

A climate risk index for species of commercial and conservation interest across Canada

Prepared by Dr. Dan Boyce on behalf of [Wild Ocean Research](#)



Daniel Boyce (PhD, MFA), research consultant
Cow Bay, NS, Canada

Date: February, 2025
Email: wildoceanresearch@gmail.com
Web: <https://www.danielboyce.ca/consulting>

Climate vulnerability and the CRIB framework

Climate change vulnerability assessments (CCVAs) are seen as a critical component of climate-informed management of species and ecosystems (Busch *et al.*, 2016; Hare *et al.*, 2016; FAO, 2018). CCVAs strive to address several questions related to the effects of climate on species and ecosystems, namely, *which* are most vulnerable, *where* they are most vulnerable, *when* they become vulnerable, and *why* they are vulnerable. CCVAs can also identify gaps in data and information needed to understand climate change's impacts on marine life. Over 800 peer-reviewed CCVAs have been developed to evaluate the vulnerability of marine life across different scales and systems, using various approaches (*e.g.* trait-based, correlative, mechanistic modelled, theoretical) (Pacifici *et al.*, 2015; de los Ríos *et al.*, 2018; *e.g.* Foden *et al.*, 2019). This has led to a broad agreement on what features define vulnerability. Following an early IPCC definition (IPCC, 2014) and subsequent adoption (Foden *et al.*, 2013, 2019; Pacifici *et al.*, 2015; Comte and Olden, 2017; de los Ríos *et al.*, 2018; Albouy *et al.*, 2020), species' climate vulnerability is determined by their sensitivity, exposure, and adaptive capacity (adaptivity) to climate change. Sensitivity refers to the propensity for a species to be adversely affected by its exposure to climate change. Exposure refers to the extent to which species will be subjected to hazardous climate changes, including the magnitude of the effects. Adaptivity refers to the potential of species to adapt to any adverse exposure to climate change. These dimensions have close analogies in other disciplines, including community ecology and dynamic complex systems theory (Scheffer and Carpenter, 2003; Scheffer *et al.*, 2009, 2012). For example, sensitivity is analogous to the ecological concept of resistance, exposure to reactivity, and adaptivity to resilience (Holling, 1973; May, 1973; Britten *et al.*, 2014).

Despite the tremendous interest in defining and assessing climate vulnerability (de los Ríos *et al.*, 2018; Foden *et al.*, 2019), these methods have not been consistently applied across species, locations, geographic scales, or time. Further, climate vulnerability assessments are rarely used in marine management settings (Pacifici *et al.*, 2015), such as fisheries, species at risk, or spatial planning. Reviews indicate that vulnerability studies often incorporate qualitative or semi-quantitative expert opinions, such as species rankings, rather than quantitative approaches, have been locally or regionally focused (Pacifici *et al.*, 2015; de los Ríos *et al.*, 2018; Foden *et al.*, 2019), and infrequently incorporate all dimensions that define vulnerability (sensitivity, exposure, and adaptivity). For instance, a review of 743 climate change vulnerability

studies (de los Ríos *et al.*, 2018) reported that only 11% had considered all three vulnerability dimensions, while another review (Pacifici *et al.*, 2015) reported that only 4% of assessments were global. CCVAs frequently report vulnerability as relative scores and rankings, which may hinder their uptake and application in management settings.

The Climate Risk Index for Biodiversity (CRIB) framework used here integrates the knowledge accumulated in previous climate change studies and CCVAs into a unified framework for assessing both relative climate vulnerability and absolute climate risk that fills several of these existing gaps (Boyce *et al.*, 2022a, 2024c). It enables the vulnerability and risk of marine species to be evaluated at all locations across their geographic distributions in a quantitative, reproducible, consistent, and standardized manner, can be applied at scales from local to global, can incorporate new information as it becomes available, and is transparent, and evaluates the statistical uncertainty of estimated vulnerability and risk. Perhaps most critically, the framework provides a method for translating relative vulnerability scores and rankings into definitive risk categories for species and ecosystems to aid the management and conservation of marine ecosystems under climate change. The CRIB features the following design principles:

1. **Generalized and adaptable:** The information used to define vulnerability and risk represents species responses to climate change that operate consistently across species with varying taxonomies and life histories. The approach is designed to be minimal-realistic and a starting platform to build upon. CRIB operates with the understanding that its utility depends on its goals and objectives, which may differ across users and situations. A global minimal-realistic assessment may be appropriate for those seeking a broad overview of vulnerability, but additional climate information may be required to evaluate the vulnerability of fisheries, for instance. It is also anticipated that new climate-relevant information will become increasingly available, and the framework was developed to incorporate this information flexibly should it be deemed relevant.
2. **Quantitative and comprehensive:** Semi-quantitative CCVAs based on expert opinion (*e.g.* Hare *et al.*, 2016; Albouy *et al.*, 2020) are sensible but also challenging to reproduce and labour-intensive, particularly at large scales. This limits their reproducibility, making it challenging to monitor vulnerability in a standardized manner over time. The CRIB uses measurable, quantitative information sources to facilitate transparency and reproducibility. De los Ríos *et al.* (2018) reported that

only 11% of vulnerability assessments included all three dimensions and those that did often contained only a single index to define each dimension. CRIB calculates all three vulnerability dimensions and uses four indices to represent each dimension reliably. The framework also defines the indices using diverse approaches, including correlative, trait-based, and mechanistic, across various biological organization levels, from species to ecosystems and incorporating past, present, and future climate data.

3. Globally and taxonomically standardized and scalable: Species vulnerability assessments are predominantly conducted at local or regional scales (Pacifici *et al.*, 2015), making it difficult to interpret them globally, limiting their interpretability and use. The CRIB calculates vulnerability using immutable scaling factors and statistical transformations to interpret the scores across all sites and species on a standardized scale. This process ensures that the framework can be applied at varying spatial (*e.g.* local, regional, global) and taxonomic (*e.g.* species, ecosystems) scales to better accommodate different goals and objectives. The vulnerability scores' interpretation is preserved through this scalability when they are downscaled from coarser global resolutions to higher- resolutions and more scale-appropriate data layers used (*e.g.* regional climate models).

4. Practical, transparent and parsimonious: The CRIB uses robust yet broadly interpretable methods to encourage ongoing use and development; it uses publicly available, peer-reviewed data to increase transparency and integrates it using the most parsimonious methods. It adopts an information-theoretic approach, maximizing the information related to species' climate vulnerability and risk while minimizing data volume and complexity.

Holistic principles guide the CRIB: climate change impacts on species are complex and synergistic (Scheffers *et al.*, 2016). Therefore, much like the related concept of health, climate vulnerability or risk can't be adequately defined by a single index or dimension. Building on this idea, CRIB defines vulnerability hierarchically; it is calculated from its three dimensions (sensitivity, exposure, adaptivity) (IPCC, 2014), each of which is derived from four climate indices (12 total), which in turn are calculated using data layers and ecological theory (Figure 1; Tables 1-3). Indices related to species climate sensitivity include species' thermal safety margins (Sunday *et al.*, 2012; Stuart-Smith *et al.*, 2015b; Comte and Olden, 2017; Pinsky *et al.*, 2019),

vertical habitat variability and use (Peters, 1985; Laidre *et al.*, 2008; Rosset and Oertli, 2011; Garcia *et al.*, 2014), conservation status (IUCN, 2012), and cumulative impacts (Worm *et al.*, 2002, 2006; Worm and Duffy, 2003; Ottersen *et al.*, 2006; Halpern *et al.*, 2008, 2012, 2015; Le Bris *et al.*, 2018). Indices of species climate exposure were calculated from ensemble climate projections and included the species' time of climate emergence from their thermal niche (Henson *et al.*, 2017; Bates *et al.*, 2019; Trisos *et al.*, 2020; Xu *et al.*, 2020), suitable thermal habitat loss (MacKenzie *et al.*, 2014; Shackell *et al.*, 2014; Davies *et al.*, 2017), climate-related ecosystem disruption (Frank *et al.*, 2006, 2007; Boyce *et al.*, 2015a, 2015b), and the projected climate velocity (Loarie *et al.*, 2009; Burrows *et al.*, 2011; Mora *et al.*, 2013b; IPCC, 2014). Indices related to species adaptivity to climate change include the species' geographic range extent (Burek *et al.*, 2008; Laidre *et al.*, 2008; Loarie *et al.*, 2009; Boyce *et al.*, 2010; Mora *et al.*, 2013b; Poloczanska *et al.*, 2016; Staude *et al.*, 2020), geographic habitat fragmentation (Warren *et al.*, 2001; Kaschner *et al.*, 2006; Moore and Huntington, 2008; Gonzalez-Suarez *et al.*, 2013; Rogan and Lacher, 2018; Albouy *et al.*, 2020), maximum body length (Fenchel, 1974; Davidson *et al.*, 2012; Chessman, 2013; Cheung *et al.*, 2013; Gonzalez-Suarez *et al.*, 2013; Healy *et al.*, 2014; Foden *et al.*, 2019; Albouy *et al.*, 2020), and historical thermal habitat variability and use (Carilli *et al.*, 2012; Guest *et al.*, 2012; Rehm *et al.*, 2015; Donner and Carilli, 2019; Albouy *et al.*, 2020). These climate indices were selected based on pre-defined criteria, prioritizing those grounded in ecological theory, widely accepted, and validated, preferably through peer review and publication. Indices were restricted to those where the mechanism of climate change effects were widely accepted and well documented in existing climate change vulnerability studies (*e.g.* Loarie *et al.*, 2009; Mora *et al.*, 2013b; Halpern *et al.*, 2015; Stuart-Smith *et al.*, 2015a; Henson *et al.*, 2017; Pinsky *et al.*, 2019; Trisos *et al.*, 2020; IUCN, 2021). Indices were also chosen to maximize their unique information content and minimize redundancies; their uniqueness was evaluated by testing their collinearity and through sensitivity analyses. Parsimony was critical: indices that were easy to interpret and calculate were given priority. The CRIB constitutes a 'combined approach' (Pacifici *et al.*, 2015; de los Ríos *et al.*, 2018; Foden *et al.*, 2019); it integrates trait-based, correlative, and mechanistic information and incorporates abiotic, biotic, and human pressures across multiple biological organization levels (species to ecosystems).

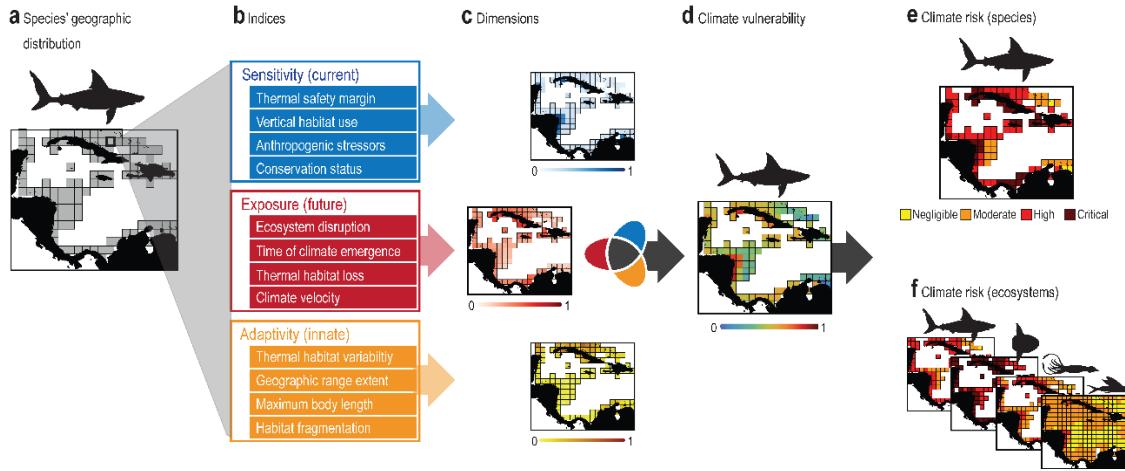


Figure 1 / Spatially explicit CRIB framework for species and ecosystems.

Within each grid cell across the native geographic distribution of a species (a), 12 standardized climate indices are calculated (b) and used to define the three dimensions of climate vulnerability (c): present-day sensitivity (blue), projected future exposure (red), and innate adaptivity (yellow). The dimensions are used to calculate the species' climate vulnerability (d), and the relative vulnerability scores are translated into absolute climate risk categories (e). f) Species maps are superimposed to assess the climate vulnerability and risk for marine ecosystems. Figure taken from Boyce *et al.* (2022b).

This report describes an adaptation of the CRIB framework to evaluate climate vulnerability and risk for marine species of commercial and/or conservation interest to the Canadian Government across the Canadian Exclusive Economic Zone (EEZ). Previous CRIB implementations estimated the vulnerability and risk of species that spend significant time in the epipelagic zone (e.g., the upper 200 m) based on sea surface temperatures (Boyce *et al.*, 2022b, 2023, 2024c, 2024a; Keen *et al.*, 2023; Lewis *et al.*, 2023). However, this implementation expands these analyses to also include deep-dwelling species that primarily or exclusively dwell in deeper waters, using measurements or estimates of bottom temperature. These outputs are provided as high-resolution (0.25 degree) spatially-resolved estimates under high (SSP5-8.5) and low (SSP1-2.6) emission scenarios. The following text describes the data layers used, the rationale and analysis methods, summaries of the output products, and guidance for interpreting the outputs.

Data layers

The data used here are in Table 1 and Table 2, and the indices used to calculate the CRIB are in Table 3; both are fully described by Boyce *et al.* (2022a, 2024c). The data originate from publicly available sources. All analyses were undertaken using the R statistical computing platform

(version 4.3 (R Core Team, 2021) and are available through a publicly available GitHub repository¹.

Following most previous CCVAs (*e.g.* Foden *et al.*, 2013, 2019; Pacifici *et al.*, 2015; Stortini *et al.*, 2015; Comte and Olden, 2017; de los Ríos *et al.*, 2018; Greenan *et al.*, 2019; Albouy *et al.*, 2020), the CRIB uses temperature as the primary indicator of climate change, even though it may not capture every aspect of climate risk (McHenry *et al.*, 2019). Temperature is widely available over historical and future eras at high spatiotemporal resolutions, and there is a greater understanding of its effects on species relative to other climate change variables (Scheffers *et al.*, 2016; Boyce *et al.*, 2020b).

Table 1| Data sources used in this study.

Type	Variable	Source	Temporal	Spatial	References	url
Taxonomic, spatial	Species native geographic distribution	AquaMaps	2000-2014	0.5°	(Kaschner <i>et al.</i> , 2019)	AquaMaps Search Page
Taxonomic	Conservation status	Wild Species, IUCN Red List	-	-	(IUCN, 2021)	Home - Wild Species: The General Status of Species in Canada IUCN Red List of Threatened Species
Taxonomic, spatial	Vertical habitat variability and use	FishBase, SeaLifeBase, AquaMaps	-	-	(Froese and Pauly, 2000; Kaschner <i>et al.</i> , 2019; Palomares and Pauly, 2022)	AquaMaps Search Page Search FishBase Search SeaLifeBase
Taxonomic	Maximum body length	FishBase, SeaLifeBase	-	-	(Froese and Pauly, 2000; Palomares and Pauly, 2022)	Search FishBase Search SeaLifeBase
Taxonomic	Thermal niche	AquaMaps	2000-2014	-	(Kaschner <i>et al.</i> , 2019)	AquaMaps Search Page
Spatial	Cumulative impacts	Cumulative human impact index	-	1km ²	(Halpern <i>et al.</i> , 2008, 2012, 2015)	A Global Map of Human Impacts to Marine Ecosystems
Spatial	Bathymetry	General Bathymetric Chart of the Oceans (GEBCO)	-	4km ²	(Gebco gridded global bathymetry data, 2009)	GEBCO - The General Bathymetric Chart of the Oceans
Spatiotemporal	Sea surface temperature	Global Ocean Reanalysis (GLORYS)	1993-2023	0.25°	(Xue <i>et al.</i> , 2012; Zuo <i>et al.</i> , 2019; E.U. Copernicus Marine Service Information, 2023)	Global Ocean Physics Reanalysis Copernicus Marine Service
Spatiotemporal	Projected sea surface temperature	Coupled model intercomparison project phase 6 (CMIP6)	2015-2100	0.25°	(Eyring <i>et al.</i> , 2016)	CMIP6-IPSL Data Search CMIP6-IPSL ESGF-CoG
Spatiotemporal	Sea bottom temperature	Global Ocean Reanalysis (GLORYS)	1993-2023	0.25°	Xue <i>et al.</i> , 2012; Zuo <i>et al.</i> , 2019; E.U. Copernicus Marine Service Information, 2023)	Global Ocean Physics Reanalysis Copernicus Marine Service
Spatiotemporal	Projected sea bottom temperature	Coupled model intercomparison project phase 6 (CMIP6)	2015-2100	0.25°	(Eyring <i>et al.</i> , 2016)	CMIP6-IPSL Data Search CMIP6-IPSL ESGF-CoG

¹ <https://github.com/danielgboyce/DFO-NCR-Climate-Risk-2024>

Species identification

Species of primary interest

Climate vulnerability and risk were estimated for species of interest. We compiled a list of all marine species managed by Fisheries and Oceans Canada (DFO) or of conservation concern as species at risk. This list was generated from three independent sources:

1. The Sustainability Survey for Fisheries (SSF)². The Sustainability Survey for Fisheries tracks the performance of 195 fish stocks managed by DFO. The survey aims to assess the sustainability of fisheries by implementing the Sustainable Fisheries Framework policies. Stocks are categorized by their health status, such as “healthy,” “cautious,” or “critical,” to inform management practices. Most landings come from the surveyed stocks, providing a broad understanding of Canada’s fisheries sustainability. The SSF has been operational since 2015 and contains a list of marine species of commercial importance.
2. The Government of Canada Species at Risk public registry³. The registry provides information on species at risk of extinction or extirpation in Canada. It was established under the Species at Risk Act (SARA), which came into effect in 2003, to help protect wildlife and their habitats. The registry includes a comprehensive list of species considered endangered, threatened, or of particular concern across Canada, including plants, animals, and insects. It also provides access to recovery strategies, action plans, management plans, and critical habitat information for listed species. Species are assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), which evaluates the conservation status of species based on scientific data. The public registry is designed to promote transparency and provide a centralized platform for

² [Sustainability survey for fisheries](#)

³ [Species at risk public registry - Canada.ca](#)

Canadians to access updates on the legal protection status of species, government actions, and public consultations.

