climate change will continue to alter key physical and biological oceanographic processes throughout the global ocean, modifying environmental conditions for U.S. highly migratory fish species found in the Atlantic Ocean. The Atlantic Highly Migratory Species Climate Vulnerability Assessment evaluated the vulnerability of 58 species and stocks to projected ocean conditions, using a combined qualitative and quantitative analysis of species sensitivity (physiological, ecological, and behavioral attributes) and estimated exposure to possible future ocean stressors. Key modeled environmental variables included bottom and sea surface temperature, sea surface oxygen, and ocean acidification (pH), whereas the most influential

in exposure analysis can be extracted by the user from NOAA's Climate Change Web Portal: CMIP6.

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biological attributes considered were population growth rate, stock size, and stock status. We produced vulnerability rankings (i.e., low, moderate, high, and very high) based on biological attribute sensitivity and exposure to the environmental variables, and separate analyses including estimated ability of distributional shifts, predicted directional effects of climate change, certainty, and data quality scores for the species and stocks assessed, with exceptions for species with undetermined geographic distributions. Of the 58 species and stocks assessed, 4 had very high vulnerability to climate change, 14 had high vulnerability, 22 had moderate vulnerability, 6 had low vulnerability, and 12 could not be assigned a rank. The majority (n = 45) of species and stocks had high ability for distributional shifts in response to projected changes in climate. Further, directional effect results suggest that climate change impacts on the majority of species and stocks will be neutral, implying that these species have life history or behavioral traits that impart some level of resilience and adaptability to the impacts of climate change. These results provide information for use in ecosystem-based fisheries management, particularly for prioritization of vulnerable species and stocks in conservation activities and research endeavors.

1. Introduction

Anthropogenic climate change is extensively affecting the oceans, impacting environmental and biological oceanographic processes that form the foundations of marine ecosystems [1–4]. Climate change effects are particularly acute in the western North Atlantic Ocean where ocean temperatures are projected to increase three times faster than the global average [5]. Anthropogenic climate change is in part driving the weakening of ocean circulation systems, such as the Atlantic Meridional Overturning Circulation (AMOC), which affects key oceanographic features (e.g., Gulf Stream and the Labrador Current) throughout the Atlantic Ocean [5,6]. In response to a weakening AMOC, the extent of the Gulf Stream has shifted in recent years, affecting sea surface temperatures (SSTs) throughout the northwest Atlantic Ocean [6,7]. Rising SSTs have also been found to negatively impact sensitive biogenic habitats throughout the Gulf of America (GOA) (This document uses the Gulf of America to refer to the area formerly known as the Gulf of Mexico consistent with Executive Order (E.O.) 14172 (Restoring Names That Honor American Greatness), and the Gulf of Mexico areas outside of the United States Exclusive Economic Zone.) and Caribbean Sea through coral bleaching and seagrass bed degradation [8,9]. In the Caribbean Sea and oceanic portions of the Florida Reef Tract, coral reef habitats are further degraded by ocean acidification [10–13].

Climate change-driven environmental changes in marine ecosystems are projected to affect the distribution, productivity, and physiology of marine species globally [14–16]. Evaluating vulnerabilities of marine species to these climate-driven environmental changes is of growing importance to fishery managers as the effects of climate change are further considered in management actions and prioritization of

research efforts. This is of particular interest for Atlantic highly migratory species (HMS), such as sharks, tunas, and billfishes, which are characterized by their widespread distributions and considerable vagility, some migrating across ocean basins or specific habitat types [17]. Distribution of HMS throughout the western North Atlantic Ocean is largely influenced by temperature, dissolved oxygen, and prey availability, all of which are affected by climatic changes to key oceanographic features such as the Gulf Stream [18–24].

Recent examples of climate-related alterations of HMS distributions include evidence of poleward shifts in 11 recreational HMS fisheries in response to elevated SSTs throughout the Northeast U.S. Continental Shelf [25]. These findings are further supported by projected poleward suitable habitat shifts for HMS in the western North Atlantic Ocean [26,27] and globally for carcharhinid sharks [28]. Decreases in the productivity of five tuna species are projected by 2050, with up to an estimated 15% decline in body size in part due to climate stressors [29]. Finally, climate-related physiological impacts associated with ocean acidification are predicted for some HMS. *Ex situ* experiments found that ocean acidification conditions, such as decreased pH and elevated CO_2 concentrations, reduced the survival of various larval yellowfin tuna (*Thunnus albacares*) life stages [30] and reduced the odor-tracking capabilities of the smooth dogfish shark (*Mustelus canis*) [31].

The vulnerability of HMS to climate-related stressors can be assessed by evaluating the species' exposure to climate-related factors and their sensitivity to changing climatic conditions. Fish Climate Vulnerability Assessments (FCVAs) are a trait-based assessment tool that analyzes climate impacts on living marine resources. Developed by the National Oceanic and Atmospheric Administration (NOAA), NOAA FCVAs take a holistic approach to examining a suite of climate stressors and life history characteristics of marine species and rank species and stocks into distinct vulnerability categories. The NOAA FCVAs employ a two-pronged methodology to assess the vulnerability of marine species to climate change first described by Morrison et al. (2015) [32] and Hare et al. (2016) [33]: (1) evaluation of species- and stock-specific biological sensitivities (e.g., mobility, diet, reproduction) using scientific panel scoring; and, (2) climate exposure (i.e., the amount of environmental change a species may be exposed to in a defined time period) using ocean and climate modeling combined. Together, these qualitative and quantitative analyses combine panelists' knowledge of HMS life history traits, species' distribution, and ocean climate model projections.

Previous NOAA FCVAs have investigated the vulnerabilities of fish and invertebrate species and stocks to climate change within distinct regions or oceanographic features, such as the Northeast U.S. Continental Shelf (NE), California Current, GOA (previous NOAA FCVAs referred to this as the Gulf of Mexico), South Atlantic (SE), and Bering Sea, to assess climate-related stressors unique to the areas and species [33–38]. Lettrich et al. (2023) [39] performed a separate assessment of the vulnerability of marine mammals to climate change, as they were not included in the regional NOAA FCVAs. Similarly, many HMS species and stocks were not incorporated in the regional NOAA FCVAs, as many HMS distributions span multiple regions and lack basic life history data. The purpose of the HMS Climate Vulnerability Assessment (HMS CVA) was to provide a comprehensive assessment of the climate change vulnerabilities of 58 species and stocks managed under the 2006 Consolidated Atlantic HMS Fishery Management Plan (HMS FMP) [40] (Table 1), integrating their projected exposure to climate stressors and sensitivity given their unique life histories, physiologies, and behaviors. In addition to vulnerability rankings, estimated abilities of distributional shifts, predicted directional effects of climate change, and data quality scores were provided to produce detailed information for use in fisheries management.

2. Materials and methods

The HMS CVA used a modified methodology based on Morrison et al. (2015) [32], which relied on a combined quantitative and qualitative approach, taking advantage of scientific professionals' knowledge and advances in climate modeling. The HMS CVA modified techniques from other NOAA FCVA methodologies as found in Figure 1 of Hare et al. (2016) [33] and

Table 1. List of species and stock analyzed.

Common Name	Scientific Name	Species and Stock Complexes
Blue marlin	*Makaira nigricans*	Billfish and Swordfish
Longbill spearfish	*Tetrapturus pfluegeri*	Billfish and Swordfish
North Atlantic swordfish	*Xiphias gladius*	Billfish and Swordfish
Roundscale spearfish	*Tetrapturus georgii*	Billfish and Swordfish
West Atlantic sailfish	*Istiophorus platypterus*	Billfish and Swordfish
White marlin	*Kajikia albida*	Billfish and Swordfish
Basking shark	*Cetorhinus maximus*	Large Coastal Sharks
Bigeye sand tiger shark	*Odontaspis noronhai*	Large Coastal Sharks
Bignose shark	*Carcharhinus altimus*	Large Coastal Sharks
Blacktip shark - Atlantic stock	*Carcharhinus limbatus*	Large Coastal Sharks
Blacktip shark - Gulf of America stock	*Carcharhinus limbatus*	Large Coastal Sharks
Bull shark	*Carcharhinus leucas*	Large Coastal Sharks
Caribbean reef shark	*Carcharhinus perezii*	Large Coastal Sharks
Dusky shark	*Carcharhinus obscurus*	Large Coastal Sharks
Galapagos shark	*Carcharhinus galapagensis*	Large Coastal Sharks
Great hammerhead shark	*Sphyrna mokarran*	Large Coastal Sharks
Lemon shark	*Negaprion brevirostris*	Large Coastal Sharks
Narrowtooth shark	*Carcharhinus brachyurus*	Large Coastal Sharks
Night shark	*Carcharhinus signatus*	Large Coastal Sharks
Nurse shark	*Ginglymostoma cirratum*	Large Coastal Sharks
Sand tiger shark	*Carcharias taurus*	Large Coastal Sharks
Sandbar shark	*Carcharhinus plumbeus*	Large Coastal Sharks
Scalloped hammerhead shark	*Sphyrna lewini*	Large Coastal Sharks
Silky shark	*Carcharhinus falciformis*	Large Coastal Sharks
Smooth hammerhead shark	*Sphyrna zygaena*	Large Coastal Sharks
Spinner shark	*Carcharhinus brevipinna*	Large Coastal Sharks
Tiger shark	*Galeocerdo cuvier*	Large Coastal Sharks
Whale shark	*Rhincodon typus*	Large Coastal Sharks
White shark	*Carcharodon carcharias*	Large Coastal Sharks
Bigeye sixgill shark	*Hexanchus nakamurai*	Pelagic Sharks
Bigeye thresher shark	*Alopias superciliosus*	Pelagic Sharks
Sixgill shark	*Hexanchus griseus*	Pelagic Sharks
Longfin mako shark	*Isurus paucus*	Pelagic Sharks
North Atlantic blue shark	*Prionace glauca*	Pelagic Sharks
North Atlantic shortfin mako shark	*Isurus oxyrinchus*	Pelagic Sharks
Northwest Atlantic porbeagle shark	*Lamna nasus*	Pelagic Sharks
Oceanic whitetip shark	*Carcharhinus longimanus*	Pelagic Sharks
Sevengill shark	*Heptranchias perlo*	Pelagic Sharks
Common thresher shark	*Alopias vulpinus*	Pelagic Sharks
Atlantic angel shark	*Squatina dumerili*	Small Coastal Sharks and Smoothhound Sharks
Atlantic sharpnose shark - Atlantic stock	*Rhizoprionodon terraenovae*	Small Coastal Sharks and Smoothhound Sharks
Atlantic sharpnose shark - Gulf of America stock	*Rhizoprionodon terraenovae*	Small Coastal Sharks and Smoothhound Sharks
Smooth dogfish shark - Atlantic stock	*Mustelus canis*	Small Coastal Sharks and Smoothhound Sharks
Smooth dogfish shark - Gulf of America complex stock	*Mustelus canis*	Small Coastal Sharks and Smoothhound Sharks

(Continued)

Table 1. (Continued)

Common Name	Scientific Name	Species and Stock Complexes
Blacknose shark - Atlantic stock	*Carcharhinus acronotus*	Small Coastal Sharks and Smoothhound Sharks
Blacknose shark - Gulf of America stock	*Carcharhinus acronotus*	Small Coastal Sharks and Smoothhound Sharks
Bonnethead shark - Atlantic stock	*Sphyrna tiburo*	Small Coastal Sharks and Smoothhound Sharks
Bonnethead shark - Gulf of America stock	*Sphyrna tiburo*	Small Coastal Sharks and Smoothhound Sharks
Caribbean sharpnose shark	*Rhizoprionodon porosus*	Small Coastal Sharks and Smoothhound Sharks
Finetooth shark	*Carcharhinus isodon*	Small Coastal Sharks and Smoothhound Sharks
Florida smoothhound shark - Gulf of America complex stock	*Mustelus norrisi*	Small Coastal Sharks and Smoothhound Sharks
Gulf smoothhound shark - Gulf of America complex stock	*Mustelus sinusmexicanus*	Small Coastal Sharks and Smoothhound Sharks
Smalltail shark	*Carcharhinus porosus*	Small Coastal Sharks and Smoothhound Sharks
Atlantic bigeye tuna	*Thunnus obesus*	Tunas
North Atlantic albacore tuna	*Thunnus alalunga*	Tunas
West Atlantic bluefin tuna	*Thunnus thynnus*	Tunas
West Atlantic skipjack tuna	*Katsuwonus pelamis*	Tunas
Atlantic yellowfin tuna	*Thunnus albacares*	Tunas

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subsequent NOAA FCVAs to better reflect the highly migratory nature of species evaluated and newly available climate models by adjusting biological sensitivity attribute (BSA) definitions and applying a quantitative overlap approach to exposure analysis.

