

A climate risk index for marine life across the Canadian exclusive economic zone

Daniel G. Boyce, Nancy Shackell, Blair Greenan

Fisheries and Oceans Canada
Science Branch, Maritimes Region
Bedford Institute of Oceanography
PO Box 1006
1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2

2024

**Canadian Technical Report of
Fisheries and Aquatic Sciences 3568**

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3568

2024

**A climate risk index for marine life across the Canadian exclusive
economic zone**

by

Daniel G. Boyce, Nancy Shackell, Blair Greenan

Fisheries and Oceans Canada
Science Branch, Maritimes Region
Bedford Institute of Oceanography
PO Box 1006
1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2

© His Majesty the King in Right of Canada, as represented by the
Minister of the Department of Fisheries and Oceans, 2024
Cat. No. Fs97-6/3568E-PDF ISBN 978-0-660-69319-4 ISSN 1488-5379

Correct citation for this publication:

Boyce, D.G., Shackell, N., Greenan, B. 2024. A climate risk index for marine life across the Canadian exclusive economic zone. *Can. Tech. Rep. Fish. Aquat. Sci.* 3568: iv + 40 p.

Table of Contents

ABSTRACT	iv
RÉSUMÉ	iv
Introduction	1
Materials and methods	3
Analyses	3
Data	4
<i>Species native geographic distribution</i>	6
<i>Thermal niches</i>	6
<i>Species conservation status</i>	6
<i>Maximum body lengths</i>	7
<i>Temperature</i>	7
<i>Cumulative impacts</i>	7
<i>Climate projections</i>	7
Results	8
Climate sensitivity	9
<i>Thermal safety margins</i>	9
<i>Conservation status</i>	10
<i>Cumulative impacts</i>	10
<i>Vertical habitat variability and use</i>	11
Climate exposure.....	12
<i>Projected time of climate emergence</i>	12
<i>Projected ecosystem disruption</i>	13
<i>Projected loss of suitable thermal habitat</i>	14
<i>Projected climate velocity</i>	15
Climate adaptivity	16
<i>Geographic range extent</i>	16
<i>Geographic habitat fragmentation</i>	17
<i>Thermal habitat variability and use</i>	17
<i>Maximum body length</i>	18
Climate dimensions	19
Climate vulnerability.....	20
Climate risk.....	21
<i>Sensitivity risk thresholds</i>	23
<i>Exposure risk thresholds</i>	23
<i>Adaptivity risk thresholds</i>	24
Ecosystem climate risk	25
Ongoing work and next steps	26
References	27

ABSTRACT

Boyce, D.G., Shackell, N., Greenan, B. 2024. A climate risk index for marine life across the Canadian exclusive economic zone. Can. Tech. Rep. Fish. Aquat. Sci. 3568: iv + 40 p.

In Canada, DFO assessments have reported a high probability of significant climate change impacts in all marine and freshwater basins, with effects increasing over time (DFO 2012a, 2012b), while climate projections indicate that ecosystems and fisheries will be disrupted into the foreseeable future (Lotze et al. 2019b; Bryndum-Buchholz et al. 2020; Tittensor et al. 2021; Boyce et al. 2022c). Despite its imminence, climate change is infrequently factored into Canada's primary marine conservation strategies, such as spatial planning (O'Regan et al. 2021) or fisheries management (Boyce et al. 2021a; Pepin et al. 2022). The Climate Risk Index for Biodiversity was developed to assess climate risk for marine species in a quantitative, spatially explicit, and scalable way to better support climate-informed decision-making. It has been used to evaluate climate risks for marine life globally (Boyce et al. 2022a), regionally (Lewis et al. 2023), and for fisheries (Boyce et al. 2022c). Here, we describe how the CRIB framework was used to estimate climate risks for 2,959 species and ecosystems across the Canadian marine territory under contrasting emission scenarios. Using Atlantic cod (*Gadus morhua*) as an example, we describe the approach's data, methods, and outputs to transparently and tangibly show how it quantifies risk and can inform and support climate-informed decision-making in Canada. Climate risk estimates for species and ecosystems accompany the report.

RÉSUMÉ

Boyce, D.G., Shackell, N., Greenan, B. 2024. A climate risk index for marine life across the Canadian exclusive economic zone. Can. Tech. Rep. Fish. Aquat. Sci. 3568: iv + 40 p.

Au Canada, les évaluations du MPO ont signalé une forte probabilité d'impacts importants des changements climatiques dans tous les bassins marins et d'eau douce, les effets augmentant avec le temps (DFO 2012a, 2012b), tandis que les projections climatiques indiquent que les écosystèmes et les pêches seront perturbés dans un avenir prévisible (Lotze et al. 2019b; Bryndum-Buchholz et al. 2020; Tittensor et al. 2021; Boyce et al. 2022c). Malgré son imminence, le changement climatique est rarement pris en compte dans les principales stratégies de conservation marine du Canada, comme la planification spatiale (O'Regan et al. 2021) ou la gestion des pêches (Boyce et al. 2021a; Pepin et al. 2022). L'indice de risque climatique pour la biodiversité a été développé pour évaluer le risque climatique pour les espèces marines de manière quantitative, spatialement explicite et évolutive afin de mieux soutenir la prise de décision éclairée par le climat. Il a été utilisé pour évaluer les risques climatiques pour la vie marine à l'échelle mondiale (Boyce et al. 2022a), régionale (Lewis et al. 2023) et pour la pêche (Boyce et al. 2022c). Nous décrivons ici comment le cadre du CRIB a été utilisé pour estimer les risques climatiques pour 2 959 espèces et écosystèmes sur l'ensemble du territoire marin canadien selon des scénarios d'émissions contrastés. En utilisant la morue franche (*Gadus morhua*) comme exemple, nous décrivons les données, les méthodes et les résultats de l'approche pour montrer de manière transparente et tangible comment elle quantifie le risque et peut éclairer et soutenir la prise de décision éclairée sur le climat au Canada. Des estimations des risques climatiques pour les espèces et les écosystèmes accompagnent le rapport.

Introduction

Climate change vulnerability and risk assessments (CCVAs and CCRAs) are widely viewed as a critical component of climate-aware management of species and ecosystems and quantifying climate change impacts (Busch et al. 2016; Hare et al. 2016; FAO 2018). CCVAs help address several critical 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. They can also identify gaps in data and information needed to understand climate change impacts on species and ecosystems. As of 2015, over 800 peer-reviewed CCVAs have been developed to evaluate the vulnerability of species, communities and ecosystems across different scales and systems using various approaches (e.g. trait-based, correlative, mechanistic modelled, theoretical); (Pacifci et al. 2015; de los Ríos et al. 2018; e.g. Foden et al. 2019). This interest has led to a broad acceptance of what features define vulnerability. Following an early IPCC definition (IPCC 2014) and subsequent broad adoption (Foden et al. 2013, 2019; Pacifci et al. 2015; Comte and Olden 2017; de los Ríos et al. 2018; Albouy et al. 2020), species' climate vulnerability has been defined by three dimensions: 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 (May 1973; Holling 1973; Britten et al. 2014). Thus, the dimensions that define climate vulnerability are firmly rooted in ecological theory.