3. DFO consultations. DFO personnel provided a list of 31 species that were not present within the SSF or Species at Risk public registry but were of conservation and/or management concern.

These data sources were standardized and consolidated into a single database containing species common and scientific names. This process involved filling in missing species Latin names (SSF) common names, resolving instances where the same species possessed different common or species names, and converting subspecies to species. Some entries could not be identified to the species level and were removed (e.g., “intertidal clams”). Birds, freshwater, anadramous, and catadramous species were removed as their habitat is not exclusively marine. The complete taxonomy of the remaining species was retrieved from the World Register of Marine Species.

Table 2 | Species of primary interest

N	Phylum	Order	Family	Species	Common Name
1	Arthropoda	Decapoda	Cancridae	<i>Cancer irroratus</i>	Rock Crab
2	Arthropoda	Decapoda	Cancridae	<i>Metacarcinus magister</i>	Dungeness Crab
3	Arthropoda	Decapoda	Nephropidae	<i>Homarus americanus</i>	American Lobster
4	Arthropoda	Decapoda	Oregoniidae	<i>Chionoecetes opilio</i>	Snow Crab
5	Arthropoda	Decapoda	Pandalidae	<i>Pandalus borealis</i>	Northern Shrimp
6	Arthropoda	Decapoda	Pandalidae	<i>Pandalus montagui</i>	Striped Shrimp
7	Bryozoa	Cheilostomata	Membraniporidae	<i>Membranipora membranacea</i>	Coffin Box Bryozoan
8	Chordata	Atheriniformes	Atherinopsidae	<i>Menidia menidia</i>	Atlantic Silverside
9	Chordata	Carcharhiniformes	Carcharhinidae	<i>Prionace glauca</i>	Blue Shark
10	Chordata	Carcharhiniformes	Scyliorhinidae	<i>Apristurus brunneus</i>	Brown Cat Shark
11	Chordata	Carcharhiniformes	Triakidae	<i>Galeorhinus galeus</i>	Tope
12	Chordata	Carnivora	Mustelidae	<i>Enhydra lutris</i>	Sea Otter
13	Chordata	Carnivora	Otariidae	<i>Callorhinus ursinus</i>	Northern Fur Seal
14	Chordata	Carnivora	Otariidae	<i>Eumetopias jubatus</i>	Steller Sea Lion
15	Chordata	Carnivora	Otariidae	<i>Zalophus californianus</i>	California Sea Lion
16	Chordata	Carnivora	Phocidae	<i>Cystophora cristata</i>	Hooded Seal
17	Chordata	Carnivora	Phocidae	<i>Erignathus barbatus</i>	Bearded Seal
18	Chordata	Carnivora	Phocidae	<i>Halichoerus grypus</i>	Grey Seal
19	Chordata	Carnivora	Phocidae	<i>Mirounga angustirostris</i>	Northern Elephant Seal
20	Chordata	Carnivora	Phocidae	<i>Pagophilus groenlandicus</i>	Harp Seal
21	Chordata	Carnivora	Phocidae	<i>Phoca vitulina</i>	Harbour Seal
22	Chordata	Carnivora	Phocidae	<i>Pusa hispida</i>	Ringed Seal
23	Chordata	Cetacea	Balaenidae	<i>Balaena mysticetus</i>	Bowhead Whale
24	Chordata	Cetacea	Balaenidae	<i>Eubalaena glacialis</i>	North Atlantic Right Whale

25	Chordata	Cetacea	Balaenidae	<i>Eubalaena japonica</i>	North Pacific Right Whale
26	Chordata	Cetacea	Balaenopteridae	<i>Balaenoptera acutorostrata</i>	Mike Whale
27	Chordata	Cetacea	Balaenopteridae	<i>Balaenoptera borealis</i>	Sei Whale
28	Chordata	Cetacea	Balaenopteridae	<i>Balaenoptera musculus</i>	Blue Whale
29	Chordata	Cetacea	Balaenopteridae	<i>Balaenoptera physalus</i>	Fin Whale
30	Chordata	Cetacea	Balaenopteridae	<i>Megaptera novaeangliae</i>	Humpback Whale
31	Chordata	Cetacea	Delphinidae	<i>Delphinus delphis</i>	Short-Beaked Common Dolphin
32	Chordata	Cetacea	Delphinidae	<i>Globicephala macrorhynchus</i>	Short-Finned Pilot Whale
33	Chordata	Cetacea	Delphinidae	<i>Globicephala melas</i>	Long-Finned Pilot Whale
34	Chordata	Cetacea	Delphinidae	<i>Grampus griseus</i>	Risso's Dolphin
35	Chordata	Cetacea	Delphinidae	<i>Lagenorhynchus acutus</i>	Atlantic White-Sided Dolphin
36	Chordata	Cetacea	Delphinidae	<i>Lagenorhynchus albirostris</i>	White-Beaked Dolphin
37	Chordata	Cetacea	Delphinidae	<i>Lagenorhynchus obliquidens</i>	Pacific White-Sided Dolphin
38	Chordata	Cetacea	Delphinidae	<i>Lissodelphis borealis</i>	Northern Right Whale Dolphin
39	Chordata	Cetacea	Delphinidae	<i>Orcinus orca</i>	Killer Whale
40	Chordata	Cetacea	Delphinidae	<i>Pseudorca crassidens</i>	False Killer Whale
41	Chordata	Cetacea	Delphinidae	<i>Stenella coeruleoalba</i>	Striped Dolphin
42	Chordata	Cetacea	Delphinidae	<i>Tursiops truncatus</i>	Common Bottlenose Dolphin
43	Chordata	Cetacea	Eschrichtiidae	<i>Eschrichtius robustus</i>	Grey Whale
44	Chordata	Cetacea	Kogiidae	<i>Kogia breviceps</i>	Pygmy Sperm Whale
45	Chordata	Cetacea	Monodontidae	<i>Delphinapterus leucas</i>	Beluga Whale
46	Chordata	Cetacea	Monodontidae	<i>Monodon monoceros</i>	Narwhal
47	Chordata	Cetacea	Phocoenidae	<i>Phocoena phocoena</i>	Harbour Porpoise
48	Chordata	Cetacea	Phocoenidae	<i>Phocoenoides dalli</i>	Dall's Porpoise
49	Chordata	Cetacea	Physeteridae	<i>Physeter macrocephalus</i>	Sperm Whale
50	Chordata	Cetacea	Ziphiidae	<i>Berardius bairdii</i>	Baird's Beaked Whale
51	Chordata	Cetacea	Ziphiidae	<i>Hyperoodon ampullatus</i>	Northern Bottlenose Whale
52	Chordata	Cetacea	Ziphiidae	<i>Mesoplodon bidens</i>	Sowerby's Beaked Whale
53	Chordata	Cetacea	Ziphiidae	<i>Mesoplodon carlhubbsi</i>	Hubbs' Beaked Whale
54	Chordata	Cetacea	Ziphiidae	<i>Mesoplodon densirostris</i>	Blainville's Beaked Whale
55	Chordata	Cetacea	Ziphiidae	<i>Mesoplodon mirus</i>	True's Beaked Whale
56	Chordata	Cetacea	Ziphiidae	<i>Ziphium cavirostris</i>	Cuvier's Beaked Whale
57	Chordata	Clupeiformes	Clupeidae	<i>Clupea harengus</i>	Atlantic Herring
58	Chordata	Clupeiformes	Clupeidae	<i>Clupea pallasii</i>	Pacific Herring
59	Chordata	Clupeiformes	Clupeidae	<i>Sardinops sagax</i>	Pacific Sardine
60	Chordata	Enterogona	Cionidae	<i>Ciona intestinalis</i>	Vase Tunicate
61	Chordata	Enterogona	Didemnidae	<i>Diplosoma listerianum</i>	Compound Sea Squirt
62	Chordata	Gadiformes	Gadidae	<i>Gadus macrocephalus</i>	Pacific Cod
63	Chordata	Gadiformes	Gadidae	<i>Gadus morhua</i>	Atlantic Cod
64	Chordata	Gadiformes	Gadidae	<i>Melanogrammus aeglefinus</i>	Haddock
65	Chordata	Gadiformes	Gadidae	<i>Pollachius virens</i>	Pollock
66	Chordata	Gadiformes	Lotidae	<i>Brosme brosme</i>	Cusk

67	Chordata	Gadiformes	Macrouridae	Coryphaenoides rupestris	Roundnose Grenadier
68	Chordata	Gadiformes	Macrouridae	Macrourus berglax	Roughhead Grenadier
69	Chordata	Gadiformes	Merlucciidae	Merluccius bilinearis	Silver Hake
70	Chordata	Gadiformes	Merlucciidae	Merluccius productus	Pacific Hake
71	Chordata	Gadiformes	Phycidae	Urophycis chuss	Red Hake
72	Chordata	Gadiformes	Phycidae	Urophycis tenuis	White Hake
73	Chordata	Hexanchiformes	Hexanchidae	Hexanchus griseus	Bluntnose Sixgill Shark
74	Chordata	Lamniformes	Cetorhinidae	Cetorhinus maximus	Basking Shark
75	Chordata	Lamniformes	Lamnidae	Carcharodon carcharias	White Shark
76	Chordata	Lamniformes	Lamnidae	Isurus oxyrinchus	Shortfin Mako
77	Chordata	Lamniformes	Lamnidae	Lamna nasus	Porbeagle
78	Chordata	Osmeriformes	Osmeridae	Mallotus villosus	Capelin
79	Chordata	Osmeriformes	Osmeridae	Osmerus mordax	Rainbow Smelt
80	Chordata	Osmeriformes	Osmeridae	Thaleichthys pacificus	Eulachon
81	Chordata	Perciformes	Anarhichadidae	Anarhichas denticulatus	Northern Wolffish
82	Chordata	Perciformes	Anarhichadidae	Anarhichas lupus	Atlantic Wolffish
83	Chordata	Perciformes	Anarhichadidae	Anarhichas minor	Spotted Wolffish
84	Chordata	Perciformes	Anarhichadidae	Anarhichas orientalis	Bering Wolffish
85	Chordata	Perciformes	Anarhichadidae	Anarrhichthys ocellatus	Wolf-Eel
86	Chordata	Perciformes	Moronidae	Morone saxatilis	Striped Bass
87	Chordata	Perciformes	Scombridae	Scomber scombrus	Atlantic Mackerel
88	Chordata	Perciformes	Scombridae	Thunnus alalunga	Albacore Tuna
89	Chordata	Perciformes	Scombridae	Thunnus orientalis	Pacific Bluefin Tuna
90	Chordata	Perciformes	Scombridae	Thunnus thynnus	Atlantic Bluefin Tuna
91	Chordata	Perciformes	Stichaeidae	Acantholumpenus mackayi	Blackline Prickleback
92	Chordata	Perciformes	Xiphiidae	Xiphias gladius	Swordfish
93	Chordata	Pleurogona	Styelidae	Botryllus schlosseri	Golden Star Tunicate
94	Chordata	Pleuronectiformes	Pleuronectidae	Glyptocephalus cynoglossus	Witch Flounder
95	Chordata	Pleuronectiformes	Pleuronectidae	Hippoglossoides platessoides	American Plaice
96	Chordata	Pleuronectiformes	Pleuronectidae	Hippoglossus hippoglossus	Atlantic Halibut
97	Chordata	Pleuronectiformes	Pleuronectidae	Hippoglossus stenolepis	Pacific Halibut
98	Chordata	Pleuronectiformes	Pleuronectidae	Limanda ferruginea	Yellowtail Flounder
99	Chordata	Pleuronectiformes	Pleuronectidae	Pseudopleuronectes americanus	Winter Flounder
100	Chordata	Pleuronectiformes	Pleuronectidae	Reinhardtius hippoglossoides	Greenland Halibut
101	Chordata	Rajiformes	Arhynchobatidae	Bathyraja interrupta	Sandpaper Skate
102	Chordata	Rajiformes	Rajidae	Amblyraja radiata	Thorny Skate
103	Chordata	Rajiformes	Rajidae	Dipturus laevis	Barndoor Skate
104	Chordata	Rajiformes	Rajidae	Leucoraja ocellata	Winter Skate
105	Chordata	Rajiformes	Rajidae	Malacoraja senta	Smooth Skate
106	Chordata	Rajiformes	Rajidae	Raja rhina	Longnose Skate
107	Chordata	Scorpaeniformes	Anoplopomatidae	Anoplopoma fimbria	Sablefish
108	Chordata	Scorpaeniformes	Cottidae	Asemichthys taylori	Spinynose Sculpin

109	Chordata	Scorpaeniformes	Cottidae	Myoxocephalus octodecemspinosus	Longhorn Sculpin
110	Chordata	Scorpaeniformes	Cyclopteridae	Cyclopterus lumpus	Lumpfish
111	Chordata	Scorpaeniformes	Hexagrammidae	Ophiodon elongatus	Lingcod
112	Chordata	Scorpaeniformes	Sebastidae	Sebastes aleutianus	Rougheye Rockfish
113	Chordata	Scorpaeniformes	Sebastidae	Sebastes alutus	Pacific Ocean Perch
114	Chordata	Scorpaeniformes	Sebastidae	Sebastes crameri	Darkblotched Rockfish
115	Chordata	Scorpaeniformes	Sebastidae	Sebastes fasciatus	Acadian Redfish
116	Chordata	Scorpaeniformes	Sebastidae	Sebastes maliger	Quillback Rockfish
117	Chordata	Scorpaeniformes	Sebastidae	Sebastes mentella	Deepwater Redfish
118	Chordata	Scorpaeniformes	Sebastidae	Sebastes paucispinis	Bocaccio Rockfish
119	Chordata	Scorpaeniformes	Sebastidae	Sebastes pinniger	Canary Rockfish
120	Chordata	Scorpaeniformes	Sebastidae	Sebastes reedi	Yellowmouth Rockfish
121	Chordata	Scorpaeniformes	Sebastidae	Sebastes ruberrimus	Yelloweye Rockfish
122	Chordata	Squaliformes	Etmopteridae	Centroscyllium fabricii	Black Dogfish
123	Chordata	Squaliformes	Squalidae	Squalus acanthias	Spiny Dogfish
124	Chordata	Squaliformes	Squalidae	Squalus suckleyi	North Pacific Spiny Dogfish
125	Chordata	Testudines	Cheloniidae	Caretta caretta	Loggerhead Sea Turtle
126	Chordata	Testudines	Dermochelyidae	Dermochelys coriacea	Leatherback Sea Turtle
127	Cnidaria	Alcyonacea	Isididae	Acanella arbuscula	Large Gorgonian
128	Echinodermata	Dendrochirotida	Cucumariidae	Cucumaria frondosa	Sea Cucumber
129	Echinodermata	Echinoida	Strongylocentrotidae	Mesocentrotus franciscanus	Red Sea Urchin
130	Echinodermata	Echinoida	Strongylocentrotidae	Strongylocentrotus droebachiensis	Green Sea Urchin
131	Mollusca	Myoida	Hiatellidae	Panopea generosa	Geoduck
132	Mollusca	Myoida	Myidae	Mya arenaria	Soft Shell Clam
133	Mollusca	Myoida	Pholadidae	Barnea truncata	Atlantic Mud-Piddock
134	Mollusca	Neogastropoda	Buccinidae	Buccinum undatum	Whelk
135	Mollusca	Ostreoida	Ostreidae	Ostrea lurida	Olympia Oyster
136	Mollusca	Ostreoida	Pectinidae	Chlamys hastata	Spiny Scallop
137	Mollusca	Ostreoida	Pectinidae	Chlamys islandica	Icelandic Scallop
138	Mollusca	Ostreoida	Pectinidae	Chlamys rubida	Pink Scallop
139	Mollusca	Ostreoida	Pectinidae	Placopecten magellanicus	Sea Scallop
140	Mollusca	Patellogastropoda	Haliotidae	Haliotis kamtschatkana	Northern Abalone
141	Mollusca	Teuthida	Ommastrephidae	Illex illecebrosus	Northern Shortfin Squid
142	Mollusca	Veneroida	Mactridae	Mactromeris polynyma	Stimpson's Surfclam
143	Mollusca	Veneroida	Mactridae	Spisula solidissima	Surf Clam
144	Mollusca	Veneroida	Pharidae	Siliqua patula	Pacific Razor Clam

The resulting list of potential species of primary interest was cross-referenced with those for which distribution estimates were available within AquaMaps across the Canadian exclusive economic zone (EEZ) (see below for a description of these data). The final list of 144 primary species contained 69 marine fish (36%), 45 mammals (31%), 14 molluscs (10%), eight echinoderms (6%), six crustaceans (4%), and two reptiles (1%); (Table 2 and Figure 2).