2.1. Scoping

2.1.1. Species and stock selection. All species and stocks managed by the 2006 Consolidated Atlantic HMS Fisheries Management Plan (HMS FMP) were included in the HMS CVA [40] (Table 1). These species and stocks (n = 58) were split into five complexes based on the 1999 Atlantic Highly Migratory Species Fishery Management Plan: Tunas, Billfish and Swordfish; Pelagic Sharks; Large Coastal Sharks; and Small Coastal Sharks including Smoothhound Sharks [41]. Regional stocks were determined by the Southeast Data, Assessment, and Review (SEDAR) process and International Commission for the Conservation of Atlantic Tunas (ICCAT) stock assessments, and those stocks were individually analyzed.

Species and stock names are consistent with management unit designations as found within Essential Fish Habitat (EFH), stock assessment procedures for HMS (i.e., SEDAR), and ICCAT.

2.1.2. Study area. The study area of the HMS CVA encompassed the distribution of all the species and stocks considered in the Atlantic Ocean. Given the trans-Atlantic migrations and stock mixing of certain species, the study area for some species encompassed portions of the South Atlantic Ocean and Mediterranean Sea. Coastal, estuarine, and pelagic habitats were considered throughout the assessment to account for all stages of life history.

2.1.3. Participants and scientific panel. A scientific panel was assembled to score the BSAs, data quality, and directional effect portions of the HMS CVA, and additional participants external to the panel were selected to take part in pilot studies to evaluate methodological changes and review assessment materials. Selected professionals for the scientific panel and other CVA tasks consisted of climate policy specialists and scientists, NOAA Northeast and Southeast Fisheries Science Center staff, academic fisheries scientists and oceanographers, scientists from state governments and non-governmental organizations, and a Core Plan Team made up of HMS fishery managers and scientists. The fifteen members of the scientific panel were selected based on their research experience and proficiency with the five species

and stock complexes. Panelists were considered proficient in one to three complexes, resulting in each complex being represented by at least three panelists. Each panelist scored 19 or 20 species and stocks, most of which fell within their identified complex expertise. The remaining assigned species spanned multiple or all complexes to minimize the influence of expert bias, as described in Morrison et al. (2015) [32].

2.1.4. Species profiles. Brief summaries of ecology, life history, behavior, and adaptations, hereafter termed "species profiles," were compiled for each species or stock based on the methods outlined by Hare et al. (2016) [33]. Information was gathered and synthesized for each BSA to provide panel members with background information for each species and stock. Species profiles were generated using a combination of primary, peer-reviewed, and secondary literature, including federal management documents (e.g., [40,42,43]), stock assessments, and textbooks (e.g., [44,45]). The amount of information available differed for each species and stock; for example, there was an abundance of documentation with background information and data to share with panelists regarding the BSAs for species such as the sandbar shark (*Carcharhinus plumbeus*) and Atlantic bluefin tuna (*Thunnus thynnus*), but for data-limited species, like the roundscale spearfish (*Tetrapturus georgii*) and longbill spearfish (*Tetrapturus pfluegeri*), relevant information for closely related species was used as a proxy for BSAs. No information was provided if there were no comparable species available, which was the case for narrowtooth shark (*Carcharhinus brachyurus*). Each profile was peer-reviewed by Core Plan Team members, pilot study participants, and members of the scientific community with subject matter expertise.

2.2. Scientific panel scoring assessment

The scientific panel was engaged to score BSAs, directional effects, and data quality during a preliminary scoring round for BSAs and data quality between April and May 2023, followed by a final scoring round from May to July 2023. The HMS CVA Workshop was held in May 2023 during the final scoring round to provide opportunities for panelists to discuss scores, clarify BSA definitions and interpretations, and request assistance with the scoring process. Scoring for BSAs, directional effects, and data quality followed frameworks outlined in Morrison et al. (2015) [32] and Hare et al. (2016) [33], and were guided by definitions and rubrics provided by the Core Plan Team. These materials were based on similar NOAA FCVA scoring materials used in past assessments. Panelists completed directional effect scoring after the completion of BSA and data quality scoring.

2.2.1. Biological sensitivity attribute selection. A total of 13 BSAs were identified to evaluate the biological sensitivity and adaptive capacity of the HMS included in this CVA (Table 2). These BSAs included biological and behavioral characteristics that may make a species or a stock in a given region more or less sensitive to climate change. Some CVA approaches have elected to evaluate adaptive capacity and biological sensitivity separately, [46–49], in contrast to the methodology defined in Morrison et al. (2015) [32] which includes adaptive capacity as part of biological sensitivity. Adaptive capacity within the HMS CVA and other FCVAs was evaluated by inversing BSA scores, e.g., low sensitivity scores indicated high adaptive capacity. For the purposes of this study, species and stocks classified as having low sensitivity and high adaptive capacity are likely to be able to mitigate or adapt to the effects of environmental change through existing life history characteristics or evolutionary responses [32,50,51]. The selection of BSAs was initially informed by previously-conducted CVAs [33,35,36,38,39]. Since those CVAs were used to evaluate species with substantially different life history characteristics (e.g., sessile species), the initial BSAs chosen for this assessment were modified to be more relevant to the highly migratory nature of the species being assessed. More specifically, some attributes were redefined, and scoring rubrics (low- vs. high-score definitions) were tailored specifically for HMS, using considerations from a similar CVA [39]. The modified scoring rubrics and definitions were based on elasmobranch considerations in the Northeast Climate Vulnerability Assessment (NE CVA) of fish and invertebrates species in the Northeast U.S. Continental Shelf Large Marine Ecosystem [33], stock status guidelines in the HMS Stock Assessment and Fishery Evaluation Report [43], and overall HMS traits (e.g., high adult mobility). The purpose for evaluating a particular

Table 2. BSAs used to assess biological sensitivity of HMS species and stocks.

Biological Sensitivity Attribute	Purpose	Scoring Rubric Guidelines	
		Low	Very High
Habitat Specificity	Determine the relative dependence a stock has on habitat and the abundance of the habitat	Habitat generalist with abundance habitat available	Habitat specialist on a limited habitat type
Prey Specificity	Determine if the stock is a prey generalist or specialist	Generalist	Specialist
Sensitivity to Ocean Acidification	Determine the stock's relationship to "sensitive taxa"	Is not a sensitive taxon or does not rely on a sensitive taxon for food or shelter	Stock is a sensitive taxon, or relies on a sensitive taxon for food or shelter
Reproductive Strategy Sensitivity	Identify complex reproductive strategies that are more sensitive to changes in the environment	Few characteristics of a complex reproductive strategy; does not require specific conditions for successful reproduction	Several characteristics of a complex reproductive strategy, requiring specific conditions for successful reproduction
Sensitivity to Temperature	Known temperature of occurrence or distribution as a proxy for sensitivity to temperature	Species found in wide temperature range or has a distribution across wide latitudinal range and depths	Species found in limited temperature range or has a limited distribution across latitude and depths
Specificity in Early Life History Requirements	Determine the relative importance of early life history requirements for a stock	Larval/young-of-year requirements are minimal and relatively resistant to environmental change	Larval/young-of-year requirements are specific and likely to be impacted by environmental change
Stock Size/ Status	Determine if the stock's resilience is compromised due to low abundance	High abundance and/or not overfished	Low abundance and/or overfished
Other Stressors	Account for other factors that could limit population responses to climate change	Stock is experiencing no known stressor (other than fishing)	Stock is experiencing high stress from multiple stressors (other than fishing)
Population Growth Rate	Estimate the productivity of a stock	High productivity	Low Productivity
Mobility and Dispersal of Early Life Stages	Estimate the ability of the stock to colonize new habitats	High dispersal	Low dispersal
Adult Mobility	Determine the ability of the stock to move if their current location becomes unsuitable	Highly mobile adults	Sessile adults
Reproductive Cycle	Identify spawning strategies that are more sensitive to changes	Year-round spawners	Short-duration and infrequent spawners
Site Fidelity	Assess the degree to which individuals utilize the same sites year after year.	No site fidelity	High degree of site fidelity (i.e., specific bays, estuaries, or inlets)

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attribute (Purpose) and the definitions used for assigning low and very high scores (Scoring Rubric Guidelines) are included in Table 2. See S1 File for more details on BSAs.

A pilot study with the scientific panel was conducted to determine the validity of modifications to the initial BSA criteria. We evaluated the variance in sensitivity scoring (described in detail in 2.2.2) of 10 species based on the descriptions of the sensitivity analyses in the NE CVA [33] and the modified HMS BSAs. The outcomes revealed minor or no differences in scoring for most species and BSAs; therefore, we proceeded with the changes to BSAs that would best reflect the range of life history strategies, characteristics and attributes specific to HMS when evaluating their climate vulnerability.

2.2.2. Biological sensitivity attribute scoring. During the assessment scoring period, the 15-member scientific panel was tasked to individually score 13 BSAs for each species and stock assessed in the HMS CVA (S1 Data). For each BSA, panelists were granted five tallies that could be distributed across four different scoring bins (bin 1 = low, bin 2 = moderate, bin 3 = high, bin 4 = very high) for each species. BSA definitions and scoring rubrics were provided to guide

panelist scoring, supplying clear direction on how each BSA should be interpreted and specific values or descriptions for each scoring bin (S1 File).

Panelists indicated confidence or uncertainty in their scoring using the distribution of the five tallies throughout four scoring bins. Panelists were instructed to spread their tallies across the scoring bins and use one or more tallies, based on supporting information or their judgment, to weigh which bin best represented the attributes of the species or stock. For example, if the population growth rate of a species is uncertain, but the species or stock is known to be long-lived and slow-growing, panelists could place one tally in each bin and the additional fifth tally in the very high bin. If a panelist is confident in their score, they may place the majority or all tallies in a single bin. For the purposes of the HMS CVA, species and stocks were evaluated in comparison to each other rather than to non-HMS complexes, such as shellfish or groundfish.

Following methods from previously completed NOAA FCVAs, a weighted average was calculated for individual BSAs for each species and stock analyzed:

$$\text{Weighted Average} = \frac{((L*1) + (M*2) + (H*3) + (VH*4))}{(L + M + H + VH)} \quad (1)$$

where L, M, H, and VH correspond to the sum number of tallies in each low, moderate, high, and very high scoring bin, respectively. The multipliers (1, 2, 3, and 4) were used to weight the averages which were later used to calculate Overall Vulnerability Rankings.

2.2.3. Data quality scoring. Data quality was scored individually by panelists for each of the 13 BSAs per species or stock. A scoring rubric (Table 3) was provided to guide panelist scoring. Data quality scores were based on the information provided in species profiles, the amount and quality of information available regarding the attribute, and the panelists' own understanding and knowledge of the species or stock. Panelists were able to indicate confidence or uncertainty in their scoring by submitting scores between a range of 0–3. Data quality was ranked using the proportion of scores above two. High data quality was defined as 80% of data quality scores 2 or higher, moderate data quality as 50–79% scores 2 or higher, and poor data quality as 0–50% of scores 2 or higher.

2.2.4. Potential for distributional change. Distributional shift refers to the ability of a species or stock to move beyond its current range in response to changing environmental conditions. The potential for a distributional shift was calculated individually for each species and stock using a subset of BSAs: Adult Mobility; Habitat Specificity; Mobility and Dispersal of Early Life Stages; and Sensitivity to Temperature. All BSA scores, except Sensitivity to Temperature, were inverted because species that have highly mobile adults, broadly dispersed early life history stages, low habitat specificity, and high-temperature sensitivity would likely have the ability to shift distribution under changing conditions. The NOAA FCVA logic model (Table 4) was applied to combine and then sort the combined scores from these analyses into four bins: low, moderate, high, and very high. A low potential for distributional change indicates that the species or stock is less able to shift in response to a changing environment, whereas a very high potential indicates that the species or stock is able to,

Table 3. Data quality scoring rubric.

Data Quality Score	Description
3	Adequate Data. The score is based on data which have been observed, modeled or empirically measured for the species in question and comes from a reputable source.
2	Limited Data. The score is based on data which has a higher degree of uncertainty. The data used to score the attribute may be based on related or similar species, come from outside the study area, or the reliability of the source may be limited.
1	Expert Judgment. The attribute score reflects the expert judgment of the reviewer and is based on their general knowledge of the species, or other related species, and their relative role in the ecosystem.
0	No Data. No information to base an attribute score on. Very little is known about the species or related species and there is no basis for forming an expert opinion.

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Table 4. FCVA logic model.