Despite the advancement in developing CCVAs (de los Ríos et al. 2018; Foden et al. 2019) and their potential to support climate adaptation (Stortini et al. 2015; Hare et al. 2016; FAO 2018; Tittensor et al. 2019; Greenan et al. 2019; Bryndum-Buchholz et al. 2022), existing frameworks have limitations that could help to explain their low incorporation into management settings such as fisheries, species at risk, or spatial planning (e.g. Boyce et al. 2021b, 2021a; Pepin et al. 2022):

1. With some exceptions (Foden et al. 2013; Comte and Olden 2017; Albouy et al. 2020), CCVAs often yield a single vulnerability value across species ranges, even though geographic variation in vulnerability is often significant (Sunday et al. 2012; Foden et al. 2013; Munday et al. 2013; Pacifci et al. 2015; Stuart-Smith et al. 2015b; Stanley et al. 2018; Pinsky et al. 2019; Albouy et al. 2020; Layton et al. 2021) and critical to

developing climate-considered conservation strategies (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022).

2. They often rely on semi-quantitative expert opinions rather than being quantitatively derived from empirical data (Hare et al. 2016; Foden et al. 2019; Albouy et al. 2020), which is a barrier to consistently tracking changing vulnerability through time and limits their reproducibility.
3. They rarely evaluate all three component dimensions of vulnerability: exposure, sensitivity, and adaptivity (de los Ríos et al. 2018).
4. They are rarely spatially or taxonomically comprehensive (Pacifci et al. 2015). Instead, they are often undertaken regionally (Stortini et al. 2015; Hare et al. 2016) on taxonomic subgroups (Comte and Olden 2017; Albouy et al. 2020) rather than the global species pool. This limits the capacity to understand how risk for some species or locations compares against others and prohibits comparability of risks across studies.
5. They almost exclusively rank and compare species vulnerabilities in dimensionless units (Foden et al. 2013, 2019; Pacifci et al. 2015; Hare et al. 2016; Comte and Olden 2017; de los Ríos et al. 2018; Albouy et al. 2020). This can be problematic, as stakeholders and associated structured decision-making frameworks often require explicit risk assessments on absolute rather than relative scales.

The Climate Risk Index for Biodiversity (CRIB) was recently developed as a unified framework for assessing relative and absolute climate vulnerability that fills several of these gaps (Boyce et al. 2022a). It incorporates climate risk information that is often required in applied settings, including 1) it is spatially explicit, evaluating risk at all 0.25-degree grid cells across species' geographic distributions, 2) it uses quantitative, well-validated, and publicly available data, ensuring reproducibility, 3) it is flexible, can be applied at scales from local to global, can incorporate new information as it becomes available, 4) it is comprehensive, evaluating all three dimensions that define vulnerability and risk (IPCC 2014) using multiple assessment types (e.g., trait-based, mechanistic, correlative); (Foden et al. 2019), 5) it assesses the statistical uncertainty (variability) of the vulnerability and risk scores, 6) it assesses the impacts of anticipated future climate conditions on species to facilitate decisions regarding emission mitigation, and 7) the framework provides a robust method for translating relative vulnerability scores and rankings into absolute risk categories for species and ecosystems to aid the management and conservation of marine ecosystems under climate change. It is designed hierarchically, thus maximizing its flexibility and information content.

This report describes the steps taken to estimate climate vulnerability and risk for marine ecosystems across Canada's marine territory using the CRIB framework (Boyce et al. 2022a). To illustrate the workflow and methods, the climate vulnerability and risk for Atlantic cod (*Gadus*

morhua) is estimated as an illustrative example. The relevance and potential applications to management decisions in Fisheries and Oceans Canada is also discussed, along with opportunities for further development.

Materials and methods

Analyses

Boyce et al. (2022b) fully describe the CRIB framework. The 12 climate indices that define it capture climate change impacts generalized across species with varying life histories grounded in ecological theory, widely accepted and validated through peer review. The indices maximize parsimony and minimize redundancy and pseudoreplication; those that were easy to interpret and calculate were prioritized. The indices collectively include trait-based, correlative, and mechanistic information and incorporate abiotic, biotic, and human pressures acting across multiple biological organization levels from species to ecosystems. The indices integrate historical, present-day, and projected future information about species' climate vulnerability and are calculated or obtained in their native units. The 12 climate indices are described in Table 1.

Each index was calculated from environmental or ecological data and/or a mix of the two on a geographic grid across the native geographic distribution of the focal species, defined by the focal species' traits. This produces indices that are taxonomically (*e.g.*, each species) and geographically (*e.g.*, each grid cell) explicit. The indices are transformed to ensure they are on a standardized scale (0-1) across all species and locations. This step ensures that indices with different native units can be compared, normalized, and combined while simultaneously ensuring that vulnerability can be calculated at different spatial resolutions or points in time without losing information. Reference values and scaling functions were used to meet these criteria and are described in Boyce *et al.* (2022b). The 12 standardized climate indices are used to calculate three climate dimensions (sensitivity, exposure, and adaptivity), which ultimately define climate vulnerability and risk.

Species that do not live in the upper 100 m of the ocean are excluded from the analysis, and species with a maximum depth tolerance of more than 1000 m and a preference of more than 600 m are also excluded, as surface temperature may not well define the climate risk of these species. To verify this threshold, a validation analysis was carried out in advance (Boyce et al. 2022b); (Fig S42 in ref. (Boyce et al. 2022b)). Seabirds were also excluded from the analysis because only a small part of their time is spent in surface water. However, mammals and endothermic fishes (*e.g.* tunas, billfishes) that can sometimes inhabit depths over 1000 m were not excluded; despite their ability to range into deeper waters, their distribution is often well-explained by surface temperatures (Boyce et al. 2008; Tittensor et al. 2010). We excluded species with large

freshwater distributions or spending most of their time in freshwater habitats (e.g., sturgeons, salmon, shads, eels). Finally, guided by validation analyses (Supplementary Fig 43 in Boyce *et al.* (2022b)), we restricted our analysis to species and cells containing all 12 indices and species that lacked at least one climate index in more than 10% of their native range were removed from the analysis.

Data

The 12 indices to calculate the CRIB are listed in Table 1, and the data used to calculate them are in Table 2; both are described in Boyce *et al.* (Boyce *et al.* 2022c, 2022b). As per most 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 sea surface temperature (SST) as the primary indicator of climate change, even though it may not capture all aspects of risk (McHenry *et al.* 2019). Species thermal niches were also derived from SST co-occurrence records. SST is widely available over historical and future eras at high spatial and temporal resolutions, and there is a more complete understanding of SST's effects on species relative to other climate change variables (Scheffers *et al.* 2016; Boyce *et al.* 2021b).