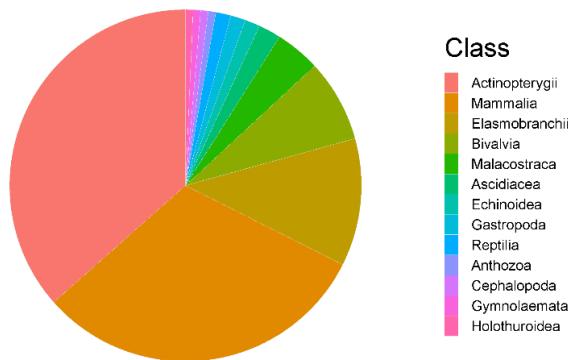


Figure 2 / The availability of marine species of primary interest (n=144) summarized by their taxonomy (class).

Species of secondary interest

Marine species that are not of interest but reside in the study area were also identified to evaluate the climate risk to the species of interest that stemmed from climate-driven ecosystem disruption (see below). These species of secondary interest were identified as those whose geographic distributions intersected with the geographic domain of the study area, here the Canadian Exclusive Economic Zone (EEZ). A total of 5,038 species of secondary interest were identified.

Species native geographic distribution

The native geographic distributions of each species of interest were obtained from the AquaMaps website (Kaschner *et al.*, 2019). The methods AquaMaps uses to calculate species distributions are described in Kaschner *et al.* (2019) and summarized in Boyce *et al.* (2022a). The native geographic distributions for each species were statistically rescaled to a 0.25° grid using nearest neighbour interpolation to ensure that they were compatible with the spatial resolution of the analysis. The suitability of the bilinear interpolation was evaluated through sensitivity analyses by comparing the interpolated probabilities of occurrence from bilinear, nearest neighbour, and spatially averaged approaches and the native 0.5° resolution data (Figure 3).

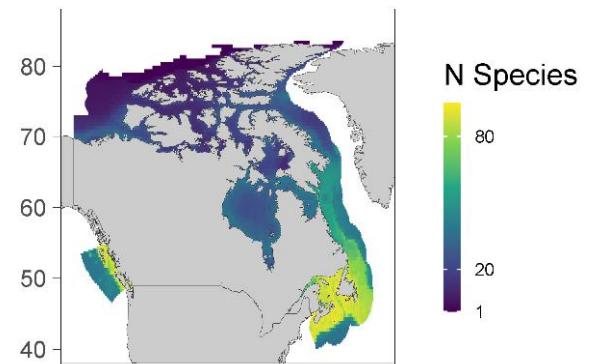


Figure 3 / Average projected surface and bottom sea temperature under a high emission scenario (SSP5-8.5) from three ESM models (Table 1) to 2100.

Species thermal niches

The realized thermal niche of marine species was derived from AquaMaps (Kaschner *et al.*, 2019) and described in Boyce et al. (Boyce *et al.*, 2022a). This study focuses on upper-temperature tolerance values, which are used to calculate various climate indices. These values reflect the species' realized, rather than fundamental, upper thermal tolerances. Boyce et al. (Boyce *et al.*, 2022a) assessed the accuracy of AquaMaps' upper thermal tolerances by comparing them with experimentally determined critical thermal maxima for species documented in published sources (Comte and Olden, 2017; Bennett *et al.*, 2018; Pinsky *et al.*, 2019). Specifically, AquaMaps' realized upper thermal tolerances were evaluated against the fundamental thermal tolerances for 60 species in the GlobTherm database (Bennett *et al.*, 2018), 76 species reported by Pinsky *et al.* (2019), 58 species by Comte et al. (2017), and 767 species imputed in Comte *et al.* (2017). These comparisons revealed a strong positive correlation between the realized upper thermal tolerances in AquaMaps and the fundamental upper thermal tolerances reported in these databases ($r = 0.8\text{--}0.88$). However, as expected, fundamental tolerances were typically higher than the realized tolerances from AquaMaps. This discrepancy is likely due to differences in the duration of thermal exposure considered in the assessments. Realized tolerances are based on time-averaged sea temperatures, whereas fundamental tolerances are determined through experiments that measure responses to acute heat exposure (e.g., over minutes, hours, or days). If we were to use the hottest hourly or daily temperatures within a year, it is expected that the realized and fundamental tolerances would align more closely.

Species conservation status

Species conservation statuses' that were specifically relevant to different regions within Canada were obtained from the Wild Species General Status of Species in Canada reports(Canadian Endangered Species Conservation Council, 2016). The Wild Species reports are produced by a National General Status Working Group composed of representatives from each Canadian province and territory and of the three federal agencies (Canadian Wildlife Service of Environment and Climate Change Canada, Fisheries and Oceans Canada, and Parks Canada). The assessments are completed using the best available knowledge, including museum collections, scientific literature, scientists and specialists, Aboriginal traditional and community

knowledge, and conservation and government data centres. The Working Group assesses the status of species in Canada using strategies contingent on the amount of information available. The working group usually evaluates information-rich species.

In contrast, those for information-poor species are conducted by experts hired to support the working group. The government with the final signoff on the ranks varies depending on the type of species. For aquatic species, DFO has the final signoff on the ranks. The information is then used to produce the *Wild Species* reports and is updated every five years. Species within the Wild Species reports are assessed regionally and/or nationally. We selected species' conservation statuses hierarchically based on their availability: we prioritized Wild Species regional species assessments over National, and for species that were not assessed in Wild Species, their global conservation status, as extracted from the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species(IUCN, 2021) in Boyce *et al.* (Boyce *et al.*, 2022a) were used. The full methodology for extracting or calculating species' global extinction risk is described in Boyce *et al.* (Boyce *et al.*, 2022a).

Species' maximum body lengths

The maximum body sizes of species were estimated from the FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.ca) databases using methods described in Boyce et al. (Boyce *et al.*, 2022a).

Historical and present-day temperatures

Surface and bottom temperature

Surface and bottom temperatures with the requisite geographic and temporal coverage were obtained from a Global Ocean Reanalysis produced by the Copernicus Marine Service Global Monitoring and Forecasting Centre (GLORYS). Previous regional iterations of CRIB used daily SST estimates from the NOAA 0.25° daily Optimum Interpolation Sea Surface Temperature dataset (OISST); (Reynolds *et al.*, 2007). However, using surface temperatures from the Reynolds dataset and bottom temperatures from GLORYS could lead to biased risk estimates for pelagic versus demersal species. To avoid this and ensure that the surface and bottom temperature datasets were strictly comparable, surface and bottom temperatures were extracted from the same GLORYS dataset.

GLORYS global ocean reanalyses are homogeneous 3D gridded descriptions of the physical state of the ocean produced with a numerical ocean model constrained with data assimilation of satellite and *in situ* observations. A multi-model ensemble of three separate ocean reanalyses products was used to increase confidence in the reanalyses and quantify their statistical uncertainty (Xue *et al.*, 2012; Zuo *et al.*, 2019; E.U. Copernicus Marine Service Information, 2023). Such multi-model ensemble approaches in climate modelling are generally more reliable than individual model projections (Mora *et al.*, 2013a).

The reanalyses time series used in the ensemble include:

- 1) GLORYS2V4 from Mercator Ocean (Fr): A global ocean reanalysis product of temperature, salinity, currents, and sea surface height, covering the period from 1993 to 2018. Designed for climate research, marine ecosystems, and operational applications, GLORYS2V4 offers data at a 1/4° horizontal resolution with 75 vertical levels. The reanalysis combines satellite observations and in-situ measurements with model simulations, offering a detailed view of ocean state changes over time.
- 2) ORAS5 from the European Centre for Medium-Range Weather Forecasts (ECMWF): Provides a comprehensive record of historical ocean conditions, integrating observational data with model outputs to produce accurate and consistent data on oceanic variables, such as temperature, salinity, currents, and sea level. From 1979 to the present, ORAS5 includes data at various depths and offers high spatial resolution. The dataset is widely used for climate research, seasonal forecasting, and understanding ocean-atmosphere interactions.
- 3) Global Ocean Reanalysis System version 5 (C-GLORS05) from Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) (It): Provides a global ocean reanalysis covering the period from 1958 to the present. It offers temperature, salinity, currents, and sea level data at multiple depths. This reanalysis integrates satellite observational data and in-situ measurements with a sophisticated ocean model to reconstruct past ocean states. Its high spatial and temporal resolution makes it a widely used tool in research and operational oceanography.

These reanalyses are as close as possible to the observations and in agreement with the model physics. The data are available when altimetric data were available, since 1 January 1993, and were extracted as daily averages describing the ocean from surface to bottom (5900 m). All extracted surface and bottom temperatures were interpolated to a regular 0.25 x 0.25° grid across the Canadian EEZ using bilinear interpolation (Figure 4).

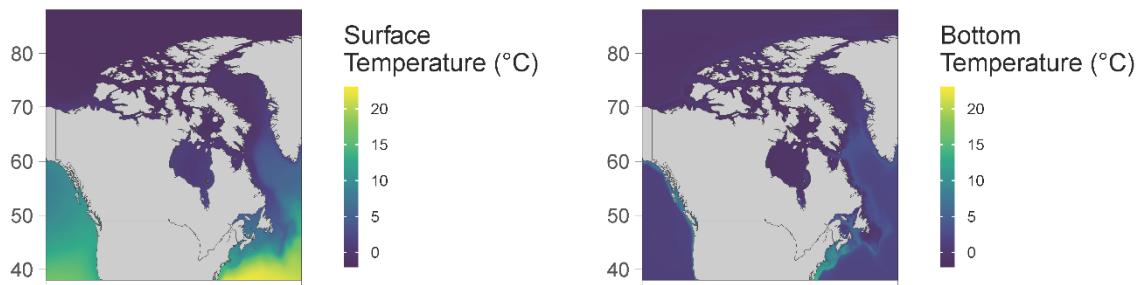


Figure 4 / Average projected surface and bottom sea temperature under a high emission scenario (SSP5-8.5) from three ESM models (Table 3) to 2100.

Projected temperatures

The projected monthly surface (SST) and bottom temperature time series were obtained from the coupled model intercomparison project phase 6 (CMIP6) between 1850 and 2100. All temperature projections were interpolated to a regular global $0.25 \times 0.25^\circ$ grid. An ensemble of temperature projections was obtained from three published Global Climate (GCM) or Earth System Models (ESMs) within the CMIP6 archive. These models span a broad range of temperature projections within the CMIP6 model set. Temperature projections ($^{\circ}\text{C}$) were made under the IPCC's shared socioeconomic pathway (SSP) scenarios SSP5-8.5, representing continued fossil fuel development, and SSP1-2.6, representing an increase in sustainable development (Riahi *et al.*, 2017; Meinshausen *et al.*, 2020). All extracted surface and bottom temperature projections were interpolated to a regular $0.25 \times 0.25^\circ$ grid across the Canadian EEZ using bilinear interpolation (Figure 5).

Table 3 | Earth System Models used.

N	Model	Modeling Center (or Group)	References
1	CNRM-CM6-1-HR	Centre National de Recherches Meteorologiques	(Volodire <i>et al.</i> , 2019)
2	HadGEM3	Met Office Hadley Centre	(Hewitt <i>et al.</i> , 2011)
3	AWI-CM-1-1-MR	Helmholtz Centre for Polar and Marine Research	(Sein <i>et al.</i> , 2018)

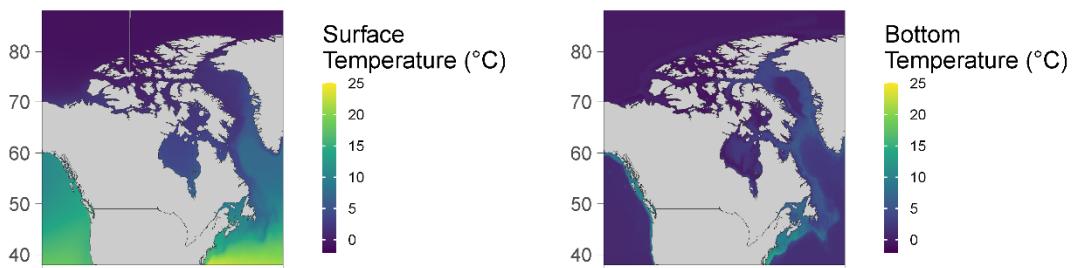


Figure 5 / Average projected surface and bottom sea temperature under a high emission scenario (SSP5-8.5) from three ESM models (Table 3) to 2100.

Cumulative impacts

A multivariate index of cumulative human impacts (HI) on ocean ecosystems was developed by Halpern *et al.* (2008, 2015). The HI index integrates 17 global anthropogenic drivers of ecological change, including fishing pressure, pollution, invasive species, eutrophication, climate change, and others. The HI estimates were available at a global 1km^2 native resolution. These values were rescaled to a global 0.25° grid using bilinear interpolation.

Analyses

Climate index calculations

The 12 climate indices used in the CRIB and their description, rationale, and supporting citations are listed in Table 4 and is described below. For upper ocean species that utilize the upper 200 m of the water column, the indices were calculated according to the specifications outlined in Boyce *et al.* (2022b, 2024c, 2024a). However, for deep ocean species that do not use the upper 200 m, the indices were calculated using sea bottom temperature rather than SST. The vertical habitat variability and use index were calculated using a different approach.

For upper ocean species, climate sensitivity to upper ocean warming declined exponentially, with both the maximum depth of occupancy and vertical range of each species as

$$S VR_s = e^{-\lambda VR_s} \quad \text{Equation 1}$$

$$S Mdep_s = e^{-\lambda Mdep_s} \quad \text{Equation 2}$$

where VR_s and $Mdep_s$ are the vertical range and maximum depth of occupancy for species s in meters, and λ is the rate parameter (0.007). The rate parameter, λ , corresponds to the rate of decline in climate sensitivity over depth and depth range and was empirically derived as the exponential rate of change in the difference between surface and subsurface temperatures across depths between 0 and 1000m globally. These equations allow sensitivity to scale between 0 and 1, with most of the change in sensitivity occurring between the surface and 500 m depth or range, with sensitivity being very similar below 500 m (Figure 6). Maximum sensitivity occurred for surface-dwelling species with narrow vertical ranges, while the lowest sensitivity occurred for species below 500 m with wider vertical ranges. Estimates of the maximum depth of occupancy and vertical habitat range were retrieved from AquaMaps (Kaschner *et al.*, 2019) and FishBase (Froese and Pauly, 2022). The maximum depth of occupancy and vertical habitat range were truncated by the maximum bathymetry in each grid cell across its native geographic distribution for each species.

Bathymetry values were extracted from the General Bathymetric Chart of the Oceans (GEBCO). Cumulative climate sensitivity was then calculated as the mean of the species' standardized vertical range (Equation 1) and the maximum depth of occupancy (Equation 2) indices. Refer to Boyce *et al.* (2022b) for an evaluation of how the vulnerability calculations are affected by the specification of λ .

Alternatively, for deep ocean species, climate sensitivity to bottom ocean warming declined exponentially with both the minimum depth of occupancy and vertical range of each species and the bottom depth where they reside, as

$$S VR_{s,c} = e^{-\lambda VR_{s,c}} \quad \text{Equation 3}$$

$$S MinDep_{s,c} = e^{-\lambda(|MinDep_{s,c}-B_c|)} \quad \text{Equation 4}$$

where $VR_{s,c}$, $MinDep_{s,c}$, and B_c are the vertical range, minimum depth of occupancy, and bathymetry for species s in grid cell c , in meters, and λ is the rate parameter (0.007). The rate parameter, λ , corresponds to the rate of decline in climate sensitivity over depth and depth range

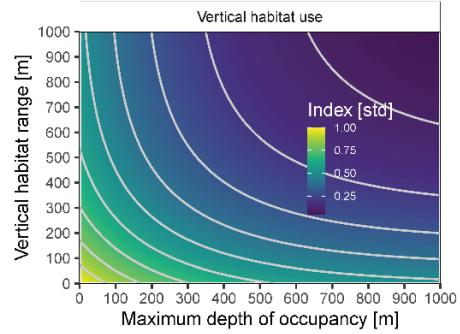


Figure 6 | Climate sensitivity of upper ocean species as a bivariate function of their maximum depth of occupancy and depth of occupancy range. Equations 1 and 2 were used to develop a standardized index of vertical habitat use that varies according to its maximum depth of occupancy and vertical range. Species living close to the surface are most sensitive to sea surface warming. The sensitivity declines rapidly below 500 m and is virtually nonexistent below 1000 m depth.

and was selected to correspond to the empirically derived parameter determined for pelagic species above. These equations allow sensitivity to scale between 0 and 1, with most of the change in sensitivity occurring within 500 m of the sea bottom (Figure 7).

Maximum sensitivity occurred for species that reside close to the sea bottom with narrow vertical ranges, while the lowest sensitivity occurred for species that can exist further from the sea bottom with wider vertical ranges.

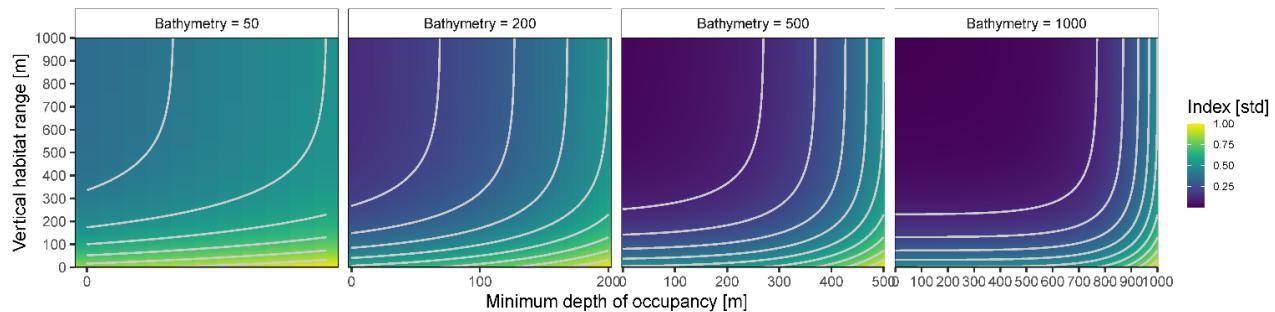


Figure 7 | Climate sensitivity of deep ocean species as a trivariate function of bathymetry, maximum depth of occupancy and depth of occupancy range.