FCVA Logic Model		
Overall sensitivity or exposure score	**Numeric score**	**Decision Rule**
Very high	4	3 or more factors with mean score ≥3.5
High	3	2 or more factors with mean score ≥ 3.0
Moderate	2	2 or more factors with mean score ≥ 2.5
Low	1	All other scores

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and readily moves to, seek suitable habitat. Additionally, a species' or stock's range was considered when evaluating the potential for distributional changes.

2.2.5. Directional effect scoring. Directional effect refers to the anticipated overall impacts of climate change on a species or stock in a future time period. For example, a species anticipated to be negatively affected by climate change may encounter loss of suitable habitat, species that are neutrally affected may be able to shift their distribution in response to unfavorable conditions, and a species positively affected may experience a range expansion. Relevant life history characteristics and information gathered throughout the sensitivity analysis were considered when scoring the directional effect on a species or stock. Panelists were provided four tallies and asked to place tallies across three scoring categories (Negative, Neutral, Positive) to reflect their understanding of likely overall impacts of climate change on a species or stock. Similar to BSA scoring, panelists were able to indicate confidence or uncertainty in their scoring using the distribution of the four tallies throughout the three scoring bins. Directional effect scoring occurred after sensitivity analysis and data quality scoring were completed.

Directional effect scores were calculated using a weighted average of the scores from five panelists. The equation is as follows:

$$\text{Directional Effect Weighted Average} = \frac{((Neg * -1) + (Neu * 0) + (Pos * 1))}{(Neg + Neu + Pos)} \quad (2)$$

where Neg, Neu, and Pos correspond to the sum number of tallies in each Negative, Neutral, and Positive scoring categories, respectively. The multipliers (-1, 0, and 1) were used to weight the average. Weighted averages were sorted into Negative, Neutral, and Positive rankings where values less than or equal to -0.333 ranked as Negative, those between -0.333 and 0.333 ranked as Neutral, and those greater than or equal to 0.333 ranked as Positive. Directional effect scores are provided as S2 Data.

2.3. Climate exposure

2.3.1. Species distributions determination. In the NOAA FCVA methodology, climate exposure analysis measures the magnitude of environmental change a species or stock may experience throughout its range by comparing conditions from a reference time period to projections of a future time period and calculating a standardized anomaly between the two periods. The exposure analysis process requires the identification of an established range for the species or stock. Species and stock distributions were determined by conducting a primary literature search and surveying professional knowledge from participating fisheries scientists. International Union for Conservation of Nature (IUCN) distributions were used as the baseline geographical limits for each species. For each complex, at least two fisheries scientists with specialized experience in the relevant species' distributions used SEDAR and ICCAT stock assessments, supporting papers, and EFH designations to recommend adjustments to the initial IUCN distributions.

Table 5. Exposure factors used to assess climate exposure of HMS species and stocks.

HMS CVA Exposure Factor	Definition	Abbreviation
Surface salinity	Sea water salinity is the salt content of seawater, often on the Practical Salinity Scale of 1978. However, the unqualified term 'salinity' is generic and does not necessarily imply any particular calculation method.	SS
Bottom salinity	Salinity of the lowest ocean model level down to 400m.	BS
Surface temperature	Temperature of the upper boundary of the liquid ocean, including temperatures below sea-ice and floating ice shelves.	SST
Bottom temperature	Temperature of the lowest ocean model level down to 400m.	BT
Precipitation	Total liquid equivalent precipitation at the surface.	Precip
Surface wind stress magnitude	Downward eastward wind stress at the surface and downward northward wind stress at the surface	SWSM
Sea surface oxygen	Dissolved oxygen concentration at the ocean surface.	SSO
Oxygen at 200m	Dissolved oxygen concentration at 200m.	O200
Magnitude of sea surface temperature gradient	Pelagic fronts and boundaries shifting, affecting offshore species.	MSSTG
Mixed layer depth	Depth that is 0.125 kg/m^3 greater than the surface value.	MLD
pH	Negative log of hydrogen ion concentration at the ocean surface.	pH
Primary production	Rate of primary organic carbon production by all types of phytoplankton integrated over all depths.	PP

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Scientists also scored their certainty in species distribution determinations using the same scale as data quality scoring (S3 Data). For species where distributional information was lacking or deficient according to the fisheries scientists, a species distribution was not confirmed, and therefore no exposure analysis was completed for them.

2.3.2. Climate exposure factors selection. Upon determining species and stocks distributions, eight exposure factors available in CMIP6 [52–54] were selected from a pool of 11 exposure factors considered because the exposure of a specific factor may not be relevant for a particular species (Table 5). For example, using bottom temperature would not be appropriate as an exposure factor for Atlantic bluefin tuna given their epipelagic distribution. Sea surface oxygen, pH, primary production, and mixed layer depth were evaluated for every species and stock in addition to four other exposure factors. These four exposure factors were determined to influence all species and stocks throughout their life history stages and play an integral role in the formation of suitable habitat or affect their physiological development. The remaining four factors were chosen based on life history characteristics and the behavioral ecology of each species and stock. Variables are available via the CMIP6 Data Request page [54]. All exposure factor assignments are included in S1 Table.

2.3.3. Climate projections and time periods. Exposure factor projections were obtained from an ensemble of Global Climate Models that contributed to phase 6 of the Coupled Model Intercomparison Project (CMIP6) [55] run with Shared Socio-economic Pathways (SSP) 5-8.5, which assumes a fossil-fuel intensive world and the highest greenhouse gas emission scenario [2,56–59] (the high emission scenario with high challenges to mitigation and low challenges to adaptation) from CMIP6 [52,53]. The CMIP6 multi-model ensemble reflects updated climate and socio-economic data and includes additional exposure factors, historical periods, and future periods to select from compared to CMIP5, which was used for previous NOAA FCVAs. In the case of the HMS CVA, use of SSP5-8.5 can accentuate the response of species or stocks to climate change and maintains consistency with past NOAA FCVAs [33–39] assessing the same species or stocks.

The 1985–2014 interval was selected as the historical time period, corresponding to when the greatest amount of distribution data is available for HMS. The choice of time period in this study differed from past NOAA FCVAs as the CMIP6 multi-model ensemble offers shorter time ranges compared to CMIP5, 29 years versus 49 years, respectively. Two future

periods, 2020–2049 and 2030–2059, were tested to evaluate differences in exposure score changes for selected factors. The 2020–2049 period was ultimately selected as it falls within the foreseeable future (i.e., strategic planning decisions made now could reasonably address data gaps identified in the future time period), and the time period was similar to future periods used in other recent NOAA FCVAs [33–39]. While this future period is actionable in the near term, selecting a shorter, near-term time period also implies that the magnitude of environmental changes analyzed will be lesser than if a longer, or more distant future time period was selected. This decision was made to increase the efficacy of HMS CVA findings in the near term, but may limit the use of the HMS CVA in decision-making past the selected future time period (2020–2049).

Standardized anomalies were downloaded at a resolution of 1° latitude by 1° longitude for the entire Atlantic Ocean for the aforementioned exposure factors using SSP5-8.5 for both the 1985–2014 historical time period and the 2020–2049 future time period. Anomalies between the future and historical time period were standardized by the detrended inter-annual standard deviation over the historical period.

2.3.4. Climate exposure scoring. Previous NOAA FCVAs used panelist scoring for climate exposure analysis [33,34,36–39]. However, the HMS CVA binned standardized anomalies to calculate the climate exposure ranking for applicable species. Finalized species distributions (Fig 1A) were overlaid on top of gridded standardized anomalies of each exposure factor (Fig 1B) and grid cells that overlapped with the species distribution were selected (Fig 1C). Any partial overlap between the species distribution and the exposure factor included that grid cell, which ensured coastal

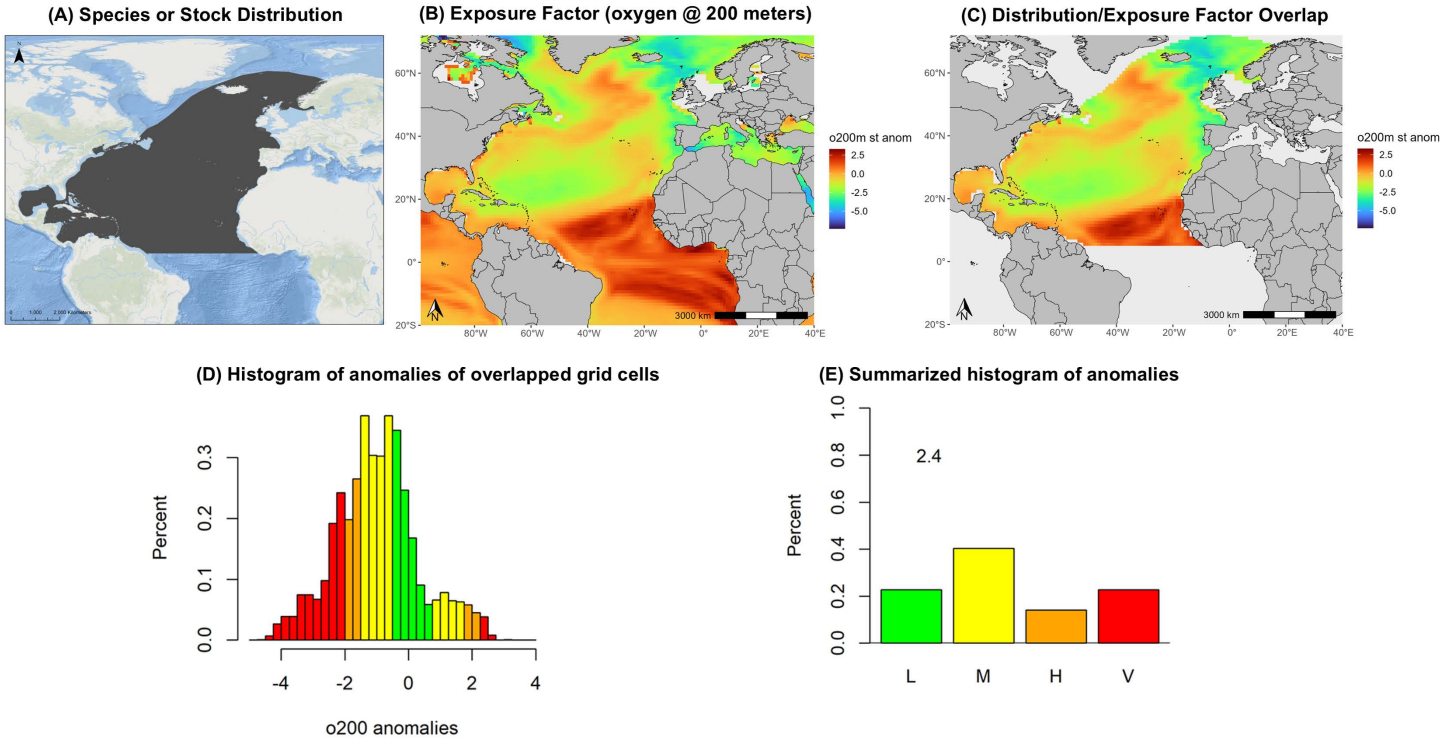


Fig 1. Exposure analysis process. An example of the five-step process to get a weighted average score for a specific exposure factor and species, is the North Atlantic swordfish (*Xiphias gladius*) stock. (A) A map showing the species or stock distribution. (B) A map of the standardized anomalies of the exposure factor, oxygen at 200 meters depth. (C) A map of the overlap between the stock distribution and the standardized anomalies. (D) Histogram of the standardized anomalies in the overlapped grid cells color-coded at four exposure levels: very high (red), high (orange), moderate (yellow), and low (green). (E) Summarized histogram of anomalies categorized in the four exposure levels with the weighted average (2.4) of that exposure factor.

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areas and edges of distributions were included. For a given species or stock and exposure factor, standardized anomalies from the gridded overlapped area were put into 0.25 standard deviation bins ranging from the minimum and maximum standardized anomalies. This binning elucidated the fine-scale distribution of the standardized anomalies for a given species or stock and exposure factor. The bins were then coded into the low, moderate, high, and very high categories, where the absolute standardized anomalies above 2.0 were classified as very high, those between >1.5 and 2.0 as high, those between 0.5 and <1.5 as moderate, and those below 0.5 as low (Fig 1D). Once all absolute standardized anomalies were placed into the four coarse bins, the exposure factor weighted average was calculated using Equation 1 (Fig 1E). These steps were completed for each selected exposure factor for each species or stock with a defined distribution so that each species- or stock-specific exposure factor would have a weighted average. Given the absence of scientific panel scoring of the exposure analysis component, no data quality scores were collected for exposure factors.