Table 1 | 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 Reynolds daily SST	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; Pinsky <i>et al.</i> 2019; Gallagher <i>et al.</i> 2019)
Conservation status	Assessed species extinction risk (categorical).	IUCN red list status	Climate effects on and species can be more severe when species are or have been impacted by additional stressors (e.g. 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	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)
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; Laidre <i>et al.</i> 2008; Burek <i>et al.</i> 2008; Ficitola 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; Staude <i>et al.</i> 2020; Chase <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	(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;

			geographic ranges are more sensitive to and less resilient to climate change impacts	Crooks et al. 2017; Rogan and Lacher 2018; Albouy et al. 2020; Palmeirim et al. 2020; Chase et al. 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 et al. 1978; Cheung et al. 2007, 2013; Davidson et al. 2012; Gonzalez-Suarez et al. 2013; Chessman 2013; Pearson et al. 2014; Healy et al. 2014; Ripple et al. 2017; Cheung and Oyinlola 2018; Foden et al. 2019; Donner and Carilli 2019; Albouy et al. 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	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	(Guest et al. 2012; Carilli et al. 2012; Mora et al. 2014; Cole et al. 2014; Rehm et al. 2015; Xu et al. 2016; Nadeau et al. 2017; Donner and Carilli 2019; Albouy et al. 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	The velocity of climate change (VoCC) represents climatic isotherms' geographic movement over time and is a widely used measure of climate exposure	(Loarie et al. 2009; Burrows et al. 2011; IPCC 2014; Li et al. 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	Individual species will be impacted by climate-driven ecosystem restructuring via altered predation, prey availability, competition.	(Frank et al. 2006, 2007; Boyce et al. 2015b, 2015a; Martin and Watson 2016; Trisos et al. 2020)
Projected time of climate emergence from species' thermal niche	The year when the projected temperature first exceeds the thermal tolerance of focal species for at least three years in a row.	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 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.	(Mora et al. 2013a; Henson et al. 2017; Bruno et al. 2018; Trisos et al. 2020; Xu et al. 2020)
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	Species that are projected to lose more of their thermal habitat are more vulnerable.	(Pinsky et al. 2013; Shackell et al. 2014; MacKenzie et al. 2014; Ochoa-Quintero et al. 2015; Davies et al. 2017)

Table 2 | Data sources used in this study.

Type	Variable	Source	Temporal	Spatial	References
Taxonomic, spatial	Species native geographic distribution	AquaMaps	2000-2014	0.5°	(Kaschner et al. 2019)
Taxonomic	Conservation status	IUCN Red List	-	-	(IUCN 2021)
Taxonomic	Vertical habitat variability and use	FishBase, SeaLifeBase, AquaMaps	-	-	(Froese and Pauly 2000; Kaschner et al. 2019; Palomares and Pauly 2022)
Taxonomic	Maximum body length	FishBase, SeaLifeBase	-	-	(Froese and Pauly 2000; Palomares and Pauly 2022)
Taxonomic	Thermal niche	AquaMaps	2000-2014	-	(Kaschner et al. 2019)
Taxonomic	Species taxonomy	World Register of Marine Species	-	-	(Horton et al. 2020)
Spatial	Cumulative impacts	Cumulative human impact index	-	1km ²	(Halpern et al. 2008, 2012, 2015)
Spatial	Bathymetry	General Bathymetric Chart of the Oceans (GEBCO)	-	4km ²	(<i>Gebco gridded global bathymetry data 2009</i>)
Spatiotemporal	Sea surface temperature	NOAA daily Optimum Interpolation Sea Surface Temperature dataset	1981-2020	0.25°	(Reynolds et al. 2007)
Spatiotemporal	Projected sea surface temperature	Coupled model intercomparison project phase 6 (CMIP6)	1850-2100	1°	(Eyring et al. 2016)

Species' native geographic distribution

The native geographic distributions of each marine species were obtained from the AquaMaps website (Kaschner et al. 2019) and are described in Boyce et al. (Boyce et al. 2022c, 2022b). 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. We verified that the interpolation was suitable through validation analyses by comparing the interpolated probabilities of occurrence from bilinear, nearest neighbour, and spatially averaged approaches and the native 0.5° resolution data. We took the conservative approach of specifying that AquaMaps species occurrence greater than 0 was a presence.

Thermal niches

The realized thermal niches of marine species were obtained from AquaMaps (Kaschner et al. 2019) and described in Boyce et al. (Boyce et al. 2022c, 2022b) and defined using the relationships between species occurrences and surface temperature records. The upper temperature tolerance values were used to calculate several of the climate indices, representing the species realized upper thermal tolerances. Boyce et al. 2022 evaluated the veracity of the species' upper thermal tolerances in AquaMaps, by comparing them against the fundamental critical thermal maximum for those species that have been determined through experimentation, compiled, and published (Comte and Olden 2017; Bennett et al. 2018; Pinsky et al. 2019). The upper realized thermal tolerances reported in AquaMaps were compared against the fundamental thermal tolerances for 60 matching species in the GlobTherm database (Bennett et al. 2018), 76 species reported in Pinsky *et al.* (2019), 58 species reported in Comte *et al.* (2017), and 767 species that were imputed in Comte *et al.* (2017). The AquaMaps realized upper thermal tolerances were positively correlated to the fundamental upper thermal tolerances in the published databases ($r=0.8-0.88$). However, as expected, the fundamental tolerances were generally higher than the AquaMaps realized tolerances. This discrepancy may be driven by the difference in the duration of thermal exposure. Whereas realized tolerances were evaluated using time-averaged SST, fundamental tolerances are derived from experiments that capture more acute heat exposure (e.g., responses over minutes, hours, and days). If we use the hottest hourly or daily temperature in a year, we expect the realized and fundamental tolerances to be equivalent.

Species conservation status

The conservation statuses of marine species in different Canadian regions 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 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. Information-rich species are usually evaluated by the working group, while 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 contingent 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.* (2022b) were used. The methodology used to obtain species' global extinction risk is described in Boyce *et al.* (2022b).

Maximum body lengths

The maximum body sizes of species were estimated (Boyce *et al.* 2022b) from the FishBase¹ and SeaLifeBase² databases using methods described in Boyce *et al.* (2022b).

Temperature

Temperature conditions were evaluated using daily SST estimates from the NOAA 0.25° daily Optimum Interpolation Sea Surface Temperature dataset (OISST) (Reynolds *et al.* 2007). The temperature dataset combines observations from different observation platforms (satellites, ships, buoys, and Argo floats). It has been available globally since 1981 at a spatial resolution of 0.25°.

Cumulative impacts

A multivariate index of cumulative human impacts (HI) on ocean ecosystems index integrates 17 global anthropogenic drivers of ecological change, including fishing pressure, pollution, invasive species, eutrophication, climate change, and others (Halpern *et al.* 2008, 2015)(2008, 2015). The HI estimates were available at a global 1km² native resolution. These values were rescaled to a global 0.25° grid using bilinear interpolation.

Climate projections

The projected monthly SST time series were obtained from the coupled model intercomparison project phase 6 (CMIP6) between 1850 and 2100. All SST projections were interpolated to a

¹ <http://www.fishbase.org>

² <https://www.sealifebase.ca/>

regular 0.25 x 0.25° grid. An ensemble of SST projections was obtained from three published Global Climate (GCM) or Earth System Models (ESMs) within the CMIP6 archive (Table 3). These models span a broad range of the projections of SST within the CMIP6 model set. SST projections (°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).

Table 3 | List of models from the CMIP6 multi-model ensemble archive used in this study.