Equations 3 and 4 were used to develop a standardized index of vertical habitat use that varies according to its minimum depth of occupancy, vertical range, and the bottom depth where it resides. Species living close to the sea bottom are most sensitive to bottom-ocean warming. The sensitivity declines rapidly above 500 m off the sea bottom and is virtually nonexistent above 1000 m.

Estimates of minimum depth of occupancy and vertical habitat range were retrieved from AquaMaps (Kaschner *et al.*, 2019) and FishBase (Froese and Pauly, 2022). The minimum depth of occupancy and vertical habitat range was truncated by the bathymetry present in each grid cell across its native geographic distribution for each species. Bathymetry values were extracted from the General Bathymetric Chart of the Oceans (GEBCO). Cumulative climate sensitivity was then calculated as the mean of the species' standardized vertical range (Equation 3) and the minimum depth of occupancy (Equation 4) indices. Refer to Boyce *et al.* (2022) for an evaluation of how the vulnerability calculations are affected by the specification of λ .

Table 4 | Indices used in this study

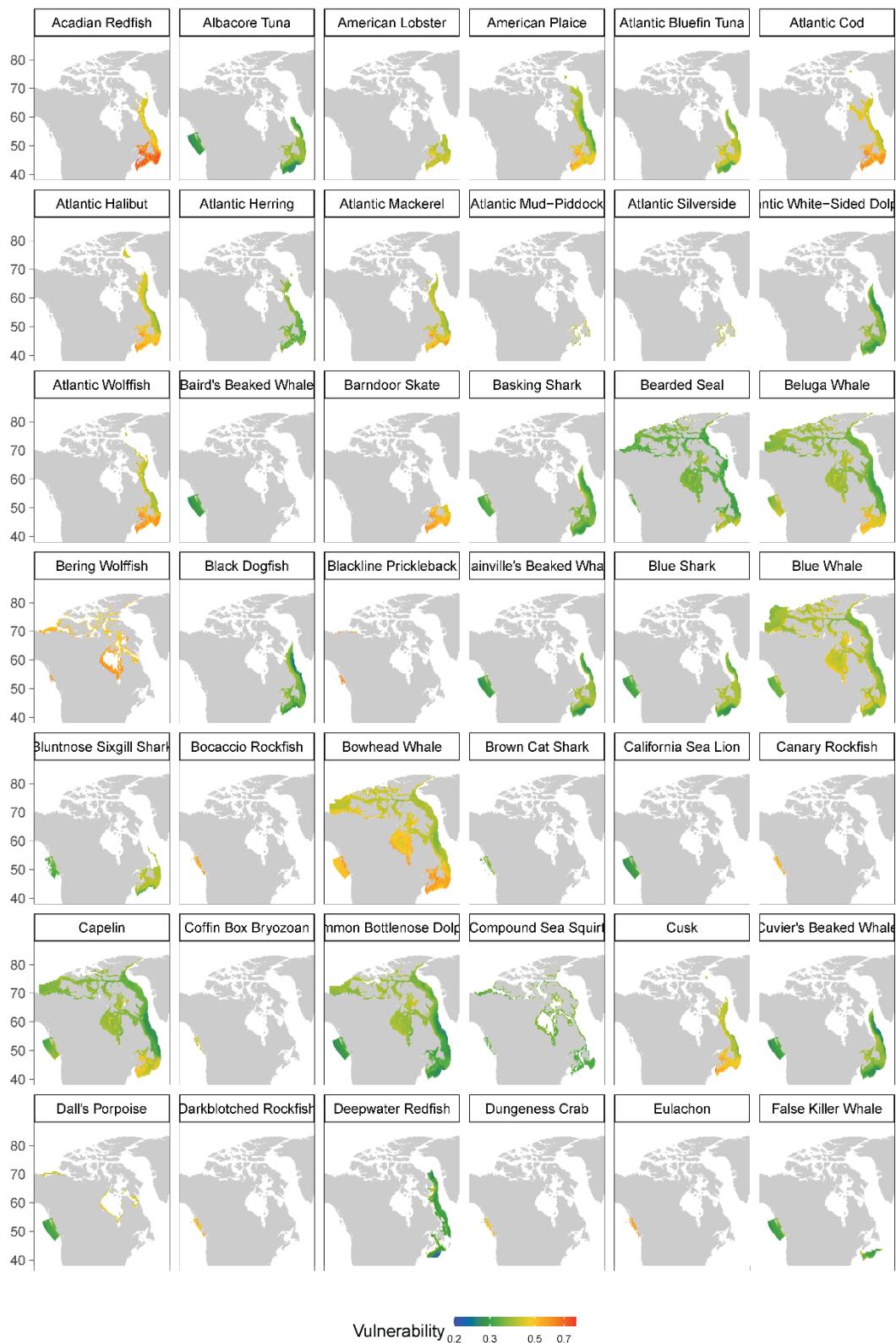
Index	Description	Data	Rationale	References
Sensitivity (S)				
Thermal safety margin	Difference between maximum environmental temperature and species upper temperature tolerance.	AquaMaps, Global Ocean Reanalysis (GLORYS) surface and bottom temperature	Species inhabiting waters at their upper thermal limits are more vulnerable to further warming. The thermal safety margin has been extensively used in climate vulnerability assessments to measure species sensitivity and tolerance to further warming.	(Sunday <i>et al.</i> , 2012; Pearson <i>et al.</i> , 2014; Stuart-Smith <i>et al.</i> , 2015b; Comte and Olden, 2017; Gallagher <i>et al.</i> , 2019; Pinsky <i>et al.</i> , 2019)
Conservation status	Assessed species extinction risk (categorical).	IUCN red list status	Climate effects on species can be more severe when species are or have been impacted by additional stressors (<i>e.g.</i> fishing, pollution, and nutrient loading) and are at low conservation status.	(IUCN, 2012; Pearson <i>et al.</i> , 2014)

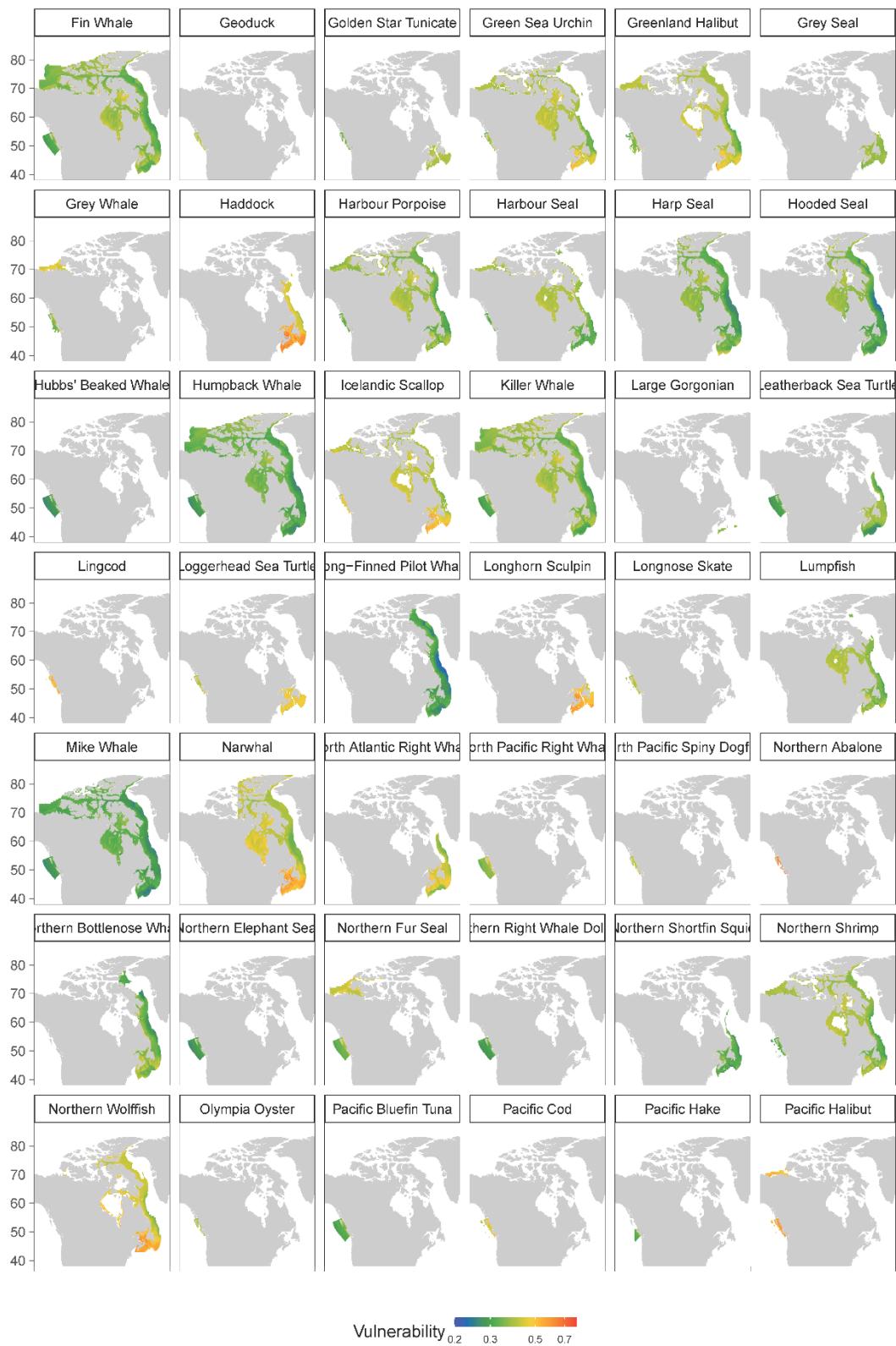
Cumulative impacts	Multivariate index of human impacts.	Human impact index	Species exposed to multiple impacts are more sensitive to additional stressors, tipping points, synergistic impacts.	(Worm <i>et al.</i> , 2002, 2006; Worm and Duffy, 2003; Ottersen <i>et al.</i> , 2006; Halpern <i>et al.</i> , 2008, 2012, 2015; Le Bris <i>et al.</i> , 2018; Butt <i>et al.</i> , 2022)
Vertical habitat variability and use	Upper ocean species: A bivariate function of maximum depth of occupancy and vertical range of species.	AquaMaps FishBase SeaLifeBase	Habitat generalist species are more adapted to climate variability and change than are specialist species due to their ability to occupy a greater variety of habitats. Species inhabiting the upper ocean and with narrow vertical habitat, ranges are more sensitive to upper ocean warming.	(Peters, 1985; Laidre <i>et al.</i> , 2008; Rosset and Oertli, 2011; Guest <i>et al.</i> , 2012; Garcia <i>et al.</i> , 2014)
	Deep ocean species: A trivariate function of minimum depth of occupancy, vertical range, and bathymetry.			
Adaptivity (AC)				
Geographic range extent	A bivariate function of the global present-day geographic habitat area and latitude span occupied by the species.	AquaMaps	Broadly distributed species are less susceptible to adverse climate change events over parts of their geographic distributions. Greater opportunity for favourable habitat (e.g. climate refugia) within larger distributions.	(Cheung <i>et al.</i> , 2007; Burek <i>et al.</i> , 2008; Laidre <i>et al.</i> , 2008; Ficetola and Denoel, 2009; Davidson <i>et al.</i> , 2012; Gonzalez-Suarez <i>et al.</i> , 2013; Garcia <i>et al.</i> , 2014; Pearson <i>et al.</i> , 2014; Albouy <i>et al.</i> , 2020; Chase <i>et al.</i> , 2020; Staude <i>et al.</i> , 2020)
Geographic habitat fragmentation	The proportion of species native geographic distribution that is fragmented.	AquaMaps	Species with less fragmented habitat ranges have greater access to potentially favourable habitats (e.g. climate refugia), migration corridors, and larval dispersal. Consequently, studies in terrestrial and marine systems have reported that species with fragmented geographic ranges are more sensitive to and less resilient to climate change impacts	(Brown and Kodric-Brown, 1977; Lehtinen <i>et al.</i> , 1999; Warren <i>et al.</i> , 2001; Fahrig, 2002; Kaschner <i>et al.</i> , 2006; Moore and Huntington, 2008; Rueda <i>et al.</i> , 2013; Gonzalez-Suarez <i>et al.</i> , 2013; Pearson <i>et al.</i> , 2014; Crooks <i>et al.</i> , 2017; Rogan and Lacher, 2018; Albouy <i>et al.</i> , 2020; Chase <i>et al.</i> , 2020; Palmeirim <i>et al.</i> , 2020)
Maximum body length	The maximum body length reached globally.	FishBase SeaLifeBase	The maximum size is a predictor of several life-history traits (e.g. generation length, time to maturity, intrinsic rate of population increase) that cumulatively define species potential reproductive capacity and population growth rate. The maximum size (length or mass) reached by species has been commonly used as a proxy of extinction risks and vulnerability of species to climate change. Smaller species that tend to be r-selected are viewed as more resilient than larger, k-selected ones.	(Fenchel, 1974; Blueweiss <i>et al.</i> , 1978; Cheung <i>et al.</i> , 2007, 2013; Davidson <i>et al.</i> , 2012; Gonzalez-Suarez <i>et al.</i> , 2013; Chessman, 2013; Healy <i>et al.</i> , 2014; Pearson <i>et al.</i> , 2014; Ripple <i>et al.</i> , 2017; Cheung and Oyinlola, 2018; Donner and Carilli, 2019; Foden <i>et al.</i> , 2019; Albouy <i>et al.</i> , 2020)
Thermal habitat variability and use	A bivariate function of the fraction of total historical temperature habitat within the species recorded thermal preference and the total temperature range experienced by the species across its global present-day geographic range.	Reynolds daily OISST, Global Ocean Reanalysis (GLORYS) surface and bottom temperature	Species inhabiting more variable thermal environments such as at the range-edges of their geographic distributions are thought to have a greater capacity to adapt to climate change and are believed to be less sensitive to it	(Carilli <i>et al.</i> , 2012; Guest <i>et al.</i> , 2012; Cole <i>et al.</i> , 2014; Mora <i>et al.</i> , 2014; Rehm <i>et al.</i> , 2015; Xu <i>et al.</i> , 2016; Nadeau <i>et al.</i> , 2017; Donner and Carilli, 2019; Albouy <i>et al.</i> , 2020)
Exposure (E)				
Projected climate velocity	The ratio of projected temporal and spatial change in thermal isotherms within the species geographic distribution.	CMIP6 monthly SST and bottom temperature	The velocity of climate change (VoCC) represents climatic isotherms' geographic movement over time and is a widely used measure of climate exposure	(Loarie <i>et al.</i> , 2009; Burrows <i>et al.</i> , 2011; IPCC, 2014; Li <i>et al.</i> , 2018)
Projected ecosystem disruption	For each grid cell across the focal species native geographic distribution, the proportion of all species projected to exceed their thermal tolerances.	CMIP6 monthly SST and bottom temperature	Individual species will be impacted by climate-driven ecosystem restructuring via altered predation, prey availability, competition.	(Frank <i>et al.</i> , 2006, 2007; Boyce <i>et al.</i> , 2015a, 2015b; Martin and Watson, 2016; Trisos <i>et al.</i> , 2020)
Projected time of climate emergence	The year when the projected temperature first exceeds the thermal tolerance of focal	AquaMaps CMIP6 monthly SST	The time of climate emergence from pre-industrial temperature variability has been widely used as a proxy for climate change timing. The	(Mora <i>et al.</i> , 2013b; Henson <i>et al.</i> , 2017; Bruno <i>et al.</i> , 2018; Trisos <i>et al.</i> , 2020; Xu <i>et al.</i> , 2020)