2.4. Overall vulnerability rankings

The NOAA FCVA logic model (Table 4) was applied to the weighted averages of BSAs and exposure factors to determine an assigned numeric score for the two components. After determining the numeric scores for the sensitivity and exposure components, these scores were multiplied to calculate a combined score. The overall vulnerability rank of low, moderate, high, or very high was assigned to the species or stock analyzed based on the criteria in Table 6. Fig 2 illustrates how the NOAA FCVA logic model was applied to calculate the overall vulnerability ranking for sand tiger shark (*Carcharias taurus*).

2.5. Additional analyses

2.5.1. Certainty in vulnerability scores. Estimates of vulnerability uncertainty (i.e., the distribution of tallies across the four vulnerability bins) were produced from 10,000 bootstraps. Specifically, the 25 tallies (5 tallies per scientific panelist) scored across the five scientific panelists for a given species and attribute were resampled with replacement 10,000 times. A new weighted average was calculated for each bootstrap iteration, and the sensitivity component numeric score was determined and multiplied by the exposure component score to get a new vulnerability score and rank. We determined the proportion of the 10,000 iterations that fell into each rank category. For example, if a species had a high vulnerability ranking and a high ranking occurred for 75% of the iterations, we determined that we could be 75% certain that the ranking was accurate. Distribution shift potential and directional effect certainty was calculated using the same bootstrapping technique and parameters.

2.5.2. Ranking influence of biological sensitivity attribute or exposure factor. A leave-one-out analysis was conducted to understand how sensitive a species' vulnerability rank was to any given BSA or exposure factor, as described in Hare et al. 2016 [33]. This analysis removed the weighted average for a particular BSA or exposure factor, a new component score was calculated, and a new vulnerability score was determined. This was done for each BSA and exposure factor. If the vulnerability rank changed by at least one rank due to leaving a BSA or exposure factor out, that attribute or factor would

Table 6. FCVA combined score rankings.

FCVA Combined Score Rankings	
Combined numeric score	**Overall Vulnerability Ranking**
1-3	Low
4-6	Moderate
8-9	High
12-16	Very High

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(A)

Sensitivity Attributes	Weighted Averages
Adult Mobility	1.76
Habitat Specificity	1.84
Mobility and Dispersal of Early Life Stages	1.28
Other Stressors	2.08
Population Growth Rate	3.56
Prey Specificity	1.6
Reproductive Cycle	1.28
Reproductive Strategy Sensitivity	2.16
Sensitivity to OA	1.56
Sensitivity to Temperature	1.8
Site Fidelity	2.96
Specificity in Early Life History Reqs	1.56
Stock Size / Status	2.68

2: Moderate

×

(B)

Exposure Factors	Weighted Averages
Bottom salinity	2.67
Bottom temperature	3.60
Mixed Layer Depth	1.4
pH	3.93
Primary productivity	1.30
Precipitation	1
Sea surface oxygen	3.84
Surface wind stress magnitude	1.05

4: Very High

= 8 **Sand Tiger Shark: High Vulnerability Ranking**

Fig 2. An example of overall climate vulnerability calculation for the sand tiger shark (*Carcharias taurus*). Weighted averages for the 13 BSAs (A) (low = green, yellow = moderate, orange = high, red = very high) resulted in a sensitivity analysis score of two or "moderate" following the logic model. Weighted averages for the eight climate exposure factors (B) (low = green, yellow = moderate, orange = high, red = very high) resulted in an exposure analysis score of four or "very high" following the logic model. Multiplying the sensitivity and exposure analysis scores resulted in an overall climate vulnerability rank of eight or "high" (orange = high).

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be considered important for predicting vulnerability ranking for that species or stock. Additional analyses were conducted to examine similarities in BSA scores across stock complex and vulnerability rank. The methods and results from these analyses can be found in S2 File. All analyses described in Sections 2.2 through 2.5 were conducted in R v4.0.4 [60].

2.6. Species narratives

Species narratives were generated to summarize the results of the CVA for each species and stock (S3 File). The narratives provided the final scores for ranked climate vulnerability, climate exposure, biological sensitivity, potential for distributional change, directional effect of climate change, and data quality. Descriptions of each species' or stock's ecology and biology were used to qualify the scores. Summaries of the climate effects on distribution and abundance were written for each species based on available primary and secondary literature. Finally, a synopsis of life history was written for each species and stock using the information gathered during species profile drafting and synthesis of additional literature identified by panelists. Species narratives were reviewed for content and consistency by two to four members of the scientific panel, Core Plan Team members, pilot study participants, or members of the scientific community with subject matter expertise.

3. Results

3.1. Overall climate vulnerability

Of the 58 species and stocks considered in the HMS CVA, only 46 were assigned final vulnerability rankings. The Large Coastal Shark complex had the highest average vulnerability score (6.79 ± 2.68) representing the largest number of scored species and stocks (41%, n = 19). The Tuna complex had the smallest average vulnerability score (3.8 ± 1.3), representing approximately 11% (n = 5) of scored species and stocks. The complex with the smallest number of scored species and stocks (n = 4), Billfish and Swordfish, had the second highest average vulnerability score (6.75 ± 2.5). Five species within the Small Coastal Sharks and Smoothhound Sharks complex did not receive exposure scores, followed by four within Large Coastal Sharks, two within Billfish and Swordfish, and one within Pelagic Sharks. Of the 58 species and stocks, 7% (n = 4) were considered to have very high vulnerability to climate change, 24% (n = 14) high vulnerability, 38% (n = 22) moderate vulnerability, 10% (n = 6) low vulnerability, and 21% (n = 12) did not receive an overall vulnerability rank because they did not receive exposure scores (Fig 3A and 3B). Very high overall vulnerability rankings spanned the three shark complexes with the distribution split across the Large Coastal Sharks (n = 2; Caribbean reef [*Carcharhinus perezi*] and dusky [*Carcharhinus obscurus*]), Pelagic Sharks (n = 1; oceanic whitetip [*Carcharhinus longimanus*]), and Small Coastal Sharks and Smoothhound Sharks (n = 1; bonnethead shark, Atlantic stock) (Fig 3). High vulnerability rankings occurred for 75% (n = 3) and 41% (n = 9) of scored species and stocks in the Billfish and Swordfish and Large Coastal Shark complexes, respectively (Fig 4). Moderate vulnerability rankings occurred for the 78% (n = 7) Pelagic Sharks and 67% (n = 6) Small Coastal Sharks and Smoothhound Sharks. Three of the six species and stocks with low vulnerability rankings were found in the Tuna complex (Fig 4).

The proportion of species and stocks within each vulnerability ranking differed between sensitivity and exposure analysis. Regarding exposure, 62% (n = 36), 17% (n = 10), and 21% (n = 12) of species and stocks ranked very high, high, and data-deficient for exposure analysis, respectively, with no species or stocks ranked as moderate or low. In contrast, no species or stocks ranked very high for sensitivity and were instead distributed across the remaining three categories: 7% (n = 4) high, 38% (n = 22) moderate, and 55% (n = 32) low sensitivity. Bootstrap resampling of overall vulnerability rankings revealed a range of confidence in the accuracy of species and stocks scores; 26% (n = 15) of species and stocks had above 95% certainty, 12% (n = 7) fell within 90–95% certainty, 28% (n = 16) fell between 67–89%, 14% (n = 8) fell below or equal to 66% certainty, and 21% (n = 12) were not evaluated due to lack of exposure analysis. By complex, 30% of Large Coastal Sharks fell within 90–100% certainty, 30% fell between 67–89%, 22% fell below or equal to 66%, and 17% were not evaluated due to lack of exposure analysis. For Small Coastal Sharks and Smoothhound Sharks, 43% of species certainty was greater than 95% and 36% were not evaluated due to lack of exposure analysis. Of the nine Pelagic Sharks, three had certainty above 95%, four fell between 67–89%, and two had certainty below or equal to 66%. The five Tuna species fell into all certainty groups except for the equal to or below 66% group. Of the four Billfish and Swordfish species that received vulnerability rankings, three had certainty above or equal to 90% and one had 67–89%.

3.2. Potential for distributional change

The majority of species and stocks considered fell into the high potential for distributional change category (78%, n = 45), followed by the very high category (21%, n = 12), and one stock was within the moderate category (2%, n = 1) (Fig 5). The species and stocks considered more able to shift their distribution (evaluated using distinct low, moderate, high, and very high categories) often displayed the following characteristics: highly mobile adults, habitat generalists, broadly dispersing early life stages, or were sensitive to temperature. Seventy percent (n = 7) of species within the Pelagic Sharks complex ranked as very high potential for distributional change, followed by 13% (n = 3) of species within the Large Coastal Sharks, and 14% (n = 2) of stocks within the Small Coastal Sharks and Smoothhound Sharks complexes (Fig 4). One hundred percent of the Billfish and Swordfish species (n = 6) and Tuna species (n = 5) were given a high potential for distributional change rankings, whereas 87% (n = 20) of Large Coastal Sharks and 79% (n = 11) of Small Coastal Sharks

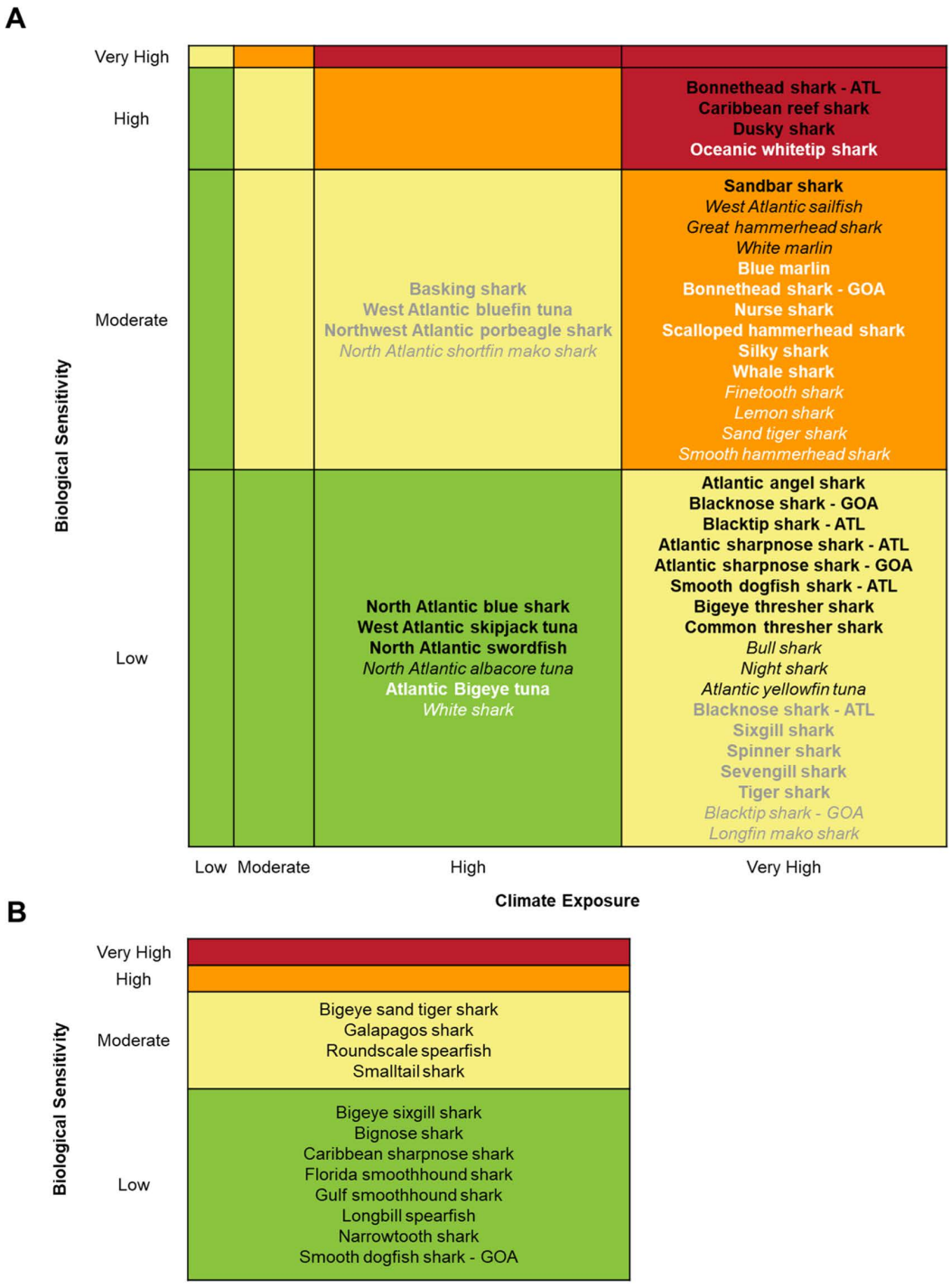


Fig 3. Overall climate vulnerability ranks. (A) Overall climate vulnerability ranks for 46 Atlantic HMS or stocks calculated from the sensitivity analysis and exposure analysis scores. Overall climate vulnerability is indicated by color: low (green), moderate (yellow), high (orange), and very high (red). Certainty scores are determined by text font and text color: very high certainty (>95%, black, bold font), high certainty (90-95%, black, italic font), moderate certainty (67-89%, gray or white, bold font), low certainty (≤66%, gray or white, italic font). (B) Sensitivity analysis score for the 12 Atlantic HMS where the exposure analysis was not performed. Sensitivity analysis score is indicated by the same color scheme as described above. Certainty scores are not available for the 12 species, therefore all species are presented in black font.