N	Model	Modeling Center (or Group)	References
1	GFDL-CM4	Geophysical Fluid Dynamics Laboratory	(Dunne et al. 2012, 2013)
2	HadGEM3	Met Office Hadley Centre	(Hewitt et al. 2011)
3	AWI-CM-1-1-MR	Helmholtz Centre for Polar and Marine Research	(Sein et al. 2018)

Results

In this section, we expand on the development of the Climate Risk Index for Biodiversity (CRIB) using the holistic principle that climate change impacts on species are complex and synergistic (Scheffers et al. 2016); species vulnerabilities can’t be adequately defined by a single index. Building on this idea, the CRIB represents vulnerability hierarchically: vulnerability is calculated from its three dimensions (sensitivity, exposure, adaptivity) (IPCC 2014), each of which is derived from four climate indices (12 indices total), which in turn are calculated using data and ecological theory (Table 1). These climate indices were selected based on pre-defined criteria, as follows: The CRIB prioritizes indices that are 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 was widely accepted and well documented in existing climate change vulnerability studies (e.g. Loarie et al. 2009; Mora et al. 2013a; 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 validation analyses described in Boyce *et al.* (2022b). Indices that are 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). The indices were transformed to ensure they were mapped onto a standardized scale (range: 0-1), using hyperbolic functions described in Boyce et al. (2022b). This critical step ensured that indices with different units could be compared, normalized, and combined. It also ensured that vulnerability could be re-estimated at different spatial resolutions or at different points in time without a loss of information. The following section describes the

interpretation, calculation, and standardization for each index, and subsequent calculation of climate sensitivity, adaptivity, exposure, vulnerability and risk, for Atlantic cod (*Gadus morhua*).

Climate sensitivity

Sensitivity quantifies species' responsiveness to climate change and is comparable to "reactivity" in community ecology (Ves et al. 2003; Britten et al. 2014).

Thermal safety margins

The thermal safety margin (TSM) has been widely used in climate vulnerability assessments to measure species sensitivity and tolerance to further warming (Stuart-Smith et al. 2015b; Comte and Olden 2017; Pinsky et al. 2019). Species inhabiting thermal environments close to their upper temperature limit (narrow thermal safety margin) are more vulnerable to climate warming than those further away. For each species within each grid cell across its geographic distribution, a thermal safety margin was calculated as the difference between the estimated upper thermal tolerance of the species and the maximum daily SST observed over the previous decade (e.g., here, between 2010 and 2020) (Figure 1). This metric was standardized to a scale of 0-1 such that climate risk rapidly declines with thermal distance from the species' upper thermal tolerance. Generally, thermal performance is strongly warm-skewed, with fitness expected to increase gradually until the thermal optima and rapidly decline to zero as the species' upper thermal tolerance limit approaches. Our assumption that risk increases continuously with temperature thus captures the risk of the species' upper thermal tolerance being exceeded rather than representing variation fitness within the thermal niche. Refer to Boyce *et al.* (2022b) for details and validation analyses.

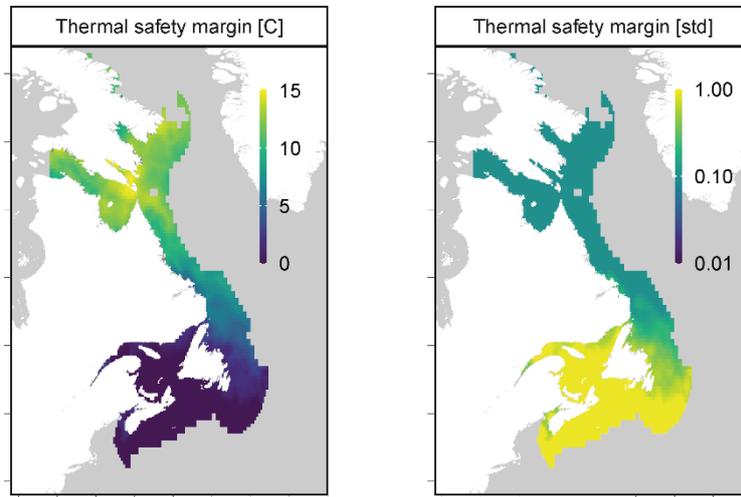


Figure 1 | Thermal safety margins for Atlantic cod.
Raw (left) and standardized (right) thermal safety margins across cods' native geographic distribution.

Conservation status

Species' conservation status makes them susceptible to additional perturbations such as climate change. Species conservation statuses, reported by Wild Species or the IUCN Red List, were transformed to numeric values as follows: Critically endangered=0.5, endangered=0.05, vulnerable=0.005, near threatened/lower risk/near threatened=0.0005, least concern/lower risk/least concern=0; they were then standardized between 0-1. The conservation status for cod in Canada is 0.5 (critically endangered).

Cumulative impacts

Climate effects on ecosystems and species can be more severe when overlaid by additional stressors, such as fishing, pollution, and nutrient loading. The multivariate index of cumulative human impacts (HI) on ocean ecosystems developed by Halpern *et al.* (2008, 2015) was used as an index of the cumulative effects on marine ecosystems (Figure 2). The 1km² HI values were re-interpolated using bilinear methods to a 0.25° grid and then standardized between 0-1. Refer to Boyce *et al.* (2022b) for full details and validation analyses.

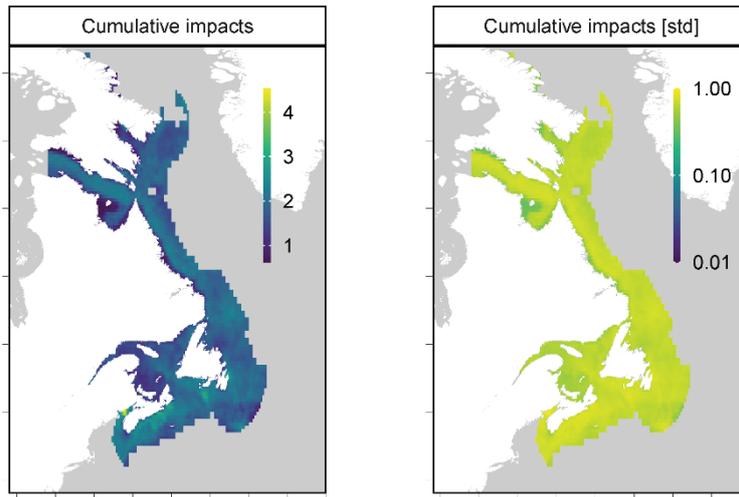


Figure 2 | Cumulative human impacts across the native geographic distribution of Atlantic cod.
Raw (left) and standardized (right) HI across cods' native geographic distribution.

Vertical habitat variability and use

Habitat generalist species are more adapted to climate variability and change than specialist species due to their ability to occupy a greater variety of habitats (Peters 1985; Laidre et al. 2008; Rosset and Oertli 2011; Garcia et al. 2014). Vertical habitat specialization, the depth of species occupancy, and the ability to inhabit different vertical habitats, and thus thermal regimes, play a significant role in determining the adaptivity of species to climate change. Species restricted to the uppermost epipelagic layers of the ocean are expected to have a lower capacity to adapt to climate change, as the upper oceans are generally more exposed to warming (e.g. Albouy et al. 2020). Similarly, species occupying a narrow range of vertical habitats are less adaptable. Each species' vertical habitat index was calculated according to its maximum occupancy and range depth (Figure 3). Climate sensitivity scales between 0 and 1, with most of the change occurring between the surface and 500 m depth or range, with sensitivity being very similar below 500 m. Maximum sensitivity occurs for surface-dwelling species with narrow vertical ranges. In contrast, the lowest sensitivity occurs for species below 500 m with wider vertical ranges. The maximum depth of occupancy and vertical habitat range was truncated by the maximum bathymetry in each grid cell across its native geographic distribution for each species. Refer to Boyce et al. (2022a) for full details and validation analyses.