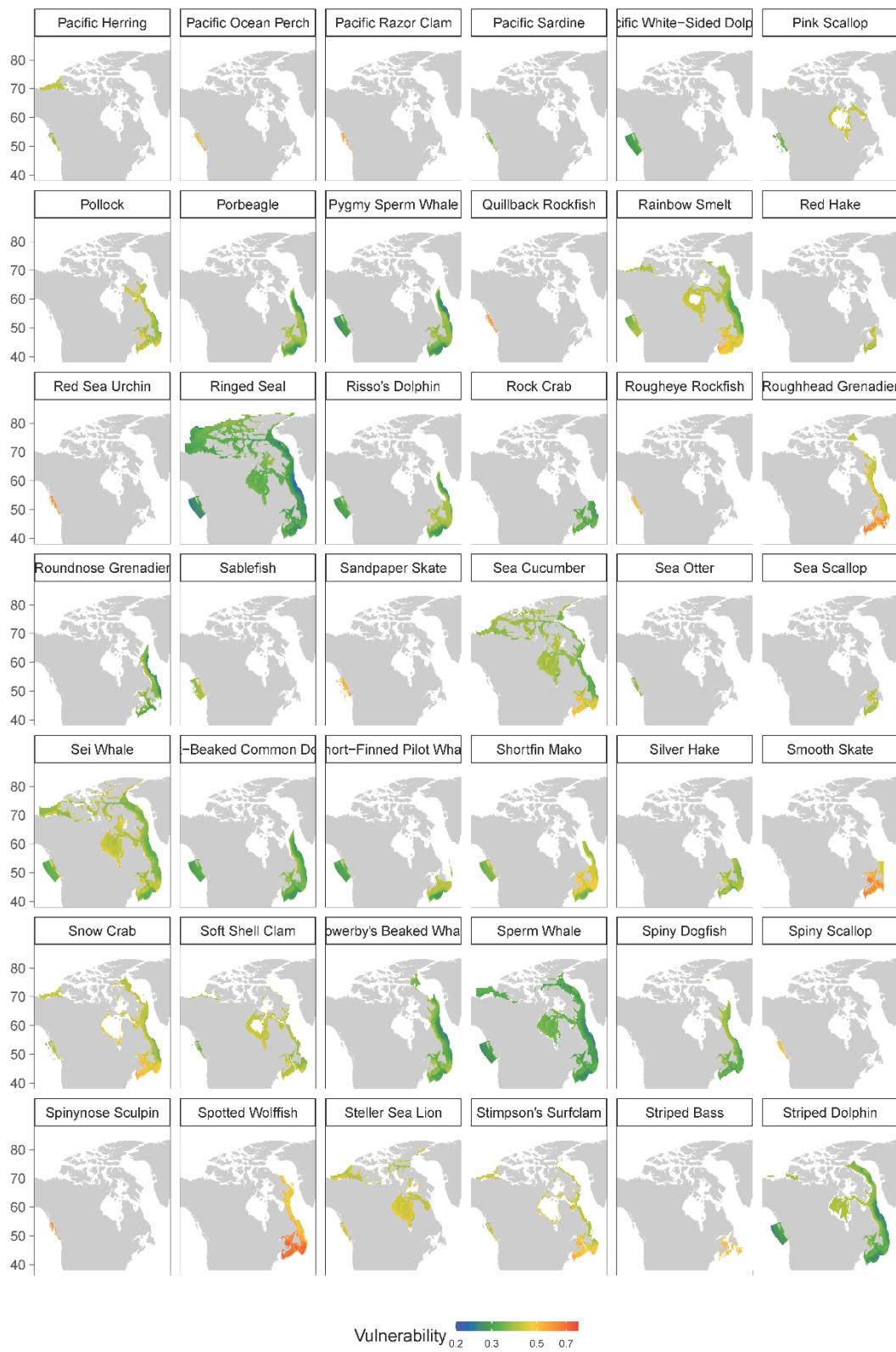
from species' thermal niche	species for at least three years in a row.	and bottom temperature	time of climate emergence from a species thermal tolerance range has recently been developed as an index of the timing of species exposure to dangerous climate conditions.	
Projected loss of suitable thermal habitat	For each focal species, the proportion of native geographic distribution lost due to projected climate change.	AquaMaps CMIP6 monthly SST and bottom temperature	Species that are projected to lose more of their thermal habitat are more vulnerable.	(Pinsky <i>et al.</i> , 2013; MacKenzie <i>et al.</i> , 2014; Shackell <i>et al.</i> , 2014; Ochoa-Quintero <i>et al.</i> , 2015; Davies <i>et al.</i> , 2017)

Outputs

Climate vulnerability and risk estimates were calculated by adapting the methods presented by Boyce *et al.* (Boyce *et al.*, 2022a, 2024c) to include deep-dwelling species. For each species of primary interest, outputs are provided as geographically explicit values at all locations where the species resides across the Canadian EEZ (Figure 8) and as geographically averaged values across the species distribution (Figure 9).







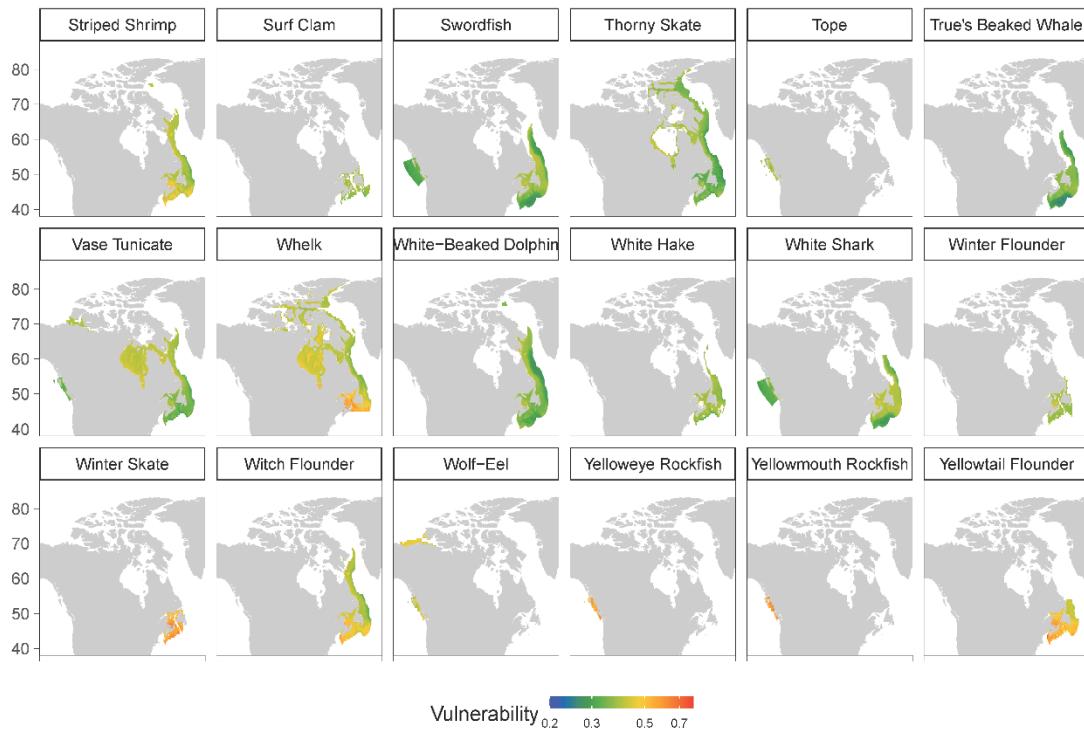


Figure 8 / Spatially explicit estimates of climate vulnerability for 144 marine species across the Canadian EEZ under a high emission scenario (SSP5-8.5) to 2100.

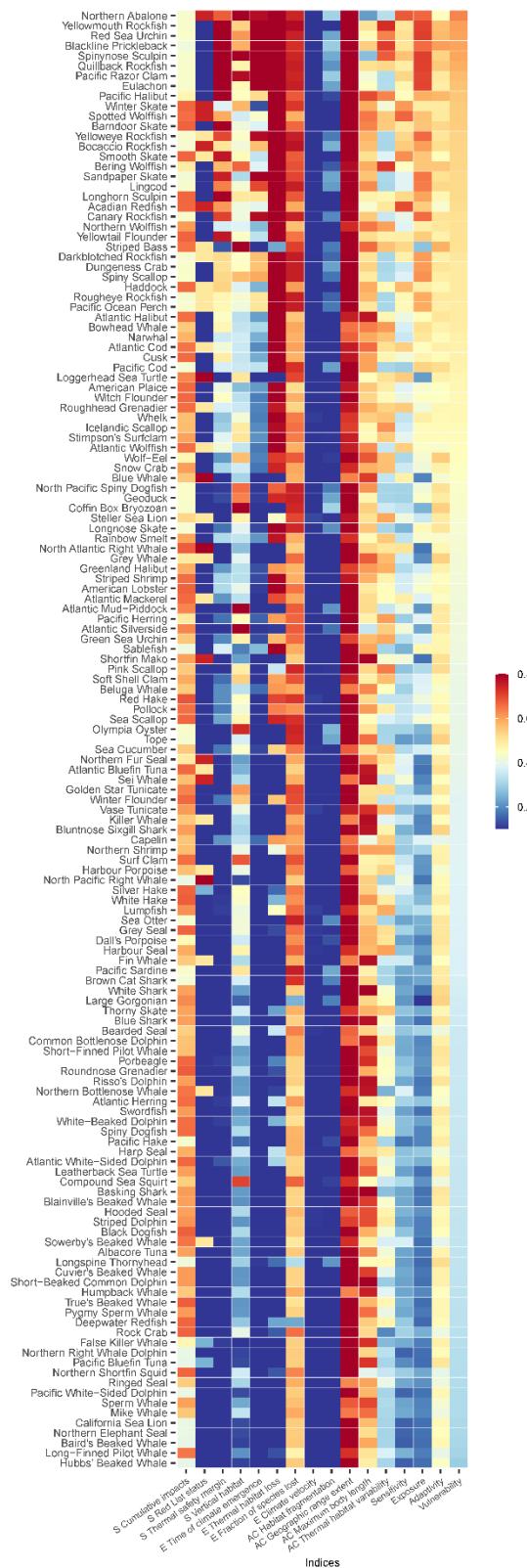


Figure 9 / Average climate index scores for 129 species of interest across the Canadian EEZ under a high emission scenario to 2100.

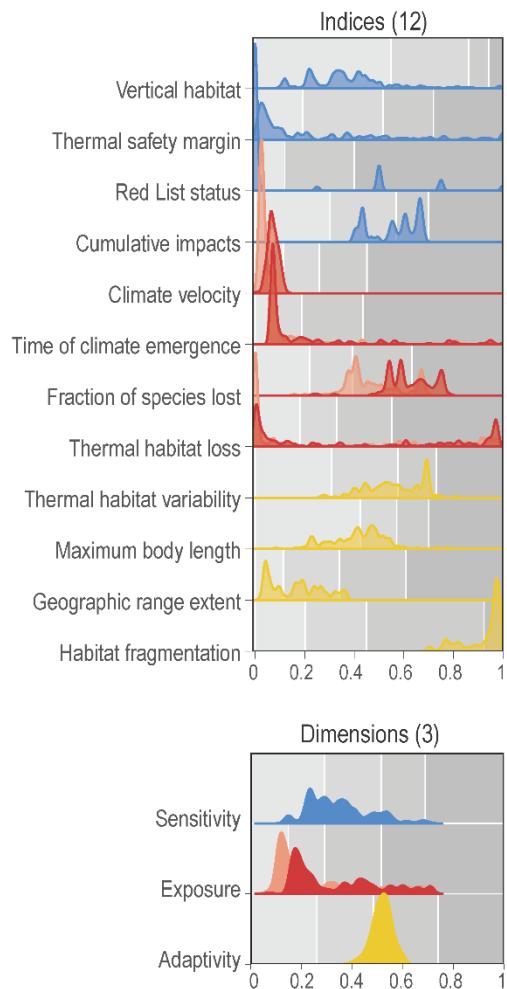


Figure 10 / Statistical distribution of the 12 climate indices and 3 dimensions for all assessed species

Shading represents the smoothed numerical distributions of the species scores for the 12 climate indices (top) and 3 dimensions (bottom). Colours depict the dimension: blue=sensitivity, red=exposure, yellow=adaptivity. Light red shading depicts scores under low emissions and dark red under high. Gray shading depicts the climate risk thresholds.

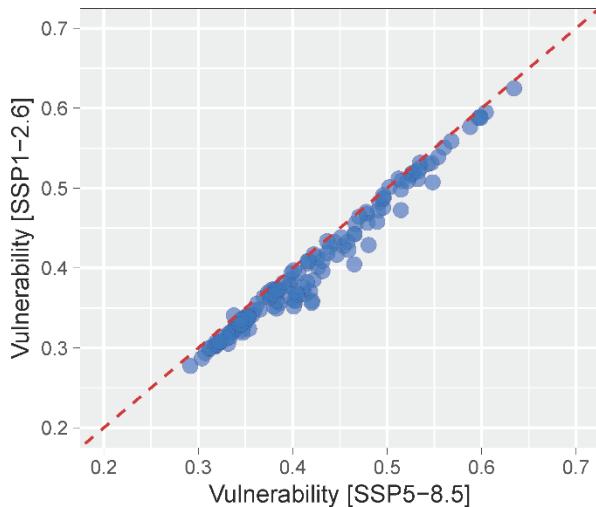


Figure 11 / Average climate vulnerability of species under different emission scenarios across the Canadian EEZ under a high emission scenario to 2100.

Interpreting CRIB outputs

The CRIB produces empirically rooted, spatially explicit estimates of relative climate vulnerability and absolute climate risk for all available marine life forms. Vulnerability scores are reported in dimensionless units, allowing species and ecosystems to be scored and ranked on relative, rather than absolute, scales between 0 and 1. This approach helps to understand patterns and trends in species' climate vulnerabilities *relative to the other species assessed within the same vulnerability analysis*. This can be tremendously useful if ranking or triaging species regarding their relative climate vulnerability is the objective. However, relative vulnerability scores can tell us little about the absolute climate risks of species that are often needed in management and policy settings; that is, the species' climate vulnerabilities *relative to all other marine species on earth*. For instance, relative vulnerability rankings cannot address the overarching question that managers and stakeholders are frequently interested in: how many and which species are at high climate risk, and where are they most at risk? Indeed, interpreting the meaning of vulnerability rankings in dimensionless units on relative scales has been a significant challenge. It could be a contributing factor to their low incorporation into management.

Previous vulnerability studies, or the comparably holistic cumulative impact index, have defined categories of high/low according to the statistical distribution of the dimensionless indices representing them (Halpern *et al.*, 2008; Stortini *et al.*, 2015; Foden *et al.*, 2019; Albouy *et al.*, 2020). Alternatively, the CRIB identifies climate risk thresholds to translate climate vulnerability into risk categories according to the ecological interpretation of the 12 climate

indices. Despite the challenges in reliably identifying such thresholds (Hillebrand *et al.*, 2020), they are increasingly being used to help guide conservation strategies and actions (Ficetola and Denoel, 2009; van der Hoek *et al.*, 2015; Arroyo-Rodríguez *et al.*, 2020; Shennan-Farpón *et al.*, 2021). In CRIB, the thresholds are defined in their native units and propagated through the analysis, preserving their meaning and interpretation yet informing the interpretation of the dimensionless vulnerability scores.

The threshold-based approach used in CRIB is comparable to the definition of extinction risk used by the IUCN Red List Index (RLI) of species (IUCN, 2021), the definition of safe operating space in planetary boundaries theory (Rockström *et al.*, 2009), and the reasons for concern (RFC) framework adopted to define climate risk by the Intergovernmental Panel on Climate Change (IPCC)(IPCC, 2001, 2014, 2021). However, whereas the RLI assesses extinction risk at the species level and is identical across species' distributions, the climate risk index for biodiversity (CRIB) disaggregates climate risk and its spatial variation across the sites throughout a species' distribution and evaluates risk for both individual species and aggregate ecosystems.

It allows the vulnerability of species and communities to be categorized according to our ecological interpretation of them and is guided rather than defined by their statistical properties. Identifying thresholds to determine risk is notoriously challenging (Hillebrand *et al.*, 2020; Zommers *et al.*, 2020) due to various factors, including a lack of knowledge needed to represent them, uncertainties in climate model projections, and differences in value judgments regarding what constitutes dangerous risk (Fischlin, 2009; Garner *et al.*, 2016; Leemans and Vellinga, 2017; Hillebrand *et al.*, 2020; Zommers *et al.*, 2020).

Yet despite these challenges, threshold-defined risk assessments have proven immeasurably valuable in helping to communicate risks to a broad audience while supporting public engagement, management, and policy decisions. For instance, since 2001, the IPCC RFC framework has communicated levels of climate risk to humans using thresholds set by expert judgment (*e.g.* IPCC, 2001). The resulting ‘burning embers’ diagrams have become widely used tools to communicate the risks stemming from anthropogenic climate change in a clear, intuitive manner that is critical for decision-making (Zommers *et al.*, 2020). For instance, the goal of the Paris Agreement to limit global warming to below 2°C was supported by IPCC reports of increasing risks beyond 1.5°C or 2°C warming (Fischlin, 2009; Leemans and Vellinga, 2017).

Since risk thresholds are identified for each index, we also derive risk categories for each climate index and dimension. It is, however, essential to define risk thresholds using transparent and, where possible, empirically supported approaches (Swart *et al.*, 2009; Budescu *et al.*, 2012; Oppenheimer *et al.*, 2016). Boyce *et al.* (2022) describe the CRIB rationale for defining thresholds that denote negligible, moderate, high and critical risk categories. These thresholds represent waypoints to guide the definition and communication of climate risk. To the extent possible, they were guided by empirical information. Nonetheless, some thresholds were unavoidably defined using less objective criteria. We anticipate that some of these thresholds may be refined as our knowledge of ecological thresholds continues to improve. The risk thresholds and their rationale and associated references are listed in Table 5.

The CRIB does not seek to evaluate climate-driven range shifts; Instead, it assesses the likelihood of adverse consequences (IPCC, 2021) at individual locations within species' native geographic distributions to inform conservation and management efforts where they operate. Because the CRIB does not consider range expansions, it represents the climate risk to the *in situ* persistence of species and the biotic intactness of their ecosystems. It represents a baseline that can be flexibly updated when confronted with new data and knowledge.

Table 5 | Thresholds used to define climate risk categories.