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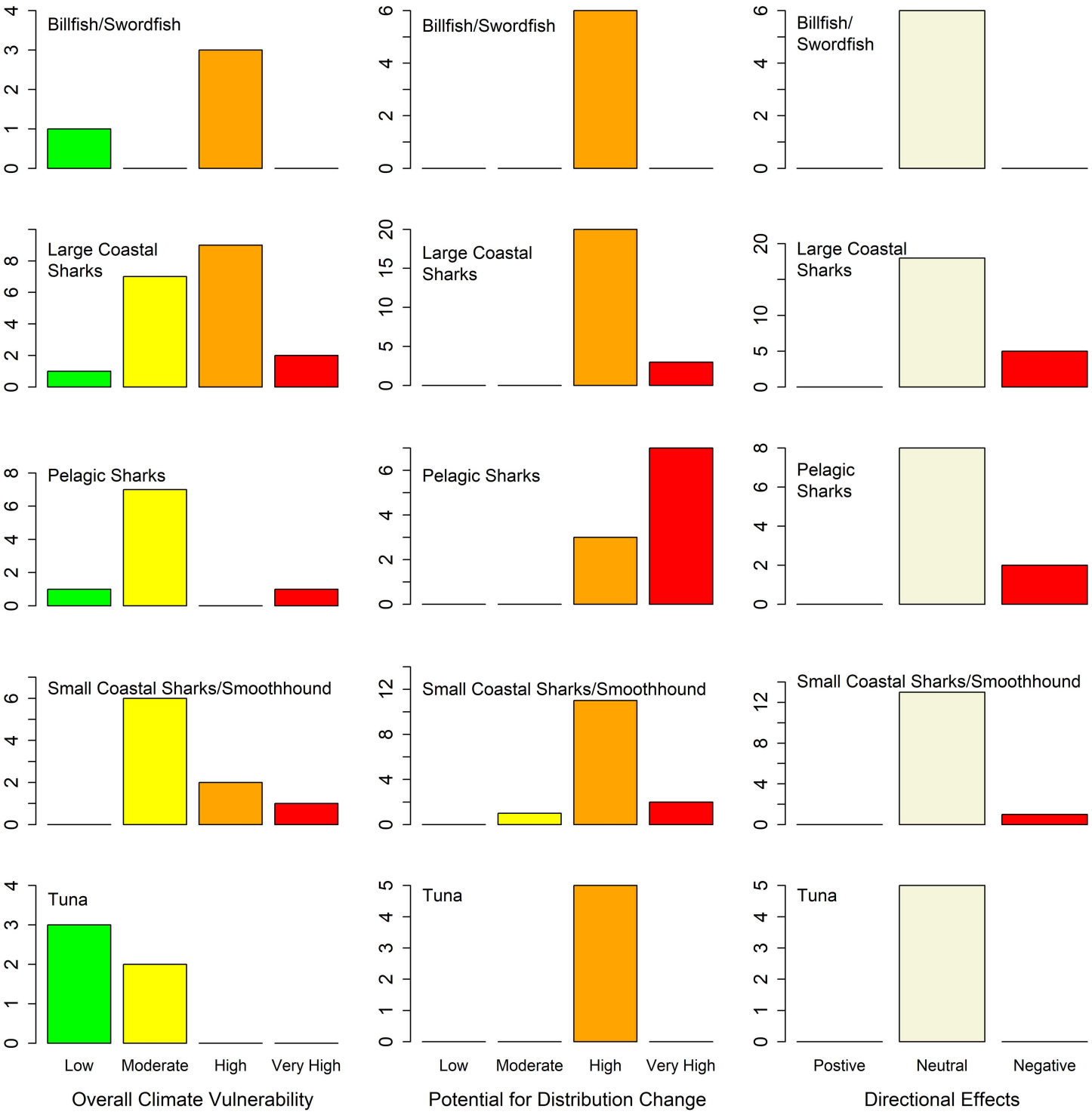


Fig 4. Number of species and stocks that occurred in each category for each analyses. Number of species and stocks from each complex that occurred in each category for overall climate vulnerability (left column), potential for distribution change (middle column), and directional effects (right column).

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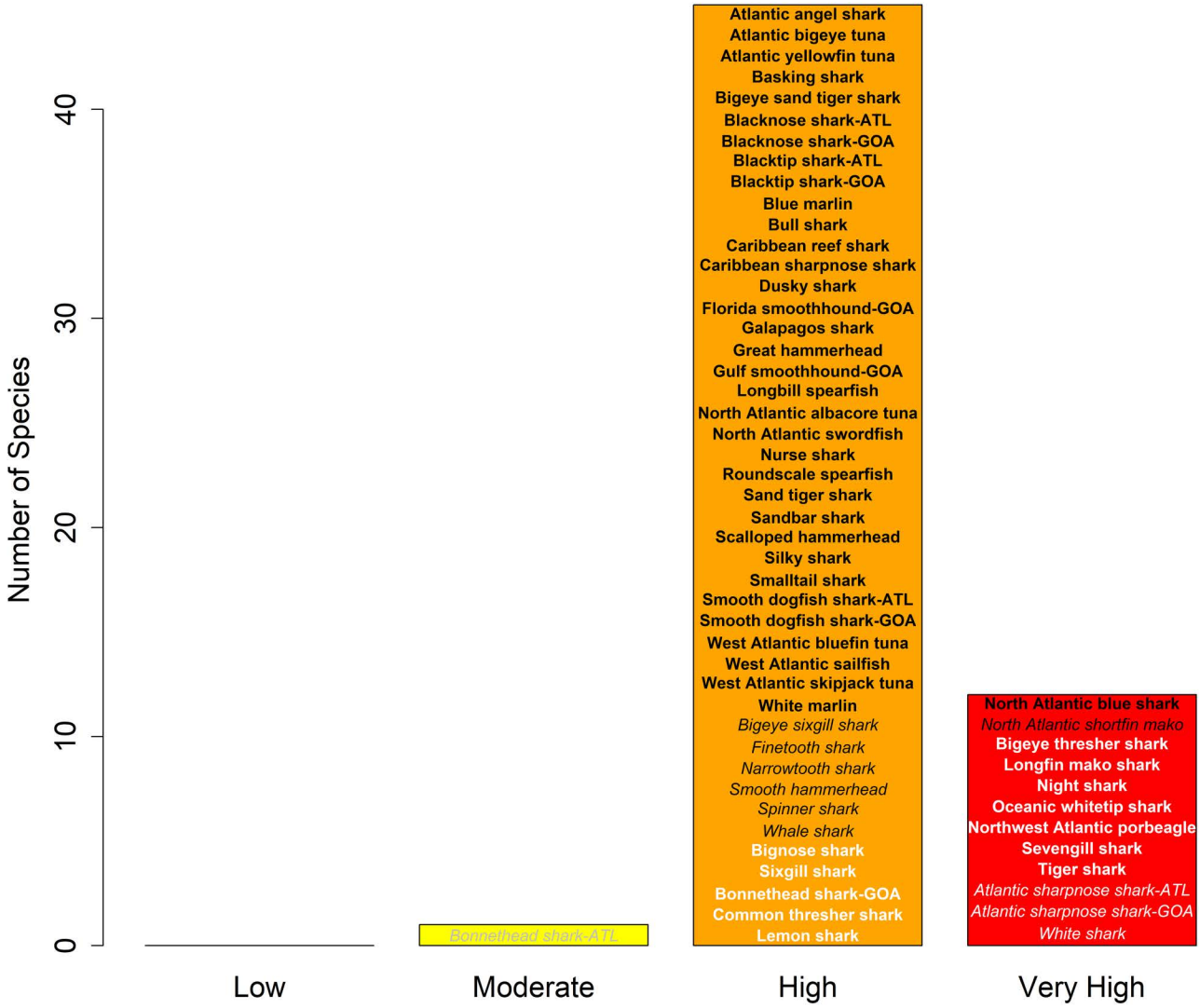


Fig 5. Potential for distributional change ranks. Potential for distributional change ranks for 58 Atlantic HMS or stocks calculated from biological sensitivity attribute scores. Potential for distributional change ranks are indicated by color: low (green), moderate (yellow), high (orange), and very high (red). Certainty scores are determined by text font and text color: very high certainty (>95%, black, bold font), high certainty (90-95%, black, italic font), moderate certainty (67-89%, gray or white, bold font), low certainty (≤66%, gray or white, italic font).

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and Smoothhound Sharks were also found in that ranking (Fig 4). The bonnethead shark (Atlantic stock) (*Sphyrna tiburo*) in the Small Coastal Sharks and Smoothhound Sharks complex was the only species or stock that received a moderate potential for distributional change ranking. Sixty percent (n = 35) of the rankings had above 95% certainty, 12% (n = 7) were in the 90–95% certainty range, 21% (n = 12) were in the 67–89% certainty range, and 7% (n = 4) were below or equal to 66% certainty (Fig 5).

3.3. Directional effect of climate change

Panelists scored the directional effect of climate change, defined as the anticipated impacts of climate change on a species or stock in the future time period (2020–2049). No species or stock received a positive ranking, 86% (n = 50) received a neutral ranking, and 14% (n = 8) received a negative ranking (Fig 6). Negative rankings were distributed across the Pelagic (n = 2), Large Coastal (n = 5), and Small Coastal Sharks and Smoothhound Sharks (n = 1) complexes (Fig 4). Seventeen percent (n = 10) of the rankings had above 95% certainty, 22% (n = 13) were in the 90–95% certainty range, 50% (n = 29) were in the 67–89% certainty range, and 10% (n = 6) were below or equal to 66% certainty (Fig 6).