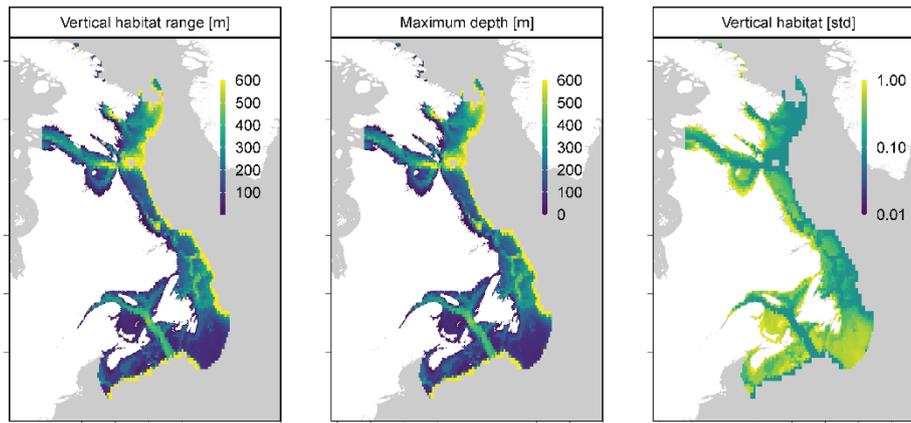


Figure 3 | Vertical habitat use of Atlantic cod.
The maximum depth of occupancy (left) and vertical habitat range (middle) and the standardized index of vertical habitat use (right panel) for cod across its native geographic distribution.

Climate exposure

The exposure of species to future climate changes was evaluated using monthly projections of sea surface temperature (SST) between 2015-2100 from Global Earth System Models (ESMs) in the coupled model intercomparison project phase 6 (CMIP6). All SST projections were gridded onto a regular 0.25 x 0.25° grid. Each exposure index (see below) was first calculated separately for each ESM projection; then, the multi-model ensemble average for each separate exposure index was calculated. Each exposure index was standardized by a constant value, described below, to facilitate comparability when using alternative data sources or spatial resolutions. The cumulative climate exposure was then estimated as the average across all standardized exposure indices.

Projected time of climate emergence

The time of climate emergence from a species' thermal tolerance range was used to index the timing of species exposure to dangerous climate conditions (Trisos et al. 2020; Xu et al. 2020). This index assesses whether exposure to hazardous climate change is an imminent or distant threat. The initial climate emergence (ToE) time for each species was estimated as the year in which the projected maximum annual monthly SST emerges from the species' thermal tolerance niche for two consecutive years (Figure 4). ToE calculations were made using the methods described in Boyce et al. (2022b) for each species within each grid cell across its native geographic distribution. The ToE index quantifies the onset of thermal stress in species rather than absolute mortality to inform climate risk. We used climate projections between 2015 and 2100. The ToE for each species and grid cell was estimated individually for each ESM and then averaged across all ensemble models. Maximal exposure occurs for species inhabiting waters that are already thermally hazardous (e.g. ToE=0). Refer to Boyce *et al.* (2022b) for full details and validation analyses.

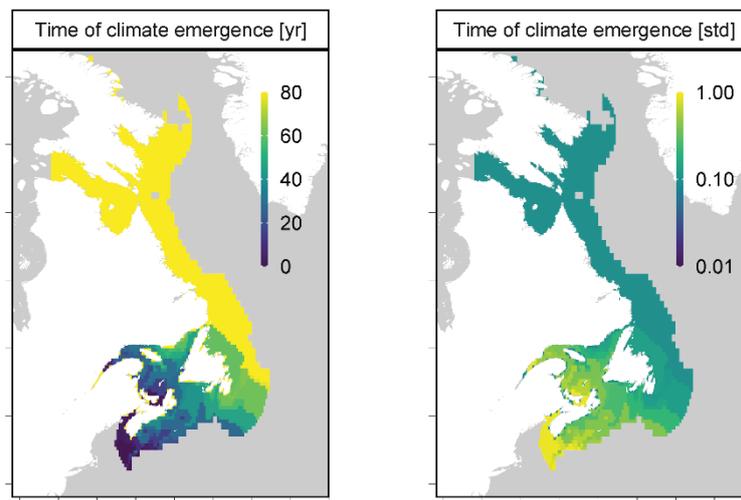


Figure 4 | Projected time of climate exposure for Atlantic cod.
 The multi-model projected time of climate exposure (left) was calculated across the native geographic distribution of Atlantic cod and standardized (right).

Projected ecosystem disruption

Healthy, intact ecosystems are generally more resilient and resistant to stressors, including climate change (Martin and Watson 2016). Stressors such as climate change can erode the structure and function of an ecosystem through several pathways. Temperature changes can directly affect species via their physiological tolerances. Still, they can also indirectly affect them by altering their predators, prey, and competitors (Frank et al. 2006, 2007; Boyce et al. 2015b, 2015a). Changes in the abundance or distribution of species can trigger cascading ecosystem effects, ecological regime shifts, and alternative stable states, causing modified ecosystem structure and function (Estes et al. 1998; Frank et al. 2005, 2011). These ecological effects tend to be more significant when the abundance or distribution of several species changes in concert rather than isolation, and that risk to ecosystem function accelerates as more species are removed from it (Worm et al. 2006). The magnitude of ecological disruption resulting from an ecosystem's exposure to climate change was calculated as the fraction of all species in our analysis in each grid cell that is thermally exposed before the maximum year in the projection window (the year 2100); (Figure 5). This index quantifies the risk of secondary ecological effects (e.g., changes in predation, prey availability, competition) due to climate change that species may be exposed to; it does not assume all species interact but instead captures the risk that a species will be impacted by the loss of other species in the system, which will increase with the number of species that are exposed. Refer to Boyce *et al.* (2022b) for full details and validation analyses.

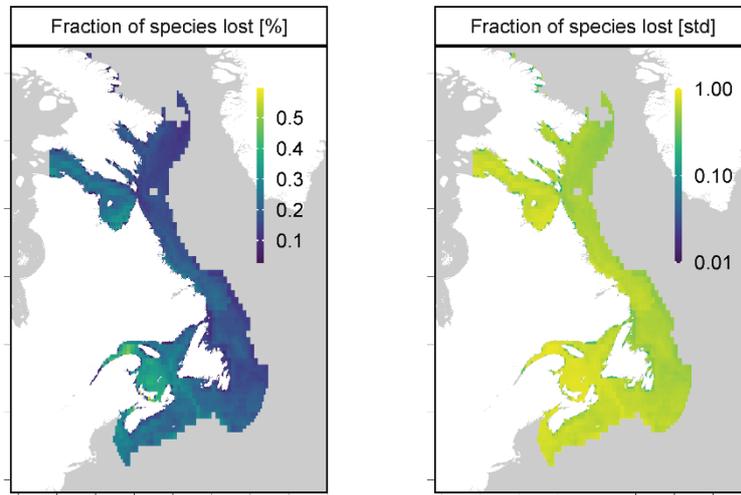


Figure 5 | Magnitude of ecological change across the native geographic distribution of Atlantic cod.
Raw (left) and the standardized (right) fraction of species projected to be lost in each grid cell across cods' native geographic distribution.