Index	Tlow	Tmed	Thigh	Rationale	References
Sensitivity					
Thermal safety margin	5°C	2°C	1°C	Guided by warming rates. 1°C and 2°C compare to the rates of Warming over the past 50 and 100 years, respectively(Boyce <i>et al.</i> , 2010). 5° to projected warming (Gattuso <i>et al.</i> , 2015a).	(Boyce <i>et al.</i> , 2010; Gattuso <i>et al.</i> , 2015b; Stuart-Smith <i>et al.</i> , 2015b; Gallagher <i>et al.</i> , 2019; Pinsky <i>et al.</i> , 2019)
Conservation status	LC	LC	V, E, CR	Defined by the IUCN RedList categories and criteria(IUCN, 2021): any category at or above 'vulnerable' is considered at high risk.	(IUCN, 2021)
Cumulative impacts	0.6	1.4	2	Guided by (Halpern <i>et al.</i> , 2008).	(Halpern <i>et al.</i> , 2008; Butt <i>et al.</i> , 2022)
Vertical habitat variability and use					
Maximum depth	200m	50m	20m	Standard pelagic biogeochemical divisions within the euphotic zone categorize variation, e.g., mixing, nutrients, photosynthetically active radiation, and primary production.	
Vertical range	200m	50m	20m	Standard biogeochemical divisions within the euphotic zone are used to categorize variation, e.g., mixing, nutrients, photosynthetically active radiation, and primary production.	
Exposure					
Projected climate velocity	6km yr ⁻¹	15km yr ⁻¹	30km yr ⁻¹	Guided by the quantiles of the statistical distribution.	
Projected time of climate	75yrs	50yrs	25yrs	Guided by the IUCN RedList assessment criteria(IUCN, 2021).	(Trisos <i>et al.</i> , 2020; IUCN, 2021)

emergence from the thermal niche					
Projected loss of suitable thermal habitat	5%	10%	20%	Guided by (Homan <i>et al.</i> , 2004; Lange <i>et al.</i> , 2010; Swift and Hannon, 2010; Yin <i>et al.</i> , 2017; Arroyo-Rodríguez <i>et al.</i> , 2020).	(Parker and Mac Nally, 2002; Homan <i>et al.</i> , 2004; Lange <i>et al.</i> , 2010; Rompre <i>et al.</i> , 2010; Swift and Hannon, 2010; Liao <i>et al.</i> , 2013; Ochoa-Quintero <i>et al.</i> , 2015; Yin <i>et al.</i> , 2017; Arroyo-Rodríguez <i>et al.</i> , 2020; Shennan-Farpón <i>et al.</i> , 2021).
Projected ecosystem disruption	5%	10%	20%	Guided by thresholds in (Hooper <i>et al.</i> , 2012; Newbold <i>et al.</i> , 2016; Trisos <i>et al.</i> , 2020).	(Scholes and Biggs, 2005; Hooper <i>et al.</i> , 2012; Newbold <i>et al.</i> , 2016; Oliver, 2016; Chase <i>et al.</i> , 2020; Trisos <i>et al.</i> , 2020; Shennan-Farpón <i>et al.</i> , 2021)
Exposure					
Geographic range extent					
Latitude span	20°	45°	60°	Based on oceanographic and ecological domains that vary by latitude and are defined by biogeographic patterns in e.g. seasonality, ocean circulation, and climate (Mann and Lazier, 1991; Longhurst, 2007; Boyce <i>et al.</i> , 2017)	(Mann and Lazier, 1991; Longhurst, 2007; Rompre <i>et al.</i> , 2010; Boyce <i>et al.</i> , 2017)
Total geographic area	0.04%	1%	4%	Referenced to the size spectrum of large marine ecosystems (Frye, 1986).	(Frye, 1986; Parker and Mac Nally, 2002; Homan <i>et al.</i> , 2004; Rompre <i>et al.</i> , 2010; Swift and Hannon, 2010; Liao <i>et al.</i> , 2013; Yin <i>et al.</i> , 2017; Arroyo-Rodríguez <i>et al.</i> , 2020; Chase <i>et al.</i> , 2020; Staude <i>et al.</i> , 2020)
Geographic habitat fragmentation	20%	10%	1%	Guided by and comparable to those defined in (Albouy <i>et al.</i> , 2020) for the vulnerability of cetaceans.	(Andren, 1994; Hill and Caswell, 1999; Fahrig, 2002; Parker and Mac Nally, 2002; Lange <i>et al.</i> , 2010; Rompre <i>et al.</i> , 2010; Rueda <i>et al.</i> , 2013; Albouy <i>et al.</i> , 2020; Arroyo-Rodríguez <i>et al.</i> , 2020; Chase <i>et al.</i> , 2020)
Maximum body length	100cm	30cm	10cm	Empirically guided by the relationship with the intrinsic rate of population increase.	(Fenchel, 1974; Blueweiss <i>et al.</i> , 1978; Ripple <i>et al.</i> , 2017)
Thermal habitat variability and use					
Thermal habitat occupancy	8%	95%	99%	Guided by the quantiles of the statistical distributions	(Carilli <i>et al.</i> , 2012; Donner and Carilli, 2019)
Thermal habitat variability	5°C	10°C	15°C	Comparable to those defined in (Albouy <i>et al.</i> , 2020) for the vulnerability of cetaceans.	(Carilli <i>et al.</i> , 2012; Guest <i>et al.</i> , 2012; Xu <i>et al.</i> , 2016; Nadeau <i>et al.</i> , 2017; Donner and Carilli, 2019; Albouy <i>et al.</i> , 2020)

Case studies

Marine fisheries

The CRIB provides scientific knowledge that can inform evidence-based decision-making under climate change, supporting climate adaptation and resilience. It operates hierarchically, providing climate vulnerability information that can be tailored to a spectrum of users, from those who seek high-level summary information (e.g., rankings and scores of overall vulnerability or risk) as well as those wanting more detailed technical information about how and why species are at high or low risk (e.g., spatially resolved climate vulnerability and risk indices). Here, case studies from Boyce *et al.* (2024b) illustrate how different output types from the CRIB can inform pathways to climate resilience in marine fisheries. Boyce *et al.* (2024b) used the CRIB to

estimate climate vulnerability and risk for 90 fish stocks across Atlantic Canada under contrasting emission scenarios to 2100.

In this study, the 4T smooth skate stock, a bycatch fishery, had the highest climate vulnerability. This fishery is at high risk because it is critically exposed to projected climate change, is highly sensitive to it, and has moderate adaptability. Smooth skate is globally endangered (IUCN, 2021), and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the smooth skate populations in the Laurentian-Scotian region, encompassing the 4T stock as special concern (COSEWIC, 2012). When determining which Atlantic Canadian stocks most need climate adaptation efforts, this stock would thus be a high priority. Resources that could further climate adaptation could potentially include pragmatic approaches that integrate climate change considerations into stock assessments, harvest advice, and decision-making (Pinsky and Mantua, 2014; Boyce *et al.*, 2020b, 2021; Duplisea *et al.*, 2020). Such approaches can range from using climate risk as a modifier to the harvest advice to a more detailed quantitative inclusion of climate variables into the stock assessment process (Holsman *et al.*, 2019; Duplisea *et al.*, 2021). For instance, management strategy evaluations (MSE) can find candidate management strategies that are potentially robust to future climate scenarios, population and ecosystem dynamics and other uncertainties (Haltuch *et al.*, 2019a, 2019b; Merino *et al.*, 2019), whereas dynamic management can set harvest rates based on climate forecasts or respond in real-time to changing conditions (Dunn *et al.*, 2016). Adaptation resources could also include instituting flexible spatial protections where the stock is particularly at risk (Tittensor *et al.*, 2019), targeted ecosystem monitoring for changes in climate vulnerability, and addressing factors affecting the sensitivity and adaptivity of smooth skate (*e.g.* reducing directed and ecosystem overfishing, bycatch, habitat destruction, and pollution); (Bryndum-Buchholz *et al.*, 2021). Since high natural mortality in the GSL is also theorized to impair species recovery (COSEWIC, 2012), understanding the influence of bycatch on their mortality and reducing any fisheries-induced mortality through bycatch reduction (*e.g.* targeted gear regulations and/or seasonal fishery closures, protected areas) could improve the climate adaptivity potential for 4T smooth skate, and species with similar climate risk.

Contrary to smooth skate, ATLSA3-4 stock for Atlantic mackerel (*Scomber scombrus*) is at moderate climate risk, likely rendering it a medium priority for climate adaptation. However, because the stock is climate-sensitive, it also has a high latent climate risk, meaning it is likely to become at risk, especially if its exposure increases. Mackerel is in the critical zone of Canada's

Precautionary Approach Framework (DFO, 2021) and is of high ecological importance, supporting many dependent species, including valuable upper trophic fisheries (Pikitch *et al.*, 2014). Thus, reducing its latent climate risk would enhance ecosystem resilience. Monitoring the stock's environment for any changes in climate exposure that could push its cumulative climate risk to high or critical could be undertaken, for instance, by tracking species' thermal safety margins over time. Additional actions could be taken to reduce the stock's high climate sensitivity, such as developing and prioritizing interventions that minimize abatable stressors (*e.g.* directed and ecosystem overfishing, bycatch, pollution, habitat or ecosystem disruption) or through fisheries closures or climate-integrated marine spatial planning (Tittensor *et al.*, 2019). For example, in 2022, commercial and bait fisheries for Atlantic Mackerel and spring-spawning Atlantic herring in the southern GSL were placed under a moratorium to permit stocks to recover from decades-long declining trends and current low abundance. These measures can reduce stress and promote the recovery of these species, serving as one example of interventions that can be applied to mitigate stressors.

The 12 impact pathways (indices) that define CRIB risk can also be helpful. For example, the timing of climate emergence from species' thermal niches (Trisos *et al.*, 2020; Xu *et al.*, 2020) can provide a chronology of when a stock will first become exposed to hazardous climate conditions across its management area. While the 4T smooth skate stock is projected to be exposed to a hazardous climate in 32 years (by 2052) on average (range=0-80 yrs.), the ATLSA3-4 Atlantic mackerel stock is not expected to be exposed for another 75 years (by 2095) on average (range: 41-80 yrs.). Such information can aid in proactively developing timelines to institute adaptation resources before those impacts and help understand the pace of climate impacts on fisheries.

Conservation and marine spatial planning

The Climate Risk Index for Biodiversity (CRIB) has also been applied to assess climate risk in marine spatial planning. Lewis *et al.* (2023) used the CRIB to predict the Time of Emergence (ToE) for 30 species in the draft network of conservation areas on the Scotian Shelf–Bay of Fundy. The study revealed a strong latitudinal gradient in climate impacts, with species associated with colder waters experiencing earlier ToEs—especially in more southwesterly areas. With high emissions, 51% of habitat and up to 42% of species were projected to be lost.

The study highlighted that the ability of marine protected areas (MPAs) to safeguard biodiversity will likely be undermined by climate change—even with strong mitigation efforts—

and that significant impacts are expected within 30 to 50 years. Climate change is expected to reduce the effectiveness of the proposed network of conservation areas and influence conservation priorities for species on the Scotian Shelf, a region projected to warm considerably. This means planning and managing sites, particularly in the southern region, should integrate climate change adaptation into their design, management, and monitoring. Adaptation strategies could include:

- Setting flexible conservation goals and objectives that can be revised over time,
- Conducting climate vulnerability or risk assessments to identify how sites might be affected in the future and
- Designing the network to account for climate risks by prioritizing lower-risk sites, areas with high carbon sequestration potential, and locations that are projected to provide future habitat for high-risk species.

Sites expected to undergo rapid shifts in species composition could benefit from flexible boundary design or even a reconfiguration of the network. This is because the current distribution of priority species may not align with future conditions, potentially reducing long-term conservation effectiveness (Tittensor *et al.*, 2019). Incorporating climate change projections into the planning of conservation areas in the Scotian Shelf–Bay of Fundy Bioregion can help improve network design and make it more resilient—or “future-proofed”—in the face of ongoing environmental change.

In a separate study, Keen *et al.* (2024) used the CRIB tool to assess the climate vulnerability of marine ecosystems within the Canadian Marine Conservation Network (CMCN). Their study found that climate risk representativity across Canada’s marine protected area network was highly spatially variable. In particular, MPAs with lower climate vulnerability were disproportionately overrepresented in the network. However, the broad-scale geographic targets used in the Scotian Shelf–Bay of Fundy network planning process achieved over 90% representativity of climate vulnerabilities. This highlights the importance of including habitat diversity and broad geographic coverage in conservation planning to build climate resilience—even when climate was not an explicit priority.

The study suggested that prioritizing protection in currently underrepresented, climate-vulnerable regions could strengthen the resilience of the CMCN under climate change. Using the CRIB, the study offers practical guidance for Canadian marine conservation practitioners on incorporating climate resilience into planning. Placing greater emphasis on biogeographic

representativity—particularly by improving protection for vulnerable coastal and shelf ecosystems, could enhance the effectiveness of the CMCN under climate change. CRIB's vulnerability data can also support site-level design, where areas with higher climate vulnerability could be given stronger protective measures to boost resilience to change.

References

- Albouy, C., Delattre, V., Donati, G., Frölicher, T. L., Albouy-boyer, S., Ru, M., Pellissier, L., *et al.* 2020. Global vulnerability of marine mammals to global warming: 1–12.
- Andren, H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *OIKOS*, 71: 355–366.
- Arroyo-Rodríguez, V., Fahrig, L., Tabarelli, M., Watling, J. I., Tischendorf, L., Benchimol, M., Cazetta, E., *et al.* 2020. Designing optimal human-modified landscapes for forest biodiversity conservation. *Ecology Letters*, 23: 1404–1420.
<https://onlinelibrary.wiley.com/doi/10.1111/ele.13535>.
- Bates, A. E., Cooke, R. S. C., Duncan, M. I., Edgar, G. J., Bruno, J. F., Benedetti-Cecchi, L., Côté, I. M., *et al.* 2019. Climate resilience in marine protected areas and the ‘Protection Paradox’. *Biological Conservation*, 236: 305–314.
- Bennett, J. M., Calosi, P., Clusella-Trullas, S., Martínez, B., Sunday, J., Algar, A. C., Araújo, M. B., *et al.* 2018. GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. *Scientific Data*, 5: 180022.
<http://www.nature.com/articles/sdata201822>.
- Blueweiss, L., Fox, H., Kudzma, V., Nakashima, D., Peters, R., and Sams, S. 1978. Relationships between body size and some life history parameters. *Oecologia*, 37: 257–272.
<http://link.springer.com/10.1007/BF00344996>.
- Boyce, D. G., Lewis, M. L., and Worm, B. 2010. Global phytoplankton decline over the past century. *Nature*, 466: 591–596. Nature Publishing Group.
<http://dx.doi.org/10.1038/nature09268>.
- Boyce, D. G., Frank, K. T., Worm, B., and Leggett, W. C. 2015a. Spatial patterns and predictors of trophic control across marine ecosystems. *Ecology Letters*, 18: 1001–1011.
- Boyce, D. G., Frank, K. T., and Leggett, W. C. 2015b. From mice to elephants: overturning the ‘one size fits all’ paradigm in marine plankton food chains. *Ecology Letters*, 18: 504–515.

- http://doi.wiley.com/10.1111/ele.12434.
- Boyce, D. G., Petrie, B., Frank, K. T., Worm, B., and Leggett, W. C. 2017. Environmental structuring of marine plankton phenology. *Nature Ecology & Evolution*: 0–1. Springer US. <http://www.nature.com/articles/s41559-017-0287-3>.
- Boyce, D. G., Lotze, H. K., Tittensor, D. P., Carozza, D. A., and Worm, B. 2020a. Future ocean biomass losses may widen socioeconomic equity gaps. *Nature Communications*, 11: 1–11.
- Boyce, D. G., Schleit, K., and Fuller, S. 2020b. Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic. *Oceans North Report*: 184. www.oceansnorth.org.
- Boyce, D. G., Fuller, S., Karbowski, C., Schleit, K., and Worm, B. 2021. Leading or lagging: How well are climate change considerations being incorporated into Canadian fisheries management? *Canadian Journal of Fisheries and Aquatic Sciences*, 78: 1120–1129. <https://cdnsciencepub.com/doi/10.1139/cjfas-2020-0394>.
- Boyce, D. G., Tittensor, D. P., Garilao, C., Henson, S., Kaschner, K., Kesner-Reyes, K., Pigot, A., *et al.* 2022a. A climate risk index for marine life. *Nature Climate Change*, 12: 854–862. [https://www.nature.com/articles/s41558-022-01437-y](http://www.nature.com/articles/s41558-022-01437-y).
- Boyce, D. G., Tittensor, D. P., Garilao, C., Henson, S., Kaschner, K., Kesner-Reyes, K., Pigot, A., *et al.* 2022b. A climate risk index for marine life. *Nature Climate Change*, 12: 854–862. [https://www.nature.com/articles/s41558-022-01437-y](http://www.nature.com/articles/s41558-022-01437-y).
- Boyce, D. G., Shackell, N., Greyson, P., and Greenan, B. 2023. A prospective framework to support climate-adaptive fisheries in Canada. *FACETS*, 8: 1–15. <https://facetsjournal.com/doi/10.1139/facets-2022-0164>.
- Boyce, D. G., Shackell, N., and Greenar, B. 2024a. A climate risk index for marine life across the Canadian exclusive economic zone. *Canadian Technical Report of Fisheries and Aquatic Sciences*, 3568: 46.
- Boyce, D. G., Tittensor, D. P., Fuller, S., Henson, S., Kaschner, K., Reygondeau, G., Schleit, K. E., *et al.* 2024b. Operationalizing climate risk in a global warming hotspot. *npj Ocean Sustainability*, 3. Springer US. <http://dx.doi.org/10.1038/s44183-024-00067-5>.
- Boyce, D. G., Tittensor, D. P., Fuller, S., Henson, S., Kaschner, K., Reygondeau, G., Schleit, K. E., *et al.* 2024c. Operationalizing climate risk in a global warming hotspot. *npj Ocean Sustainability*, 3: 33. <https://www.nature.com/articles/s44183-024-00067-5>.
- Britten, G. L., Dowd, M., Minto, C. C. C. C., Ferretti, F., Boero, F., and Lotze, H. K. 2014.