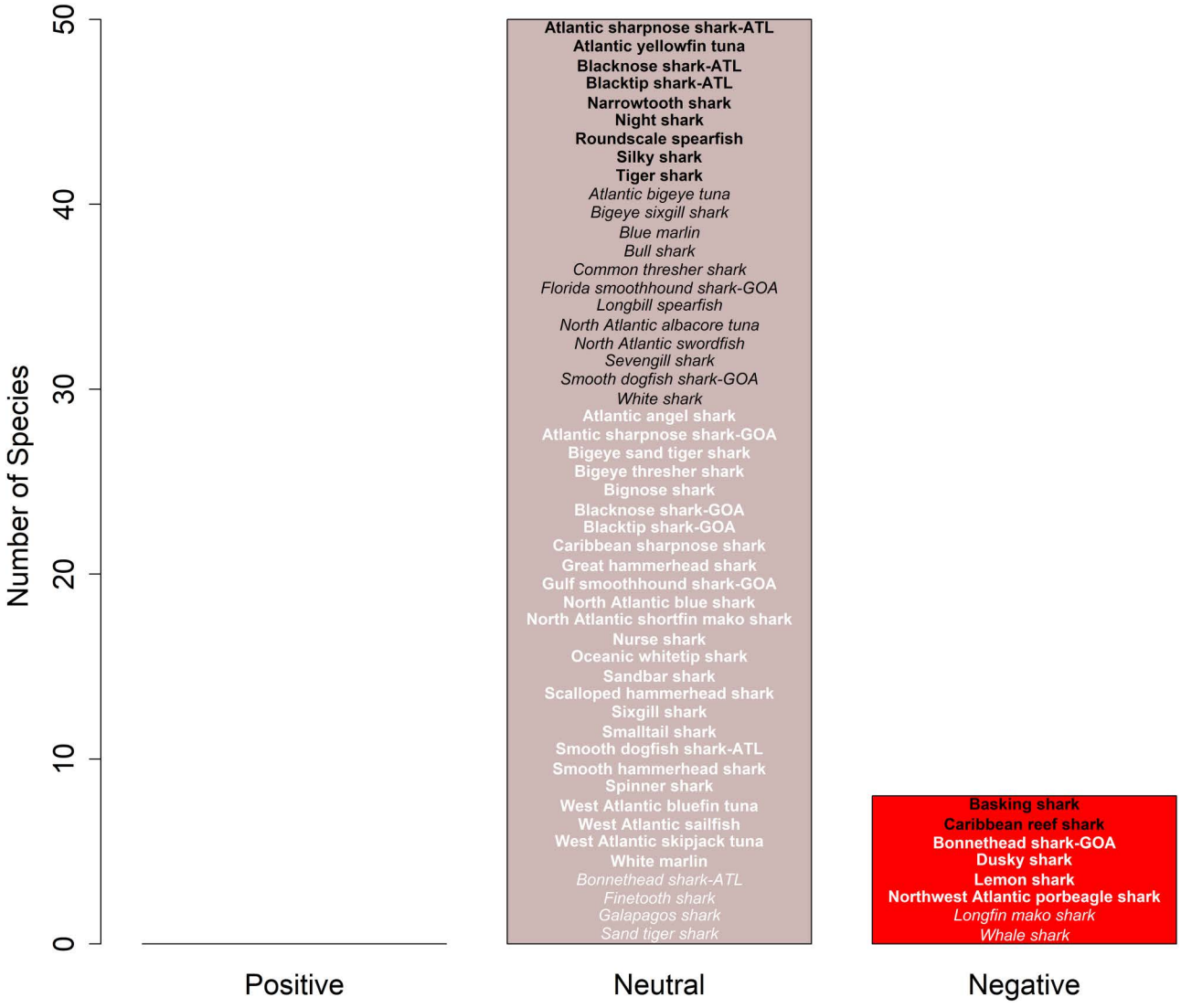


Fig 6. Directional effect of climate change ranks. Directional effect of climate change ranks for 58 Atlantic HMS or stocks calculated from panelist scores. Directional effect of climate change ranks are indicated by color: positive (white), neutral (gray), negative (red). Certainty scores are determined by text font and text color: very high certainty (>95%, black, bold font), high certainty (90-95%, black, italic font), moderate certainty (67-89%, gray or white, bold font), low certainty (≤66%, gray or white, italic font).

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3.4. Evaluation of exposure factor and biological sensitivity attributes

The exposure analysis scores were driven largely by pH, sea surface oxygen, and temperature (surface or bottom based on species), all of which had the highest median exposure factor scores across all species and stocks (Fig 7). The same factors had the greatest ability to shift vulnerability ranks of species and stocks during the leave-one-out sensitivity analysis, while none of the other exposure factors would have contributed to a shift in vulnerability if left out (Fig 8). The magnitude of SST gradient, mixed layer depth, primary production, surface wind stress magnitude, and precipitation exposure factors received low mean scores across species and stocks.

Although the spread of mean scores across species and stocks was larger for the BSAs relative to the exposure factors, three BSAs were the most influential in determining vulnerability rankings: population growth rate, stock size status, and site fidelity. These attributes had the highest median factor scores across all species and stocks (Fig 9). Based on the results of the leave-one-out analysis, the same three BSAs, plus prey specificity, had the greatest ability to shift the vulnerability ranks of species and stocks (Fig 10). Unlike the leave-one-out exposure analysis, where over 30 species and stocks would have shifted their vulnerability to a lower score if pH or sea surface oxygen were omitted, no more than 15 species and stocks would have shifted to a lower vulnerability score if any one BSA was omitted. The BSAs with the lowest mean scores across species and stocks were mobility and dispersal of early life stages, reproductive cycle, adult mobility, and specificity in early life history requirements.

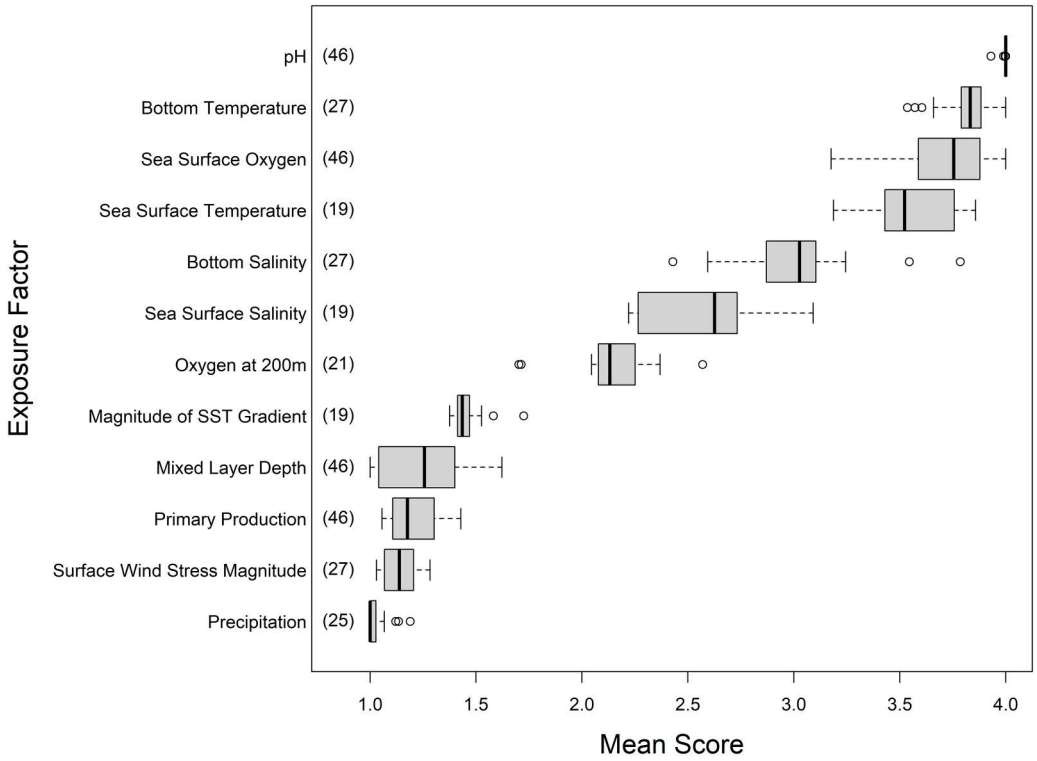


Fig 7. Distributions of exposure factor scores. The distribution of exposure factor mean scores for 46 highly migratory species and stocks. Exposure analysis was not performed for 12 species, and not all exposure factors were assigned to each species or stock; therefore, the number of species and stocks assigned to that exposure factor is in parentheses next to each exposure factor. A very high climate exposure score indicates that a species or stock may experience a great magnitude of environmental change throughout its range in the defined time periods (1985-2014; 2020-2049). The vertical bar represents the median; the edges of the box represent the first and third quartiles; whiskers represent 1.5 times the interquartile range; points represent all outlying values.

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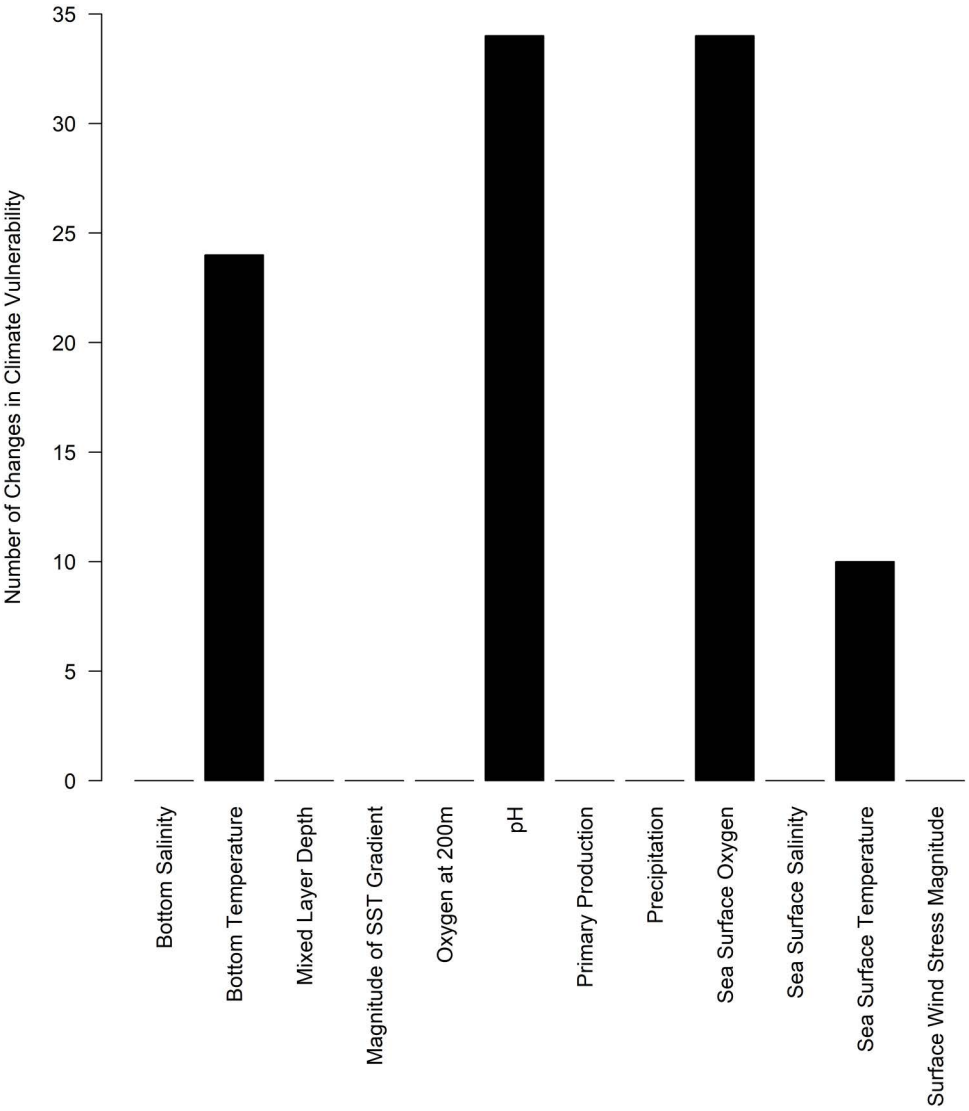


Fig 8. Leave-one-out analysis of exposure scores. Leave-one-out exposure analysis showing the number of HMS (out of 46) that would have shifted vulnerability rank if that exposure factor was omitted. Only pH, sea surface oxygen, SST, and bottom temperature changed the vulnerability ranks of species when omitted.

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3.5 Data quality

Data quality was evaluated for each of the 13 BSAs per species and stock (S2 File). Of the 58 species and stocks, 19% (n = 11) had high data quality, 45% (n = 26) had moderate data quality, and 36% (n = 21) had poor data quality. Of the poor data quality species and stocks, 10 were excluded from exposure analysis due to uncertain distributions. Of the 13 BSAs, Sensitivity to Ocean Acidification, Reproductive Strategy Sensitivity, Other Stressors, and Specificity in Early Life History Requirements routinely scored the lowest across all complexes.

4. Discussion

The HMS CVA utilized a qualitative, panel-driven scoring approach paired with a quantitative exposure analysis approach that used ocean climate models to evaluate the vulnerability of 58 species and stocks to climate change. The results of

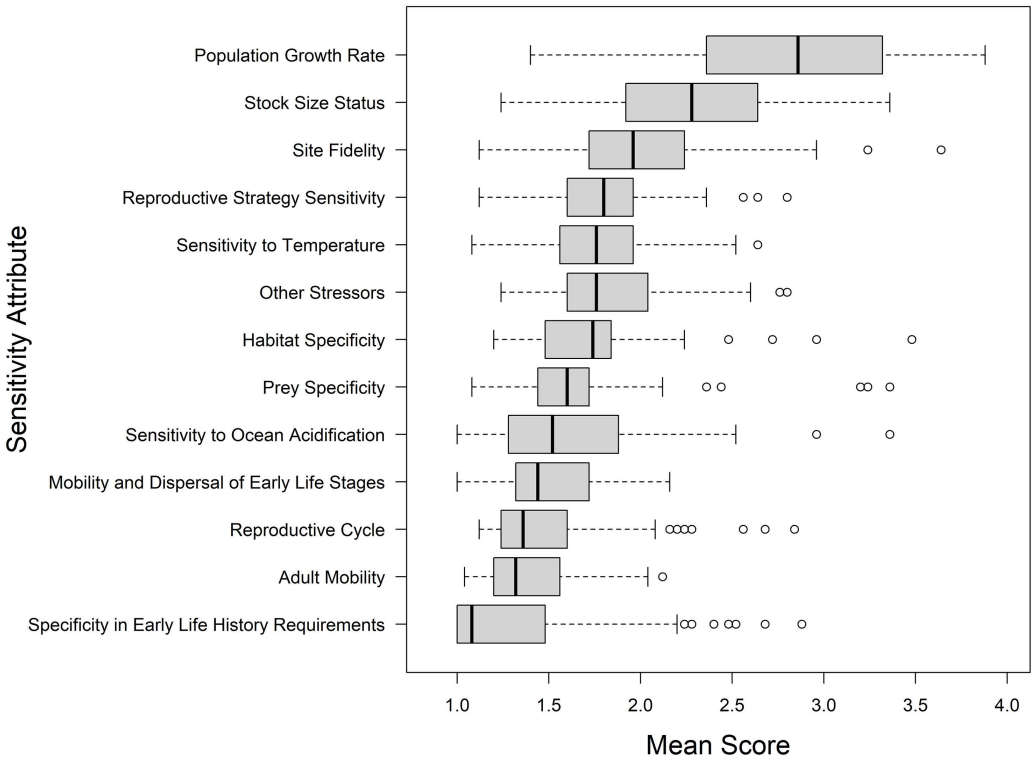


Fig 9. Distributions of BSA scores. The distribution of BSA mean scores for all 58 HMS. The vertical bar represents the median; the edges of the box represent the first and third quartiles; whiskers represent 1.5 times the interquartile range; points represent all outlying values.