Projected loss of suitable thermal habitat

Climate exposure was evaluated as the extent of each species' estimated native geographic distribution that would be lost due to projected ocean warming. Projected changes in species' geographic distributions attributable to temperature were calculated from the time of climate emergence from the thermal niche calculations described above. The number of grid cells in each species' native geographic distribution is projected to emerge from their thermal niche before the end of the climate projection window (the year 2100) was standardized by the total number of grid cells in their native geographic distribution (Figure 6). This index quantifies the geographic extent of adverse climate change impacts to which species may be exposed. Species' exposure increases asymptotically with the fraction of thermal habitat loss, with the most significant exposure occurring for species losing all of their present-day suitable thermal habitats. Refer to Boyce et al. (2022b) for full details and validation analyses.

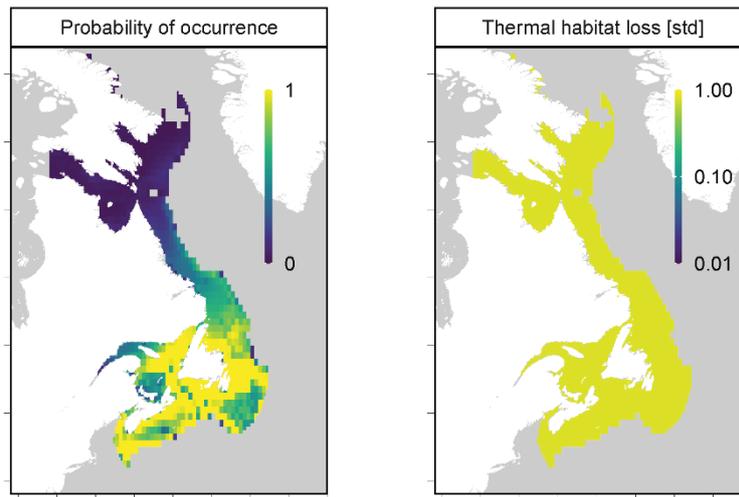


Figure 6 | Thermal habitat loss for Atlantic cod.
 Proportion of the entire native geographic distribution of Atlantic cod (left) was used to evaluate the projected thermal habitat lost due to climate change (right).

Projected climate velocity

The velocity of climate change represents climatic isotherms' geographic movement over time. It is a commonly used measure of climate exposure (Loarie et al. 2009; Burrows et al. 2011; IPCC 2014; Brito-Morales et al. 2018; Li et al. 2018). Species inhabiting waters with greater velocities of climate change are more exposed. Velocity was calculated on a 3 × 3 cell neighbourhood and averaged across all available GCM models to obtain an ensemble average and standard error (Figure 7). A species' exposure increases asymptotically with the speed at which temperature isotherms are projected to move across the ocean. The most significant exposure occurs in areas with rapid isotherm movement. These calculations were made in the R statistical computing platform using the VoCC package (Burrows et al. 2011; García Molinos et al. 2019). Refer to Boyce et al. (2022b) for full details and validation analyses.

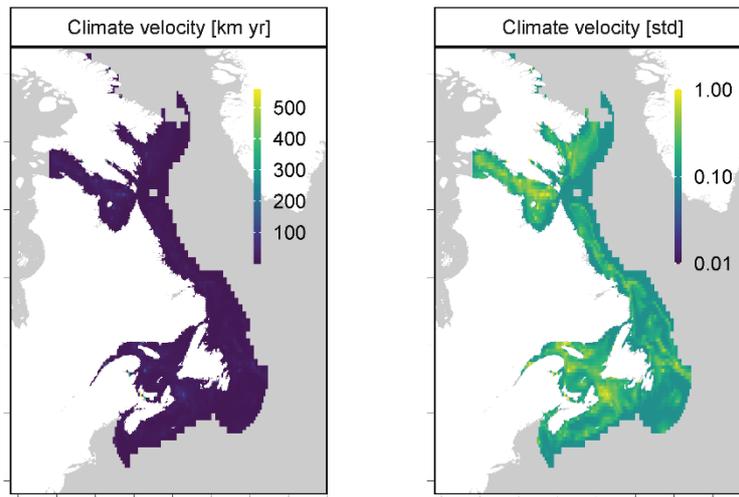


Figure 7 | Velocity of climate change for Atlantic cod.
Raw (left) and standardized (right) velocity of climate change across cods' native geographic distribution

Climate adaptivity

Adaptivity describes the extent to which species can recover from perturbations and is analogous to the concept of resilience from ecological stability theory (Holling 1973). It is predominantly defined by the life-history traits of species, their native geographic distribution characteristics, and the habitat to which they have been historically exposed (e.g. Cheung et al. 2007).

Geographic range extent

Species distributed broadly are thought to have a greater adaptivity to climate changes; there is a greater breadth of suitable climatic and habitat conditions (e.g. climate refugia) within their geographic distributions, buffering them against adverse climate changes (Laidre et al. 2008; Burek et al. 2008; Ficetola and Denoel 2009; Pearson et al. 2014; Staude et al. 2020). Range-restricted species are more likely to depend on specific habitat types and thus vulnerable to climate-driven habitat alteration. The latitude spanned by species is significant to their climate vulnerability, as temperature and climate change impacts have consistently varied by latitude (Loarie et al. 2009; Boyce et al. 2010, 2020; Mora et al. 2013a; Poloczanska et al. 2016). The total geographic range area (km²) (Cheung et al. 2007; Davidson et al. 2012; Garcia et al. 2014; Albouy et al. 2020) and the latitude range of species (Cheung et al. 2007; Gonzalez-Suarez et al. 2013; Albouy et al. 2020) are frequently used in climate vulnerability analyses to index their adaptability or sensitivity to climate change. An index of the adaptivity of each species was calculated as a bivariate function of the geographic range area (km²) and latitude spanned by their native geographic distributions relative to the maximum possibly globally (361,900,000 km²). Adaptivity increases asymptotically with geographic range area, with the greatest adaptivity occurring for

species with the largest geographic range areas. Refer to Boyce *et al.* (2022b) for full details and validation analyses. The range area for cod is 0.005, and the latitude range is 36.5°.

Geographic habitat fragmentation

Species with more contiguous (less fragmented) habitat ranges have greater access to potentially favourable habitats (*e.g.*, climate refugia), migration corridors, and larval dispersal. Alternatively, habitat fragmentation increases the isolation of habitat patches reducing the probability that they can be recolonized following local extinctions (*e.g.* the 'rescue effect' (Brown and Kodric-Brown 1977)) and increasing the amount of edge habitat in those patches. As such, studies in terrestrial and marine systems suggest that species with fragmented geographic ranges are more sensitive to and less resilient to climate change impacts (Kaschner *et al.* 2006; Moore and Huntington 2008; Gonzalez-Suarez *et al.* 2013; Pearson *et al.* 2014; Crooks *et al.* 2017; Rogan and Lacher 2018; Albouy *et al.* 2020) by affecting their extinction and colonization (*e.g.* Warren *et al.* 2001). Habitat fragmentation was calculated from the number of patches in a species' native distribution standardized by its total geographic distribution area. Analyses were undertaken using landscape analysis methods (McGarigal and Cushman 2012; Hesselbarth *et al.* 2019), where patches must be connected in eight directions (queen's case=8 cells surrounding). Adaptivity due to habitat fragmentation declines asymptotically with geographic range fragmentation, with the lowest adaptivity occurring for species with highly fragmented habitats. Habitat fragmentation calculations were made in the R statistical computing platform using the *landscapemetrics* package (Hesselbarth *et al.* 2019). Refer to Boyce *et al.* (2022b) for full details and validation analyses. The habitat fragmentation for cod across the study area is 0.001%.