- Predator decline leads to decreased stability in a coastal fish community. *Ecology Letters*, 17: 1518–1525. <http://doi.wiley.com/10.1111/ele.12354> (Accessed 17 September 2014).
- Brown, J. H., and Kodric-Brown, A. 1977. Turnover Rates in Insular Biogeography: Effect of Immigration on Extinction. *Ecology*, 58: 445–449. <http://doi.wiley.com/10.2307/1935620>.
- Bruno, J. F., Bates, A. E., Cacciapaglia, C., Pike, E. P., Amstrup, S. C., Van Hooidonk, R., Henson, S. A., *et al.* 2018. Climate change threatens the world's marine protected areas. *Nature Climate Change*, 8: 499–503. Springer US. <http://dx.doi.org/10.1038/s41558-018-0149-2>.
- Bryndum-Buchholz, A., Tittensor, D. P., and Lotze, H. K. 2021. The status of climate change adaptation in fisheries management: Policy, legislation and implementation. *Fish and Fisheries*:faf.12586. <https://onlinelibrary.wiley.com/doi/10.1111/faf.12586>.
- Budescu, D. V, Por, H. H., and Broomell, S. B. 2012. Effective communication of uncertainty in the IPCC reports. *Climatic Change*, 113: 181–200.
- Burek, K. A., Gulland, F. M. D., and O'Hara, T. M. 2008. Effects of climate change on Arctic marine mammal health. *Ecological Applications*, 18: S126–S134. <http://doi.wiley.com/10.1890/06-0553.1>.
- Burrows, M. T., Schoeman, D. S., Buckley, L. B., Moore, P., Poloczanska, E. S., Brander, K. M., Brown, C., *et al.* 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science*, 334: 652–655. <http://www.sciencemag.org/content/334/6056/652.abstract%5Cnhttp://www.sciencemag.org/content/334/6056/652.full.pdf> (Accessed 29 January 2013).
- Busch, D. S., Griffis, R., Link, J., Abrams, K., Baker, J., Brainard, R. E., Ford, M., *et al.* 2016. Climate science strategy of the US National Marine Fisheries Service. *Marine Policy*, 74: 58–67.
- Butt, N., Halpern, B. S., O'Hara, C. C., Allcock, A. L., Polidoro, B., Sherman, S., Byrne, M., *et al.* 2022. A trait-based framework for assessing the vulnerability of marine species to human impacts. *Ecosphere*, 13. <https://onlinelibrary.wiley.com/doi/10.1002/ecs2.3919>.
- Canadian Endangered Species Conservation Council. 2016. Wild Species 2015: The General Status of Species in Canada. National General Status Working Group: 128.
- Carilli, J., Donner, S. D., and Hartmann, A. C. 2012. Historical Temperature Variability Affects Coral Response to Heat Stress. *PLoS ONE*, 7: e34418. <https://dx.plos.org/10.1371/journal.pone.0034418>.

- Chase, J. M., Blowes, S. A., Knight, T. M., Gerstner, K., and May, F. 2020. Ecosystem decay exacerbates biodiversity loss with habitat loss. *Nature*, 584: 238–243.
<http://www.nature.com/articles/s41586-020-2531-2>.
- Chessman, B. C. 2013. Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes. *Biological Conservation*, 160: 40–49.
<https://linkinghub.elsevier.com/retrieve/pii/S0006320712005319>.
- Cheung, W. W. L., Watson, R., Morato, T., Pitcher, T. J., and Pauly, D. 2007. Intrinsic vulnerability in the global fish catch. *Marine Ecology Progress Series*, 333: 1–12.
- Cheung, W. W. L., Pauly, D., and Sarmiento, J. L. 2013. How to make progress in projecting climate change impacts. *ICES Journal of Marine Science*, 70: 1069–1074.
<https://academic.oup.com/icesjms/article/70/6/1069/639516>.
- Cheung, W. W. L., and Oyinlola, M. A. 2018. Vulnerability of flatfish and their fisheries to climate change. *Journal of Sea Research*, 140: 1–10.
- Cole, L. E. S., Bhagwat, S. A., and Willis, K. J. 2014. Recovery and resilience of tropical forests after disturbance. *Nature Communications*, 5: 3906.
<http://www.nature.com/articles/ncomms4906>.
- Comte, L., and Olden, J. D. 2017. Climatic vulnerability of the world's freshwater and marine fishes. *Nature Climate Change*, 7: 718–722.
- COSEWIC. 2012. COSEWIC assessment and status report on the Smooth Skate *Malacoraja senta* in Canada. Ottawa, Canada. 77 pp.
- Crooks, K. R., Burdett, C. L., Theobald, D. M., King, S. R. B., Di Marco, M., Rondinini, C., and Boitani, L. 2017. Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proceedings of the National Academy of Sciences*, 114: 7635–7640.
- Davidson, A. D. D., Boyer, A. G., Kim, H., Pompa-Mansilla, S., Hamilton, M. J., Costa, D. P., Ceballos, G., *et al.* 2012. Drivers and hotspots of extinction risk in marine mammals. *Proceedings of the National Academy of Sciences*, 109: 3395–3400.
<http://www.pnas.org/cgi/doi/10.1073/pnas.1121469109>.
- Davies, T. E., Maxwell, S. M., Kaschner, K., Garilao, C., and Ban, N. C. 2017. Large marine protected areas represent biodiversity now and under climate change. *Scientific Reports*, 7: 1–7. Springer US.
- de los Ríos, C., Watson, J. E. M., and Butt, N. 2018. Persistence of methodological, taxonomical, and geographical bias in assessments of species' vulnerability to climate change: A review.

- Global Ecology and Conservation, 15.
- DFO. 2021. Assessment of the northern contingent of Atlantic mackerel (*Scomber scombrus*) in 2020. Canadian Science Advisory Secretariat Science Advisory Report, 2021/029: 18.
- Donner, S. D., and Carilli, J. 2019. Resilience of Central Pacific reefs subject to frequent heat stress and human disturbance. *Scientific Reports*, 9: 3484. <http://www.nature.com/articles/s41598-019-40150-3>.
- Dunn, D. C., Maxwell, S. M., Boustany, A. M., and Halpin, P. N. 2016. Dynamic ocean management increases the efficiency and efficacy of fisheries management. *Proceedings of the National Academy of Sciences*, 113: 668–673. <http://www.pnas.org/lookup/doi/10.1073/pnas.1513626113>.
- Duplisea, D. E., Roux, M.-J., Hunter, K. L., and Rice, J. 2020. Resource management under climate change: a risk-based strategy to develop climate-informed science advice. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/044: 45.
- Duplisea, D. E., Roux, M.-J., Hunter, K. L., and Rice, J. 2021. Fish harvesting advice under climate change: A risk-equivalent empirical approach. *PLOS ONE*, 16: e0239503. <https://dx.plos.org/10.1371/journal.pone.0239503>.
- E.U. Copernicus Marine Service Information. 2023. Global Ocean Ensemble Physics Reanalysis [Data set].
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9: 1937–1958. <https://gmd.copernicus.org/articles/9/1937/2016/>.
- Fahrig, L. 2002. Effect of habitat fragmentation on the extinction threshold: A synthesis. *Ecological Applications*, 12: 346–353.
- FAO. 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. In FAO Fisheries and Aquaculture Technical Paper, p. 628. Ed. by M. Barange, T. Bahiri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith, and F. Poula. Rome.
- Fenchel, T. 1974. Intrinsic rate of natural increase: The relationship with body size. *Oecologia*, 14: 317–326. <http://link.springer.com/10.1007/BF00384576>.
- Ficetola, G. F., and Denoel, M. 2009. Ecological thresholds: an assessment of methods to identify abrupt changes in species-habitat relationships. *Ecography*, 32: 1075–1084.

- Fischlin, A. 2009. Do We Have Sufficient Safety Margins in Climate Policy? *GAIA-Ecological Perspectives for Science and Society*, 18: 193–199.
- Foden, W. B., Butchart, S. H. M., Stuart, S. N., Vié, J.-C., Akçakaya, H. R., Angulo, A., DeVantier, L. M., *et al.* 2013. Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS ONE*, 8: e65427. <https://dx.plos.org/10.1371/journal.pone.0065427>.
- Foden, W. B., Young, B. E., Akçakaya, H. R., Garcia, R. A., Hoffmann, A. A., Stein, B. A., Thomas, C. D., *et al.* 2019. Climate change vulnerability assessment of species. *Wiley Interdisciplinary Reviews: Climate Change*, 10: 1–36.
- Frank, K. T., Petrie, B., Shackell, N. L., and Choi, J. S. 2006. Reconciling differences in trophic control in mid-latitude marine ecosystems. *Ecology Letters*, 9: 1096–1105.
- Frank, K. T., Petrie, B., and Shackell, N. L. 2007. The ups and downs of trophic control in continental shelf ecosystems. *Trends in Ecology & Evolution*, 22: 236–242.
- Froese, R., and Pauly, D. (Eds). 2000. FishBase 2000: concepts, design and data sources. Los Banos, Laguna, Philippines. 344 pp.
- Froese, R., and Pauly, D. 2022. FishBase. FishBase: World Wide Web electronic publication. www.fishbase.org, version (02/2022).
- Frye, R. 1986. Variability and management of large marine ecosystems - Sherman, K, Alexander, LM. *Natural Resources Journal*, 26: 653–654.
- Gallagher, R. V., Allen, S., and Wright, I. J. 2019. Safety margins and adaptive capacity of vegetation to climate change. *Scientific Reports*, 9: 8241. <http://www.nature.com/articles/s41598-019-44483-x>.
- Garcia, R. A., Araujo, M. B., Burgess, N. D., Fden, W. B., Gutsche, A., Rahbek, C., and Cabeza, M. 2014. Matching species traits to projected threats and opportunities from climate change. *Journal of Biogeography*, 41: 724–735.
- Garner, G., Reed, P., and Keller, K. 2016. Climate risk management requires explicit representation of societal trade-offs. *CLIMATIC CHANGE*, 134: 713–723.
- Gattuso, J.-P. J.-P. P., Magnan, A., Billé, R., Cheung, W. W. L. L., Howes, E. L., Joos, F., Allemand, D., *et al.* 2015a. Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios. *Science*, 349: aac4722-1-aac4722-10. <http://www.sciencemag.org/cgi/doi/10.1126/science.aac4722>.
- Gattuso, J. P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., Allemand, D., *et al.*

- al.* 2015b. Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios. *Science*, 349.
- Gebco gridded global bathymetry data. 2009. . British Oceanographic Data Centre, Liverpool, UK.
- Gonzalez-Suarez, M., Gomez, A., and Revilla, E. 2013. Which intrinsic traits predict vulnerability to extinction depends on the actual threatening processes. *Ecosphere*, 4: 1–16.
- Greenan, B. J. W., Shackell, N. L., Ferguson, K., Greyson, P., Cogswell, A., Brickman, D., Wang, Z., *et al.* 2019. Climate Change Vulnerability of American Lobster Fishing Communities in Atlantic Canada. *Frontiers in Marine Science*, 6: 1–18. Frontiers Media, Lausanne, Switzerland.
- Guest, J. R., Baird, A. H., Maynard, J. A., Muttaqin, E., Edwards, A. J., Campbell, S. J., Yewdall, K., *et al.* 2012. Contrasting Patterns of Coral Bleaching Susceptibility in 2010 Suggest an Adaptive Response to Thermal Stress. *PLoS ONE*, 7: e33353. <https://dx.plos.org/10.1371/journal.pone.0033353>.
- Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, K. V, Micheli, F., D'Agrosa, C., Bruno, J. F., *et al.* 2008. A global map of human impact on marine ecosystems. *Science*, 319: 948–952. <http://www.sciencemag.org/content/319/5865/948.short> (Accessed 6 November 2013).
- Halpern, B. S., Longo, C., Hardy, D., McLeod, K. L., Samhouri, J. F., Katona, S. K., Kleisner, K., *et al.* 2012. An index to assess the health and benefits of the global ocean. *Nature*, 488: 615–620. Nature Publishing Group. <http://www.ncbi.nlm.nih.gov/pubmed/22895186>.
- Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., Lowndes, J. S., *et al.* 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications*, 6: 1–7. Nature Publishing Group.
- Haltuch, M. A., Brooks, E. N., Brodziak, J., Devine, J. A., Johnson, K. F., Klibansky, N., Nash, R. D. M., *et al.* 2019a. Unraveling the recruitment problem: A review of environmentally-informed forecasting and management strategy evaluation. *Fisheries Research*, 217: 198–216.
- Haltuch, M. A., A'Mar, Z. T., Bond, N. A., and Valero, J. L. 2019b. Assessing the effects of climate change on US West Coast sablefish productivity and on the performance of alternative management strategies. *ICES Journal of Marine Science*, 76: 1524–1542.
- Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, E. J., Griffis, R. B., Alexander, M. A., *et al.* 2016. A vulnerability assessment of fish and invertebrates to

- climate change on the northeast u.s. continental shelf. PLoS ONE, 11: 1–30.
<http://dx.doi.org/10.1371/journal.pone.0146756>.
- Healy, K., Guillerme, T., Finlay, S., Kane, A., Kelly, S. B. A., McClean, D., Kelly, D. J., *et al.* 2014. Ecology and mode-of-life explain lifespan variation in birds and mammals. Proceedings of the Royal Society B: Biological Sciences, 281: 20140298.
<https://royalsocietypublishing.org/doi/10.1098/rspb.2014.0298>.
- Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., Tjiputra, J., *et al.* 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. Nature Communications, 8: 1–9.
- Hewitt, H. T., Copsey, D., Culverwell, I. D., Harris, C. M., Hill, R. S. R., Keen, A. B., McLaren, A. J., *et al.* 2011. Design and implementation of the infrastructure of HadGEM3: the next-generation Met Office climate modelling system. Geoscientific Model Development, 4: 223–253. <https://gmd.copernicus.org/articles/4/223/2011/>.
- Hill, M. F., and Caswell, H. 1999. Habitat fragmentation and extinction thresholds on fractal landscapes. Ecology Letters, 2: 121–127. <http://doi.wiley.com/10.1046/j.1461-0248.1999.22061.x>.
- Hillebrand, H., Donohue, I., Harpole, W. S., Hodapp, D., Kucera, M., Lewandowska, A. M., Merder, J., *et al.* 2020. Thresholds for ecological responses to global change do not emerge from empirical data. Nature Ecology & Evolution, 4: 1502–1509.
<http://www.nature.com/articles/s41559-020-1256-9>.
- Holling, C. S. 1973. Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics, 4: 1–23.
<http://www.annualreviews.org/doi/10.1146/annurev.es.04.110173.000245>.
- Holsman, K. K., Ianelli, J. N., Aydin, K., and Spies, I. 2019. 2019 Climate-Enhanced Multi-Species Stock Assessment for Walleye Pollock, Pacific Cod, and Arrowtooth Flounder in the Eastern Bering Sea. In NPFMC Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, p. 43.
- Homan, R. N., Windmiller, B. S., and Reed, J. M. 2004. Critical thresholds associated with habitat loss for two vernal pool-breeding amphibians. Ecological Applications, 14: 1547–1553. <http://doi.wiley.com/10.1890/03-5125>.
- Hooper, D. U., Adair, E. C., Cardinale, B. J., Byrnes, J. E. K., Hungate, B. a, Matulich, K. L., Gonzalez, A., *et al.* 2012. A global synthesis reveals biodiversity loss as a major driver of

- ecosystem change. *Nature*, 486: 105–8. Nature Publishing Group.
<http://www.ncbi.nlm.nih.gov/pubmed/22678289> (Accessed 21 May 2013).
- IPCC. 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, U.K.
- IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1132 pp.
- IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K. 2391 pp.
- IUCN. 2012. IUCN Red List Categories and Criteria: Version 3.1. IUCN, Gland, Switzerland and Cambridge, UK. 32 pp.
- IUCN. 2021. The IUCN Red List of Threatened Species. <https://www.iucnredlist.org>.
- Kaschner, K., Watson, R., Trites, A., and Pauly, D. 2006. Mapping world-wide distributions of marine mammal species using a relative environmental suitability (RES) model. *Marine Ecology Progress Series*, 316: 285–310. <http://www.int-res.com/abstracts/meps/v316/p285-310/>.
- Kaschner, K., Kesner-Reyes, K., Garlao, C., Segschneider, J., Rius-Barile, J., Rees, T., and Froese, R. 2019. Aquamaps: Predicted range maps for aquatic species.
- Keen, L., Stortini, C., Boyce, D. G., and Stanley, R. 2023. Representing Climate Change Vulnerabilities in Canadian Marine Conservation Networks. Submitted.
- Keen, L. H., Stortini, C. H., Boyce, D. G., and Stanley, R. R. E. 2024. Assessing climate change vulnerability in Canadian marine conservation networks: implications for conservation planning and resilience. *FACETS*, 9: 1–15. <https://facetsjournal.com/doi/10.1139/facets-2023-0124>.
- Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, O., Heide-Jørgensen, M. P., and Ferguson, S. H. 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*, 18: S97–125.
- Lange, R., Durka, W., Holzhauer, S. I. J., Wolters, V., and Diekotter, T. 2010. Differential threshold effects of habitat fragmentation on gene flow in two widespread species of bush

- crickets. *Molecular Ecology*, 19: 4936–4948.
<https://onlinelibrary.wiley.com/doi/10.1111/j.1365-294X.2010.04877.x>.
- Le Bris, A., Mills, K. E., Wahle, R. A., Chen, Y., Alexander, M. A., Allyn, A. J., Schuetz, J. G., *et al.* 2018. Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences of the United States of America*, 115: 1831–1836.
- Leemans, R., and Vellinga, P. 2017. The scientific motivation of the internationally agreed ‘well below 2 degrees C’ climate protection target: a historical perspective. *Current Opinion in Environmental Sustainability*, 26–27: 134–142.
- Lehtinen, R. M., Galatowitsch, S. M., and Tester, J. R. 1999. Consequences of habitat loss and fragmentation for wetland amphibian assemblages. *Wetlands*, 19: 1–12.
<http://link.springer.com/10.1007/BF03161728>.
- Lewis, S. A., Stortini, C. H., Boyce, D. G., and Stanley, R. R. E. 2023. Climate change, species thermal emergence, and conservation design: a case study in the Canadian Northwest Atlantic. *FACETS*, 8: 1–16. <https://facetsjournal.com/doi/10.1139/facets-2022-0191>.
- Li, D., Wu, S., Liu, L., Zhang, Y., and Li, S. 2018. Vulnerability of the global terrestrial ecosystems to climate change. *Global Change Biology*, 24: 4095–4106.
- Liao, J., Li, Z., Hiebeler, D. E., El-Bana, M., Deckmyn, G., and Nijs, I. 2013. Modelling plant population size and extinction thresholds from habitat loss and habitat fragmentation: Effects of neighbouring competition and dispersal strategy. *Ecological Modelling*, 268: 9–17. <https://linkinghub.elsevier.com/retrieve/pii/S0304380013003761>.
- Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., and Ackerly, D. D. 2009. The velocity of climate change. *Nature*, 462: 1052–1056.
<http://www.ncbi.nlm.nih.gov/pubmed/20033047> (Accessed 28 January 2013).
- Longhurst, A. 2007. *Ecological geography of the sea*. Elsevier Inc., Burlington, MA. 542 pp.
- MacKenzie, B. R., Payne, M. R., Boje, J., Hoyer, J. L., Siegstad, H., H??yer, J. L., and Siegstad, H. 2014. A cascade of warming impacts brings bluefin tuna to Greenland waters. *Global Change Biology*, 20: 2484–2491.
- Mann, K. H., and Lazier, J. R. N. 1991. *Dynamics of marine ecosystems*. Blackwell, Oxford, UK. 466 pp.
- Martin, T. G., and Watson, J. E. M. 2016. Intact ecosystems provide best defence against climate change. *Nature Climate Change*, 6: 122–124. <http://www.nature.com/articles/nclimate2918>.