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the HMS CVA elucidate key climate-related drivers of vulnerability for HMS, and in certain cases, traits that may afford HMS resilience to changing ocean conditions. Further discussion of results for each species and stock is provided in species narratives (S3 File) that describe the unique vulnerabilities contributing to each ranking.

The HMS CVA joins recent NOAA FCVAs, supported by additional studies on the effects of climate change on HMS, in providing timely and detailed information for use in fisheries management and research. Beyond identifying highly vulnerable species and stocks, the results of the HMS CVA have potential application in identifying and prioritizing important life stages, habitats, and life history characteristics for further research or conservation actions. Fisheries managers can apply these findings within existing regulatory processes (e.g., fishery management plans and amendments, endangered species designations and reviews, and stock assessments) and to further the role of ecosystem-based information within management approaches. Prior CVAs for fish stocks, habitats, and protected species have already contributed to various management activities, including Fishery Management Council climate scenario planning [61] and regional status reports [62]. Outcomes of prior CVAs and risk assessments [33,46,63,64] have also been used to inform the development or amendment of fishery management plans, biological opinions, and listing decisions generated under the Endangered Species Act (ESA), and analyses consistent with National Environmental Protection Act requirements, including those for HMS (e.g., the environmental assessment for Amendment 10 to the 2006 HMS FMP) [65–69]. Furthermore, they can be used by fishery managers to explore management approaches and options that could increase the resilience of stocks to predicted changes or increase the adaptive capacity of the fisheries themselves. NOAA FCVAs have also informed fishing community CVAs [70–72] and habitat CVAs [73] that provide fine-scale assessments of climate change impacts. The results of this HMS CVA will be leveraged to advance the understanding of the consequences of climate change on HMS and augment the incorporation of ecosystem-based information into fisheries management.

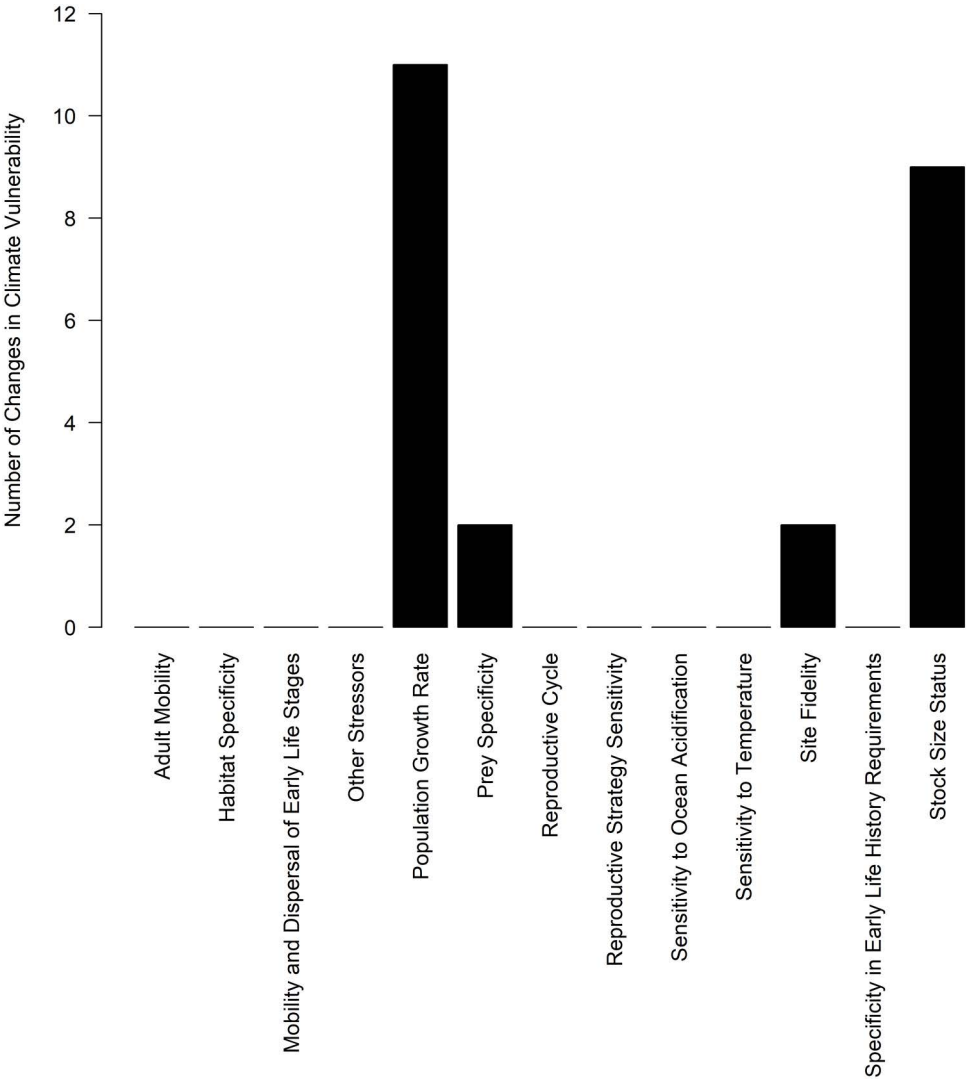


Fig 10. Leave-one-out analysis of sensitivity scores. Leave-one-out sensitivity analysis showing the number of HMS that would have shifted vulnerability rank if that sensitivity attribute was omitted. Only population growth rate, prey specificity, site fidelity, and stock size status changed vulnerability ranks of species and stocks when omitted.

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4.1. Drivers of vulnerability rankings and uncertainty

4.1.1. Biological sensitivity attributes. Interestingly, the behavioral ecology and life history of species or stocks that were categorized as having high vulnerability, overall negative impacts of climate change, and a high potential for distributional shift showed a great deal of variation. The Large Coastal, Pelagic, and Small Coastal Sharks and Smoothhound Sharks complexes each had at least one species or stock with very high overall climate vulnerability, very high potential for distribution change, and a negative directional effect (Fig 4). The behavioral ecology and physiology of the species and stocks across the three elasmobranch complexes represent a variety of characteristics, from being coastal to pelagic, ectothermic to regionally endothermic [74], top predators to filter feeders [75,76], and with different ranges of vagility, distribution, and abundance throughout the three ocean basins analyzed [17]. The remaining complexes, Tunas and Billfish and Swordfish, were dispersed throughout the high, moderate, and low vulnerability,

neutral directional effect, and high potential for distributional change rankings. Across all complexes, the Atlantic stock of bonnethead sharks was the single species or stock to receive a moderate score within the potential for distributional change rankings. This rank is attributed to the unique ecology of the bonnethead shark, as individuals in the southeastern United States exhibit strong site fidelity to specific estuaries outside of winter months [77,78]. This behavior makes it unclear how individuals will respond to varying ocean conditions within their preferred estuaries [78].

The differences in life history between species and stocks occupying similar vulnerability rankings are best demonstrated using the BSA scores. For example, Caribbean reef and dusky sharks both received a very high vulnerability ranking and a negative directional effect ranking driven by different attributes. The Caribbean reef shark ranking was driven by habitat specificity, sensitivity to ocean acidification, and site fidelity, whereas the dusky shark ranking was driven by population growth rate and stock size/status. Caribbean reef sharks depend on coral reef habitat, with certain populations displaying high site fidelity to natal reefs year-round [79–81]. This habitat specificity increases the species' sensitivity to ocean acidification, with acidification contributing to coral habitat degradation throughout the Greater Caribbean region [8,10,11]. In comparison, dusky sharks have been subject to historic overexploitation by fisheries, which, in combination with the species k-selected life history traits (i.e., slow growth rates, low fecundity [72,82,83]), contributed to its very high vulnerability ranking. The stock status of dusky sharks is currently classified as overfished with overfishing occurring despite being designated as a federally prohibited shark species within the United States since the year 2000 [84,85]. Among its many life history traits, its slow population growth (r_{max} = 0.02-0.04) limits the ability of the stock to quickly recover. As a result, NOAA Fisheries does not expect the stock to rebuild until the year 2107 [85]. Similar to the dusky shark, the oceanic whitetip shark, which is listed as threatened under the ESA, also received a very high vulnerability ranking due to conservative population growth rates and stock size/status. The last remaining very high vulnerability ranked species, bonnethead shark (Atlantic stock), received high scores for prey specificity (e.g., specialist diet of blue crabs (*Callinectes sapidus*) [86,87] and site fidelity [77,78].

Despite the range of life histories displayed by the highest ranked species, the population growth rate and stock size/status BSAs were particularly influential when determining ranks across all complexes (Figs 9 and 10). The inclusion of the stock size and status attribute, in addition to the population growth rate attribute, provides further context on how climate change will affect a species or stock at its current biomass levels and ultimately increase the vulnerability of a species or stock that may otherwise be resilient. Blue marlin (*Makaira nigricans*), for example, a species that is overfished and experiencing overfishing, may be vulnerable to post-release mortality due to elevated SSTs and limited dissolved oxygen [88]. Similarly, the scalloped hammerhead shark (*Sphyrna lewini*), a species listed as threatened under the ESA throughout the Central and Southwest Atlantic Ocean, has some of the highest metabolic rates observed in elasmobranchs [89,90], which suggests that increasing temperatures and declining dissolved oxygen may also affect their physiological performance and ultimately, post-release mortality [21,91,92]. Increases in mortality due to fisheries interactions or unsuitable environmental conditions have the potential to slow species and stock recovery, given the k-selected life history traits of many shark species.

4.1.2. Climate exposure analysis. Similar to other NOAA FCVAs, three exposure factors strongly influenced the high to very high climate exposure rankings for all species: pH, bottom or SSTs, and sea surface oxygen (Figs 7 and 8). Given the wide-ranging nature of HMS, the magnitude of environmental change for each exposure factor varied by each species and stock depending on their distribution and habitat use. Species or stocks with overlapping distributions and habitat use received similar scores across exposure factors, while species and stocks occupying different regions or habitats likely received differing exposure factor scores. As described by Lettrich et al. 2023 [39], use of standardized anomaly scores may also fail to capture critical thresholds in exposure factors such as temperature or oxygen. Use of standardized anomalies may mask the effects of elevated warming to a species or stock occupying the edge of their thermal range, while conversely evaluating the absolute change in temperature may underestimate the effects of small increases in warming.

The effect of temperature and dissolved oxygen on HMS throughout the Atlantic Ocean is underscored by recent studies on distributional shifts in catch and suitable habitat modeling, nearly all providing evidence and arguments for a poleward shift under RCP8.5. Most recently, Crear et al. (2023a) [25] used recreational fishery dockside intercept data from 2002-2019 throughout the Northeast U.S. Continental Shelf to determine changes in the timing and location of HMS catch. Hammerschlag et al. (2022) [93] used satellite telemetry and conventional tagging data of tiger sharks to determine changes in seasonal distribution and the timing of migrations. Results indicated evidence of latitudinal and temporal shifts in both studies, associated with rising SSTs. This is further supported by Braun et al. (2023) [26], which quantified suitable habitat loss and gain of HMS throughout the western North Atlantic Ocean; Erauskin-Extramiana et al. (2019) [27], which provided evidence of global poleward distribution shifts of tuna stocks; and Diaz-Carbadillo et al. (2022) [28], which modeled suitable habitat of carcharhinid species using a suite of climate change scenarios. Species-specific studies, such as Muhling et al. (2011) [94], demonstrate possible impacts of elevated SST on the timing of spawning activities of the western stock of Atlantic bluefin tuna. The GOA stock of Atlantic sharpnose shark (*Rhizoprionodon terraenovae*) was found to also shift their reproductive timing to earlier in the spring, corresponding with a 3.0°C increase in spring SST over a 29-year period [95]. The impacts of rising sea temperatures and declining dissolved oxygen on the spatiotemporal distribution and reproductive activities of HMS align with the high to very high distributional change rankings presented here for most assessed species and stocks.