Thermal habitat variability and use

Ecological disturbance theory and empirical analyses suggest that species and ecosystems that experience high natural variability are better adapted to climate change (Cole *et al.* 2014; Mora *et al.* 2015; Nadeau *et al.* 2017). Similarly, species inhabiting more variable thermal environments, such as at the range edges of their geographic distributions, have a greater capacity to adapt to climate change (Guest *et al.* 2012; Carilli *et al.* 2012; Donner and Carilli 2019) and to be less sensitive to it (Albouy *et al.* 2020). Continued exposure to temperatures close to the species' thermal preferences is thought to pre-adapt them to temperatures outside their thermal preferences. Through this mechanism, species can exhibit different levels of plasticity in their thermal sensitivity depending on the variability in their thermal environment (Rehm *et al.* 2015). The adaptivity index was calculated as a bivariate function of (1) the total environmental thermal variability and (2) the proportion of the total available thermal habitat each species has inhabited over the past 40 years (1981-2021) in relation to its thermal preference range (Figure 8).

Adaptivity due to thermal habitat pre-adaptation increases exponentially with the proportion of the thermal habitat occupied. The index characterizes the proportion of time that a species inhabits temperatures close to its thermal preference range. Species that inhabit a greater proportion of their total potential thermal habitat are, theoretically, more pre-adapted to climate change than those that inhabit less. Refer to Boyce *et al.* (2022b) for full details and validation analyses.

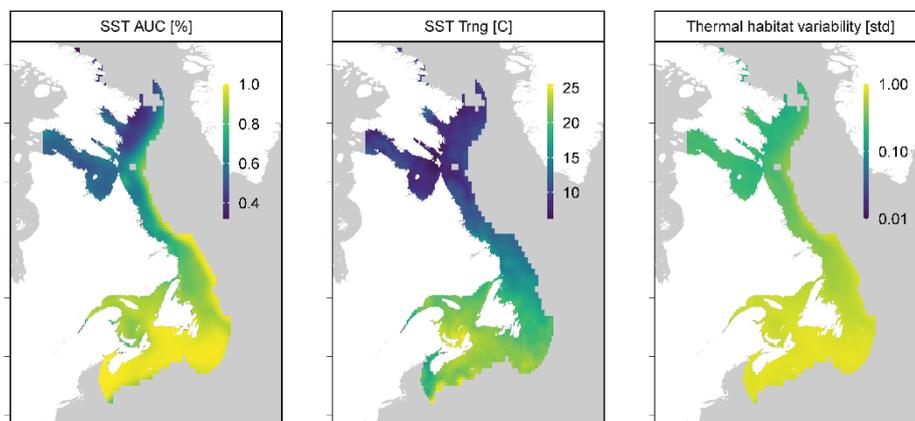


Figure 8 | Thermal habitat variability and use for Atlantic cod.
The total SST habitat variability across its geographic distribution and fraction of the time the SST habitat is within the species' (left & middle) defines cods' thermal habitat variability index (right).

Maximum body length

The maximum size (length or mass) reached by species has been commonly used as a proxy for extinction risks, exploitation susceptibility, and species vulnerability to climate change (Cheung et al. 2007, 2013; Davidson et al. 2012; Gonzalez-Suarez et al. 2013; Chessman 2013; Cheung and Oyinlola 2018; Foden et al. 2019; Albouy et al. 2020). 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 (Fenchel 1974; Blueweiss et al. 1978; Cheung et al. 2007; Healy et al. 2014; Cheung and Oyinlola 2018). Ecologically, body size has been used to classify species as *r*- (produce many offspring, high growth rates and mortality) or *K*-selected (produce fewer offspring, low growth rates and mortality). For these reasons, the maximum body length was used to indicate species' resilience or adaptivity to climate change, where smaller species that grow and reproduce faster have a higher adaptivity (Cheung et al. 2007, 2013; Davidson et al. 2012; Gonzalez-Suarez et al. 2013; Chessman 2013; Pearson et al. 2014; Cheung and Oyinlola 2018; Foden et al. 2019; Albouy et al. 2020). The maximum body length of species (cm) was estimated from the FishBase³ and SeaLifeBase⁴ databases, and a standardized adaptivity index was calculated. Much change in adaptivity occurred for changes in maximum body length between 0 and 100 cm (0-1m). Given the dramatic

³ <http://www.fishbase.org>

⁴ <https://www.sealifebase.ca/>

differences in population doubling time between the smallest plankton (days) to fish that can reach 100 cm (e.g., Atlantic cod; ~2-4 years), this pattern seems biologically plausible. A species' adaptivity declines asymptotically with its maximum possible length. The lowest adaptivity occurs for species with larger body sizes with slower growth rates, population doubling times, and lower mortality rates. The most rapid changes in adaptivity occur for small-bodied species, such as those with body lengths between 0 and 5 m and decline more moderately after that. For full details and validation analyses, refer to Boyce et al. (2022b). The maximum recorded body size for cod is 200 cm, yielding a scaled adaptivity value of 0.34.

Climate dimensions

For each species within each grid cell across its native geographic distribution, the sensitivity, exposure, and adaptivity were calculated as the average of the four indices that define them (Figure 9). The standard deviation of the vulnerability dimensions provided an estimate of their statistical uncertainty. It was propagated forward through all subsequent vulnerability calculations using variance weighting. Validation analyses suggested that the vulnerability calculations for species were affected by missing indices but relatively unaffected by missing observations across species geographic distributions. Omitting any of the 12 climate indices in any grid cell affected the vulnerability scores, so the analysis was restricted to cells containing all 12 indices. Alternatively, the validation analyses suggested that species could have upwards of 10% of grid cells across their native geographic distribution missing with minimal effect on the resulting vulnerability scores. Accordingly, vulnerability was only calculated in cells containing all 12 indices and for species with vulnerability scores in at least 90% of their geographic ranges.

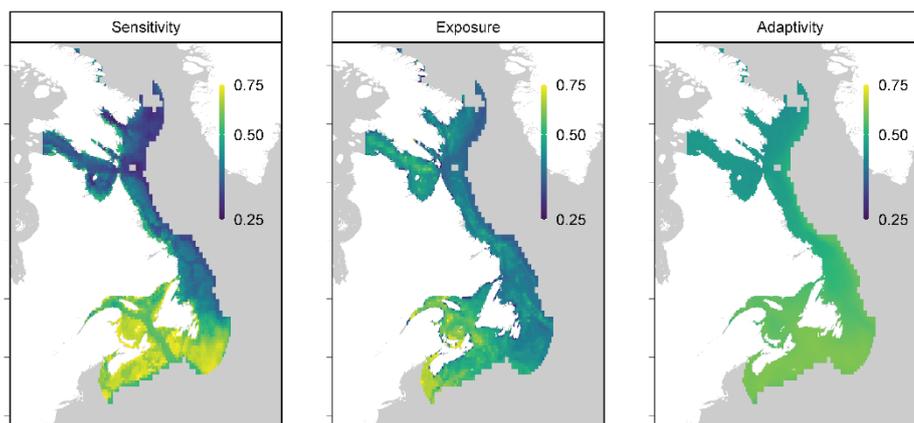


Figure 9 | Dimensions of vulnerability for Atlantic cod.
The sensitivity (left), exposure (middle) and adaptivity (right) of Atlantic cod are calculated from the 12 indices across its native geographic distribution.