- May, R. M. 1973. Stability and complexity in model ecosystems. Princeton University Press, Princeton, NJ, USA.
- McHenry, J., Welch, H., Lester, S. E., and Saba, V. 2019. Projecting marine species range shifts from only temperature can mask climate vulnerability. *Global Change Biology*, 25: 4208–4221. <https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14828>.
- Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., *et al.* 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, 13: 3571–3605. <https://gmd.copernicus.org/articles/13/3571/2020/>.
- Merino, G., Arrizabalaga, H., Arregui, I., Santiago, J., Murua, H., Urtizberea, A., Andonegi, E., *et al.* 2019. Adaptation of North Atlantic Albacore Fishery to Climate Change: Yet Another Potential Benefit of Harvest Control Rules. *Frontiers in Marine Science*, 6: 1–14. <https://www.frontiersin.org/article/10.3389/fmars.2019.00620/full>.
- Moore, S. E., and Huntington, H. P. 2008. Arctic marine mammals and climate change: impacts and resilience. *Ecological Applications*, 18: S157–S165. <http://doi.wiley.com/10.1890/06-0571.1>.
- Mora, C., Wei, C.-L., Rollo, A., Amaro, T., Baco, A. R., Billett, D., Bopp, L., *et al.* 2013a. Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. *PLoS biology*, 11: 1–14. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3797030/> (Accessed 29 May 2014).
- Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., Sanchez, J. J., *et al.* 2013b. The projected timing of climate departure from recent variability. *Nature*, 502: 183+. Nature Publishing Group. <http://www.ncbi.nlm.nih.gov/pubmed/24108050> (Accessed 6 November 2013).
- Mora, C., Danovaro, R., and Loreau, M. 2014. Alternative hypotheses to explain why biodiversity-ecosystem functioning relationships are concave-up in some natural ecosystems but concave-down in manipulative experiments. *Scientific reports*, 4: 5427. <http://www.ncbi.nlm.nih.gov/pubmed/24962477>.
- Nadeau, C. P., Urban, M. C., and Bridle, J. R. 2017. Climates past, present, and yet-to-come shape climate change vulnerabilities. *Trends in Ecology & Evolution*, 32: 786–800. <https://linkinghub.elsevier.com/retrieve/pii/S0169534717301891>.

- Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L. L., *et al.* 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science*, 353: 288–291.
- Ochoa-Quintero, J. M., Gardner, T. A., Rosa, I., de Barros Ferraz, S. F., and Sutherland, W. J. 2015. Thresholds of species loss in Amazonian deforestation frontier landscapes. *Conservation Biology*, 29: 440–451.
<https://onlinelibrary.wiley.com/doi/10.1111/cobi.12446>.
- Oliver, T. H. 2016. How much biodiversity loss is too much? *Science*, 353: 220–221.
<https://www.science.org/doi/10.1126/science.aag1712>.
- Oppenheimer, M., Little, C. M., and Cooke, R. M. 2016. Expert judgement and uncertainty quantification for climate change. *Nature Climate Change*, 6: 445–451.
- Ottersen, G., Hjermann, D. O., and Stenseth, N. C. 2006. Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (*Gadus morhua*) stock. *Fisheries Oceanography*, 15: 230–243.
- Pacifci, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., Scheffers, B. R., *et al.* 2015. Assessing species vulnerability to climate change. *Nature Climate Change*, 5: 215–225.
- Palmeirim, A. F., Santos-Filho, M., and Peres, C. A. 2020. Marked decline in forest-dependent small mammals following habitat loss and fragmentation in an Amazonian deforestation frontier. *PLOS ONE*, 15: e0230209. <https://dx.plos.org/10.1371/journal.pone.0230209>.
- Palomares, M. L. D., and Pauly, D. 2022. SeaLifeBase. World Wide Web electronic publication. www.sealifebase.org, version (11/2014).
- Parker, M., and Mac Nally, R. 2002. Habitat loss and the habitat fragmentation threshold: an experimental evaluation of impacts on richness and total abundances using grassland invertebrates. *Biological Conservation*, 105: 217–229.
<https://linkinghub.elsevier.com/retrieve/pii/S0006320701001847>.
- Pearson, R. G., Stanton, J. C., Shoemaker, K. T., Aiello-Lammens, M. E., Ersts, P. J., Horning, N., Fordham, D. A., *et al.* 2014. Life history and spatial traits predict extinction risk due to climate change. *Nature Climate Change*, 4: 217–221.
<http://www.nature.com/articles/nclimate2113>.
- Peters, R. L. 1985. The Greenhouse Effect and Nature Reserves. *Biosciences*, 35: 707–717.
- Pikitch, E. K., Rountos, K. J., Essington, T. E., Santora, C., Pauly, D., Watson, R., Sumaila, U.

- R., *et al.* 2014. The global contribution of forage fish to marine fisheries and ecosystems. *Fish and Fisheries*, 15: 43–64.
- Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., and Levin, S. A. 2013. Marine Taxa Track Local Climate Velocities. *Science*, 341: 1239–1242.
<http://www.sciencemag.org/content/341/6151/1239%5Cnhttp://www.ncbi.nlm.nih.gov/pubmed/24031017%5Cnhttp://www.sciencemag.org/content/341/6151/1239.abstract>.
- Pinsky, M. L., and Mantua, N. J. 2014. Emerging Adaptation Approaches for Climate-Ready Fisheries Management. *Oceanography*, 27: 146–159.
- Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L., and Sunday, J. M. 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*. Springer US.
<http://dx.doi.org/10.1038/s41586-019-1132-4>.
- Poloczanska, E. S., Burrows, M. T., Brown, C. J., Garcia Molinos, J., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V, *et al.* 2016. Responses of Marine Organisms to Climate Change across Oceans. *Frontiers in Marine Science*, 3: 62.
<http://journal.frontiersin.org/Article/10.3389/fmars.2016.00062/abstract>.
- R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.r-project.org/>.
- Rehm, E. M., Olivas, P., Stroud, J., and Feeley, K. J. 2015. Losing your edge: climate change and the conservation value of range-edge populations. *Ecology and Evolution*, 5: 4315–4326. <https://onlinelibrary.wiley.com/doi/10.1002/ece3.1645>.
- Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., and Schlax, M. G. 2007. Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, 20: 5473–5496.
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., *et al.* 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42: 153–168. <https://linkinghub.elsevier.com/retrieve/pii/S0959378016300681>.
- Ripple, W. J., Wolf, C., Newsome, T. M., Hoffmann, M., Wirsing, A. J., and McCauley, D. J. 2017. Extinction risk is most acute for the world's largest and smallest vertebrates. *Proceedings of the National Academy of Sciences*, 114: 10678–10683.
<https://pnas.org/doi/full/10.1073/pnas.1702078114>.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M.,

- et al.* 2009. A safe operating space for humanity. *Nature*, 461: 472–475.
<http://www.ecologyandsociety.org/vol14/iss2/art32/>.
- Rogan, J. E., and Lacher, T. E. 2018. Impacts of Habitat Loss and Fragmentation on Terrestrial Biodiversity. In Reference Module in Earth Systems and Environmental Sciences. Elsevier.
<https://linkinghub.elsevier.com/retrieve/pii/B9780124095489109133>.
- Rompre, G., Boucher, Y., Belanger, L., Cote, S., and Robinson, W. D. 2010. Conserving biodiversity in managed forest landscapes: The use of critical thresholds for habitat. *FORESTRY CHRONICLE*, 86: 589–596.
- Rosset, V., and Oertli, B. 2011. Freshwater biodiversity under climate warming pressure: Identifying the winners and losers in temperate standing waterbodies. *Biological Conservation*, 144.
- Rueda, M., Hawkins, B. A., Morales-Castilla, I., Vidanes, R. M., Ferrero, M., and Rodríguez, M. Á. 2013. Does fragmentation increase extinction thresholds? A European-wide test with seven forest birds. *Global Ecology and Biogeography*, 22: 1282–1292.
- Scheffer, M., and Carpenter, S. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol. Evol.*, 18: 648–656.
- Scheffer, M., Bascompte, J., Brock, W. A. W. A., Brovkin, V., Carpenter, S. R. S. R., Dakos, V., Held, H., *et al.* 2009. Early-warning signals for critical transitions. *Nature*, 461: 53–59.
- Scheffer, M., Carpenter, S. R., Lenton, T. M., Bascompte, J., Brock, W., Dakos, V., van de Koppel, J., *et al.* 2012. Anticipating Critical Transitions. *Science*, 338: 344–348.
- Scheffers, B. R., De Meester, L., Bridge, T. C. L. L., Hoffmann, A. A., Pandolfi, J. M., Corlett, R. T., Butchart, S. H. M. M., *et al.* 2016. The broad footprint of climate change from genes to biomes to people. *Science*, 354.
- Scholes, R. J., and Biggs, R. 2005. A biodiversity intactness index. *Nature*, 434: 45–49.
<http://www.nature.com/articles/nature03289>.
- Sein, D. V., Koldunov, N. V., Danilov, S., Sidorenko, D., Wekerle, C., Cabos, W., Rackow, T., *et al.* 2018. The Relative Influence of Atmospheric and Oceanic Model Resolution on the Circulation of the North Atlantic Ocean in a Coupled Climate Model. *Journal of Advances in Modeling Earth Systems*, 10: 2026–2041. <http://doi.wiley.com/10.1029/2018MS001327>.
- Shackell, N. L., Ricard, D., and Stortini, C. 2014. Thermal Habitat Index of Many Northwest Atlantic Temperate Species Stays Neutral under Warming Projected for 2030 but Changes Radically by 2060. *PLOS ONE*, 9.

- Shennan-Farpón, Y., Visconti, P., and Norris, K. 2021. Detecting ecological thresholds for biodiversity in tropical forests: Knowledge gaps and future directions. *Biotropica*: btp.12999. <https://onlinelibrary.wiley.com/doi/10.1111/btp.12999>.
- Staude, I. R., Navarro, L. M., and Pereira, H. M. 2020. Range size predicts the risk of local extinction from habitat loss. *Global Ecology and Biogeography*, 29: 16–25. <https://onlinelibrary.wiley.com/doi/10.1111/geb.13003>.
- Stortini, C. H. C. H., Shackell, N. L. N. L., Tyedmers, P., and Beazley, K. 2015. Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. *ICES Journal of Marine Science*, 72: 1713–1743. <https://academic.oup.com/icesjms/article/72/6/1731/918246>.
- Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Kininmonth, S. J., and Bates, A. E. 2015a. Thermal biases and vulnerability to warming in the world's marine fauna. *Nature*, 528: 88–92.
- Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Kininmonth, S. J., and Bates, A. E. 2015b. Thermal biases and vulnerability to warming in the world's marine fauna. *Nature*, 528: 88+.
- Sunday, J. M., Bates, A. E., and Dulvy, N. K. 2012. Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, 2: 686–690. Nature Publishing Group. <http://dx.doi.org/10.1038/nclimate1539>.
- Swart, R., Bernstein, L., Ha-Duong, M., and Petersen, A. 2009. Agreeing to disagree: uncertainty management in assessing climate change, impacts and responses by the IPCC. *CLIMATIC CHANGE*, 92: 1–29.
- Swift, T. L., and Hannon, S. J. 2010. Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications. *Biological Reviews*, 85: 35–53. <https://onlinelibrary.wiley.com/doi/10.1111/j.1469-185X.2009.00093.x>.
- Tittensor, D. P., Beger, M., Boerder, K., Boyce, D. G., Cavanagh, R. D., Cosandey-Godin, A., Crespo, G. O., et al. 2019. Integrating climate adaptation and biodiversity conservation in the global ocean. *Science Advances*, 5: 1–16.
- Trisos, C. H., Merow, C., and Pigot, A. L. 2020. The projected timing of abrupt ecological disruption from climate change. *Nature*, 580: 1–6. Springer US. <http://www.nature.com/articles/s41586-020-2189-9>.
- van der Hoek, Y., Zuckerberg, B., and Manne, L. L. 2015. Application of habitat thresholds in conservation: Considerations, limitations, and future directions. *Global Ecology and*

- Conservation, 3: 736–743.
<https://linkinghub.elsevier.com/retrieve/pii/S2351989415000360>.
- Volodire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., *et al.* 2019. Evaluation of CMIP6 DECK Experiments With CNRM-CM6-1. *Journal of Advances in Modeling Earth Systems*, 11: 2177–2213.
<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019MS001683>.
- Warren, M. S., Hill, J. K., Thomas, J. A., Asher, J., Fox, R., Huntley, B., Toy, D. B., *et al.* 2001. Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature*, 414: 65–69.
- Worm, B., Lotze, H. K., Hillebrand, H., and Sommer, U. 2002. Consumer versus resource control of species diversity and ecosystem functioning. *Nature*, 417: 848–851.
- Worm, B., and Duffy, J. E. 2003. Biodiversity, productivity, and stability in real food webs. *Trends Ecol. Evol.*, 18: 628–632.
- Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., *et al.* 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science*, 314: 787–90.
<http://www.ncbi.nlm.nih.gov/pubmed/17082450> (Accessed 29 January 2013).
- Xu, C., Kohler, T. A., Lenton, T. M., Svenning, J.-C., and Scheffer, M. 2020. Future of the human climate niche. *Proceedings of the National Academy of Sciences*, 117: 11350–11355. <http://www.pnas.org/lookup/doi/10.1073/pnas.1910114117>.
- Xu, Y., Shen, Z.-H., Ying, L.-X., Ciais, P., Liu, H.-Y., Piao, S., Wen, C., *et al.* 2016. The exposure, sensitivity and vulnerability of natural vegetation in China to climate thermal variability (1901–2013): An indicator-based approach. *Ecological Indicators*, 63: 258–272.
<https://linkinghub.elsevier.com/retrieve/pii/S1470160X15007281>.
- Xue, Y., Balmaseda, M. A., Boyer, T., Ferry, N., Good, S., Ishikawa, I., Kumar, A., *et al.* 2012. A Comparative Analysis of Upper-Ocean Heat Content Variability from an Ensemble of Operational Ocean Reanalyses. *Journal of Climate*, 25: 6905–6929.
<http://journals.ametsoc.org/doi/10.1175/JCLI-D-11-00542.1>.
- Yin, D., Leroux, S. J., and He, F. 2017. Methods and models for identifying thresholds of habitat loss. *Ecography*, 40: 131–143. <https://onlinelibrary.wiley.com/doi/10.1111/ecog.02557>.
- Zommers, Z., Marbaix, P., Fischlin, A., Ibrahim, Z. Z., Grant, S., Magnan, A. K., Pörtner, H.-O., *et al.* 2020. Burning embers: towards more transparent and robust climate-change risk assessments. *Nature Reviews Earth & Environment*, 1: 516–529.

[http://www.nature.com/articles/s43017-020-0088-0.](http://www.nature.com/articles/s43017-020-0088-0)

Zuo, H., Balmaseda, M. A., Tietsche, S., Mogensen, K., and Mayer, M. 2019. The ECMWF operational ensemble reanalysis–analysis system for ocean and sea ice: a description of the system and assessment. *Ocean Science*, 15: 779–808.

[https://os.copernicus.org/articles/15/779/2019/.](https://os.copernicus.org/articles/15/779/2019/)