4.1.3. Uncertainty. Multiple actions were taken throughout the HMS CVA to reduce and measure uncertainty. Panelists were encouraged to discuss and share species' knowledge though they were explicitly instructed that reaching consensus was not the goal of the scoring process, enabling a range of informed perspectives to be shared. Bootstrapping and a leave-one-out analysis were conducted to evaluate variations in the scientific panel's qualitative scoring of BSAs and data quality scores. Bootstrap resampling demonstrated the certainty of panelist scores by evaluating the distribution of tallies across the four vulnerability bins, and the leave-one-out analysis determined the relative importance of climate exposure factors and BSAs in driving vulnerability rankings.

As expected, data quality scores were lowest overall for species which are infrequently studied or encountered by scientists, fishers or other groups, usually relatively deepwater shark species such as the bigeye sixgill shark (*Hexanchus nakamurai*) and the bigeye sand tiger shark (*Odontaspis noronhai*). Analysis limitations within the HMS CVA arose from a lack of baseline information for certain species, which was reflected by low data quality scores and the absence of climate exposure analyses for those species (Fig 3B). Despite the absence of exposure analysis, biological sensitivity analysis alone can provide valuable information to assess a species' vulnerability to climate based solely on its life history and behavioral ecology. For example, in the case of the bigeye sand tiger shark, deoxygenation of the mesopelagic zone may affect prey availability [96]. Additionally, data quality scores sorted by BSA per complex may highlight key knowledge gaps in certain behaviors or life stages, such as early life history and reproduction strategies (S2 File).

Regarding uncertainty in BSAs, certain attributes such as reproductive strategy sensitivity and site fidelity in the Small Coastal Sharks and Smoothhound Sharks complex and sensitivity to ocean acidification in the Billfish and Swordfish and Tuna complexes, received generally low data quality scores across species and stocks. This was particularly evident in the GOA Smoothhound Shark Complex, which includes Florida smoothhound shark (*Mustelus norrisi*), Gulf smoothhound shark (*M. sinusmexicanus*), and smooth dogfish (*M. canis*), all of which received data quality scores between 0.5-1.1 for the reproductive strategy BSA. These low data quality scores may have stemmed from low certainty in the correct identification of the species, in addition to infrequency of encounters. This lack of information regarding a species' or stock's behavioral ecology, life history, and population dynamics, and subsequent low data quality scores or lack of climate exposure analysis underscores the importance of CVAs in determining and prioritizing areas of need for further research on baseline life history information and ecological characteristics.

The inability to weigh the relative importance of certain climate exposure factors or BSAs for species and stocks also generated uncertainty within the HMS CVA. For example, the effects of ocean acidification on HMS are largely unknown,

though this climate exposure factor was given the same relative weight value as SST, with the latter having both demonstrated and projected effects on HMS [25–28]. Building in the ability to weigh the factors and attributes driving species abundance and distribution could increase the efficacy of CVA methodology and contribute to more precise analysis of climate change stressors as they relate to specific species and stocks.

4.2. Comparison to other climate vulnerability assessments

NOAA FCVA methodology, initially described in Morrison et al. (2015) [32] and Hare et al. (2016) [33], has continued to evolve as the need for rapid vulnerability assessments of ecosystems, habitats, protected species, and fish stocks grows in response to climate change. Modifications to the sensitivity and exposure analysis portion of the HMS CVA reflect how CVA methodology can be adapted to specific living marine resources and improved using updated climate projections and taxon or complex-specific considerations. Variations in vulnerability rankings between the HMS CVA and regional NOAA FCVAs may stem from these differences in the methodologies (e.g., BSA scoring definitions and bins; quantitative overlap exposure scoring; climate exposure time periods) and geographic scope of the CVAs, though comparison of results across CVAs can help identify vulnerabilities within specific regions and how vulnerabilities may change over time.

Sixteen elasmobranch species and stocks in the HMS CVA overlap between the NE CVA, SE CVA, and GOA CVA (Table 7) [33,34,37]. Four species and stocks show agreement between HMS CVA rankings and other NOAA FCVA rankings, nine are within one vulnerability ranking of each other (e.g., high vs moderate), and three differ by two or more categories, with HMS CVA results yielding higher vulnerability rankings. Some of these differences could be attributed to timing in which analyses took place; the scoring for the NE CVA began in 2013. Over the past decade, it has become increasingly clear that marine species in the western North Atlantic are shifting distributions and migration patterns in response to climate change, including HMS [25,93,97–99]. Given the recently documented effects climate change is having on HMS populations, it was not surprising that vulnerability was higher for several species when compared to the NE CVA. Regional CVAs are sometimes limited to the extent of management boundaries or large marine ecosystems [33,36]; however, the identification of other appropriate spatial domains for analysis has

Table 7. Comparison of vulnerability rankings for HMS species and stocks assessed by other FCVAs.

Species	Overall Climate Vulnerability Ranking			
	HMS CVA	NE CVA	SE CVA	GOA CVA
Dusky shark	Very High	High	Very High	High
Great hammerhead shark	High	–	–	High
Scalloped hammerhead shark	High	–	–	High
Lemon shark	High	–	–	Moderate
Nurse shark	High	–	–	Low
Porbeagle shark	Moderate	High	–	–
Sand tiger shark	High	High	High	–
Sandbar shark	High	–	High	Moderate
Tiger shark	Moderate	–	–	Moderate
Smooth dogfish	Moderate	Low	–	–
Atlantic sharpnose shark	Moderate	–	High	Low
Blacknose shark - GOA	Moderate	–	–	Low
Blacktip shark - GOA	Moderate	–	–	Low
Bonnethead shark - Atlantic	Very High	–	High	
Bonnethead shark - GOA	High			Low
Finetooth shark	High	–	–	Moderate

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also been completed in other NOAA FCVAs [35,39]. Additionally, the HMS CVA analyzed multiple stocks of the same species, whereas regional NOAA FCVAs often analyzed a single stock in a geographic area. The inclusion of the Northeast U.S. Continental Shelf Large Marine Ecosystem within many of the HMS CVA species ranges may have also contributed to higher vulnerability compared to the SE and GOA CVAs, given that the Northeast U.S. Continental Shelf Large Marine Ecosystem is warming faster than any other U.S. region [100,101]. Use of standardized anomalies in exposure analysis may in part compensate for the influence of this rapid warming on vulnerability rankings. Existing seasonal variation in this ecosystem may partially occlude the projected magnitude of environmental change between the historic and future time periods.

The most notable modification to the HMS CVA was the inclusion of quantitative overlap scoring for exposure analysis (see 2.3.4) using the CMIP6 multi-model ensemble [52,53]. CMIP5, an earlier rendition of the CMIP6 multi-model ensemble, was used in the NE CVA, SE CVA, and GOA CVA climate exposure analysis for these respective NOAA FCVAs. The CMIP6 multi-model ensemble contains the newest climate projections available, with updated climate exposure factors and time periods for the analysis. Updates to climate projections may better reflect historical and future environmental conditions, thereby increasing the accuracy of HMS CVA results as they relate to climate exposure analysis. Shorter historical and future time periods were included in the CMIP6 multi-model ensemble, making near-term forecasts possible.

In contrast to previous regional CVAs, the HMS CVA evaluated the full migratory range, analyzed the full extent of basin-wide distributions, and accounted for unique ecological characteristics of HMS (Table 2). Further, the HMS CVA drew upon regional NOAA FCVAs and other CVAs, such as the marine mammal CVA conducted by Lettrich et al. (2023) [39], to create BSA definitions that reflected the broad life history characteristics unique to HMS. These modifications included consideration of site fidelity and early life stage dispersal, particularly as they relate to elasmobranchs. The low variability in scoring between the modified and un-modified BSA definitions during the pilot study, indicates that customizing BSA definitions to the characteristics of the study species is a viable and recommended approach.

Trait-based rapid CVA methodologies are gaining popularity worldwide. The 2021 climate impact assessment completed by Kjesbu et al. (2021) [102] for Norwegian fish stocks bears the most similarity to NOAA FCVAs as it used the same sensitivity and exposure analysis framework with slight methodological changes to account for a larger study area and differences in biophysical forcing. Two species overlapping with the HMS CVA, basking shark (*Cetorhinus maximus*) and porbeagle shark, were assessed within Kjesbu et al. (2021) [102] and found to have positive directional effects, in contrast to our findings of negative directional effects for both species. This difference is likely attributed to anticipated poleward shifts in distribution of both species as a result of warming in the Nordic Seas, which is currently their northernmost distribution [102].

Champion et al. (2023) [103] also used a sensitivity and exposure-driven approach when applying a multi-criteria analysis to evaluate the vulnerability of five Australian fishes to climate change. The multi-criteria analysis approach is similar to the NOAA FCVAs in that it uses established life history and behavioral knowledge from individual expertise. However, rather than using fixed species distributions, individual expertise was used to inform a hierarchical decision tree incorporating multiple levels of environmental variables and weighting them according to relative importance to the species assessed. This resulted in spatially explicit changes in habitat suitability when applied to historical and future conditions. Species projected to have a greater decline in suitability would therefore be considered more vulnerable.

Boyce et al. (2022) [47] added two additional layers of analysis in an assessment of Canadian fisheries, though the study did not include certain behavioral ecology considerations (e.g., habitat preferences and diet). The analysis expanded on the two-pronged NOAA FCVA approach of sensitivity and exposure by assessing the capacity of a species to adapt to changing conditions and by spatially evaluating exposure, sensitivity, and adaptability to identify where each component was most important for a species.

4.3. Recommendations and conclusions

The HMS CVA provides a detailed and comprehensive vulnerability assessment of HMS based on their behavioral ecology, biological sensitivities, and projected exposure to climate change. The findings presented within the HMS CVA, supported by recent research endeavors, indicate that HMS are currently affected by climate-related stressors throughout their range. While climate impacts to HMS are best discussed on a species-by-species basis, the overwhelming majority of results indicate that distributional shifts are broadly anticipated or already occurring, and that climate stressors may exacerbate effects to species and stocks characterized by low population growth rates and depleted stock status. The effects of climate change are anticipated to complicate the management of global fisheries, particularly HMS, given their transboundary distribution and the numerous international and domestic fora involved in management [104,105]. The outcomes of the HMS CVA can assist managers and researchers prioritize species requiring additional monitoring or conservation actions. NOAA FCVAs also demonstrate the importance of advancing ocean and climate modeling as new information becomes available. As the climate continues to change, we will continue to witness first-hand impacts that may change our understanding of species-specific vulnerabilities.

Our recommendation is to repeat the HMS CVA in coordination with the release of new Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, particularly as modeling quality and capacity increases, to best capture the continued effects of climate change on HMS. Most previous NOAA FCVAs relied on climate data (especially the Coupled Model Intercomparison Project Phase 5, or CMIP5, models) compiled in the 5th Assessment Report (2014). However, this CVA was able to take advantage of newly released IPCC data and information associated with the 6th Assessment Report (i.e., CMIP6). Iterative CVAs incorporating methodological improvements [47,103], downscaled (i.e., higher resolution) modeling efforts, assessing multiple SSPs, and focusing on specific life stages can provide further information on specific vulnerabilities to managers. The HMS CVA is an initial step in providing extensive climate-related analysis of HMS in support of ecosystem-based fisheries management decision-making and paves the way for advances in CVA methodology and application.

Supporting information

S1 File. Biological sensitivity attribute definitions.
(PDF)

S2 File. Supplementary figures.
(PDF)

S3 File. Species narratives.
(PDF)

S4 File. CVA R workflow.
(PDF)

S5 File. Distribution shapefiles.
(MPKX)

S1 Data. Biological sensitivity attribute scores.
(XLSX)

S2 Data. Directional effect scores.
(XLSX)

S3 Data. Species distributions determination certainty scores.
(XLSX)

S1 Table. Exposure factor assignments.
(XLSX)

S2 Table. Species name match list.
(CSV)

S3 Table. Exposure factor abbreviations.
(CSV)

S1 Script. Exposure analysis.
(R)

S2 Script. Sensitivity attribute scoring.
(R)

S3 Script. Data quality scores.
(R)

S4 Script. Vulnerability rankings.
(R)

S5 Script. Vulnerability uncertainty.
(R)

S6 Script. nMDS analysis.
(R)

S7 Script. Species narrative function.
(R)

S8 Script. Species narrative.
(R)

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