Climate vulnerability

Species' climate vulnerability was calculated in each grid cell across its native range from sensitivity, exposure, and adaptivity while statistically accounting for their variability and the statistical uncertainty associated with the indices of climate exposure calculated from ensemble climate projections (Figure 10). The greater uncertainty associated with unknown future states (e.g., climate exposure) was statistically accounted for through discounting (Halpern et al. 2012). With all else being equal, exposure indices derived from single ESMs that make longer-term climate projections are less reliable because the model error tends to compound over time (Mora et al. 2013b; Eyring et al. 2019; Lotze et al. 2019a; Boyce et al. 2020) and are thus more heavily discounted. Those derived from a larger ensemble of ESMs that make shorter-term projections are perceived as more reliable and are discounted less. Through this process, a maximum discount rate of 5% when projections are made for ≥ 100 years from a single projection and 0% when projections are made for < 5 years from > 19 projections. The vulnerability for cod was calculated as a weighted average of adaptivity and discounted sensitivity and exposure (Figure 10). Our study evaluated climate projections from four models over 80 years, yielding a discount rate of 4%. Details of the discount rate calculation are described in Boyce *et al.* (2022b)

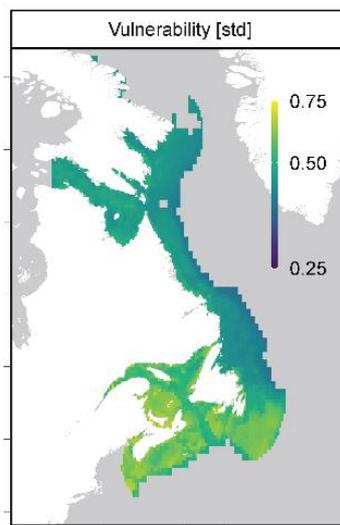


Figure 10 | Geographic patterns of climate vulnerability for Atlantic cod.
The vulnerability of Atlantic cod across its native geographic distribution was calculated from the 12 indices.

The vulnerability for each species was calculated as a variance-weighted mean of the vulnerabilities in each grid cell across its geographic distribution (Figure 11). In this manner, a greater statistical weighting is given to vulnerability estimates in grid cells where their variance (e.g., variance across the indices used to calculate them) is lower and vice-versa. Species vulnerability estimates will be more variable when the vulnerability is more dissimilar in the grid cells that comprise its geographic distribution and vice-versa.

Climate risk

The CRIB uses climate risk thresholds for each of the 12 climate indices that enable climate vulnerability to be translated into risk categories according to their ecological interpretation. Reliably defining such risk thresholds is notoriously challenging (Hillebrand et al. 2020) due to a lack of knowledge needed to define 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; Zommers et al. 2020; Hillebrand et al. 2020). Notwithstanding these challenges, thresholds 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). When successful, 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.

The CRIB defines climate risk thresholds using transparent and, where possible, empirically supported approaches (Swart et al. 2009; Budescu et al. 2012; Oppenheimer et al. 2016). The thresholds were developed for each of the 12 climate indices that defined risk in their native units and carried through the analysis, preserving their meaning and interpretation yet informing the understanding of risk. Table 4 lists the risk thresholds and their rationale, while details and descriptions are in Boyce et al. (2022b). These thresholds represent waypoints to guide the definition and communication of climate risk, and it is anticipated that some may be refined as our understanding of ecological thresholds continues to evolve.

Table 4 | Thresholds used to define climate risk categories. Notes: For Conservation statuses, LC='least concern'; V='vulnerable'; E='endangered'; CR='critically endangered'.

	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, 100 years, respectively (Boyce et al. 2010). 5° to projected warming (Gattuso et al. 2015a).	(Boyce et al. 2010; Gattuso et al. 2015b; Stuart-Smith et al. 2015b; Pinsky et al. 2019; Gallagher et al. 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 et al. 2008).	(Halpern et al. 2008; Butt et al. 2022)
	Vertical habitat variability and use					
	Maximum depth	200m	50m	20m	Standard pelagic biogeochemical divisions within the euphotic zone to categorize variation in e.g. mixing, nutrients, photosynthetically active radiation, primary production.	
	Vertical range	200m	50m	20m	Standard biogeochemical divisions within the euphotic zone to categorize variation in e.g. mixing, nutrients, photosynthetically active radiation, 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 emergence from the thermal niche	75yrs	50yrs	25yrs	Guided by the IUCN RedList assessment criteria (IUCN 2021).	(Trisos et al. 2020; IUCN 2021)
	Projected loss of suitable thermal habitat	5%	10%	20%	Guided by (Homan et al. 2004; Swift and Hannon 2010; Lange et al. 2010; Yin et al. 2017; Arroyo-Rodríguez et al. 2020).	(Parker and Mac Nally 2002; Homan et al. 2004; Rompre et al. 2010; Swift and Hannon 2010; Lange et al. 2010; Liao et al. 2013; Ochoa-Quintero et al. 2015; Yin et al. 2017; Arroyo-Rodríguez et al. 2020; Shennan-Farpón et al. 2021).
	Projected ecosystem disruption	5%	10%	20%	Guided by thresholds in (Hooper et al. 2012; Newbold et al. 2016; Trisos et al. 2020).	(Scholes and Biggs 2005; Hooper et al. 2012; Newbold et al. 2016; Oliver 2016; Trisos et al. 2020; Chase et al. 2020; Shennan-Farpón et al. 2021)
Adaptivity						
	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, climate (Mann and Lazier 1991; Longhurst 2007; Boyce et al. 2017)	(Mann and Lazier 1991; Longhurst 2007; Rompre et al. 2010; Boyce et al. 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 et al. 2004; Rompre et al. 2010; Swift and Hannon 2010; Liao et al. 2013; Yin et al. 2017; Staude et al. 2020; Chase et al. 2020; Arroyo-Rodríguez et al. 2020)
	Geographic habitat fragmentation	20%	10%	1%	Guided by and comparable to those defined in (Albouy et al. 2020) for the vulnerability of cetaceans.	(Andren 1994; Hill and Caswell 1999; Fahrig 2002; Parker and Mac Nally 2002; Rompre et al. 2010; Lange et al. 2010; Rueda et al. 2013; Albouy et al. 2020; Chase et al. 2020; Arroyo-Rodríguez et al. 2020)
	Maximum body length	100cm	30cm	10cm	Empirically guided by the relationship with the intrinsic rate of population increase.	(Fenchel 1974; Blueweiss et al. 1978; Ripple et al. 2017)
	Thermal habitat variability and use					
	Thermal habitat occupancy	8%	95%	99%	Guided by the quantiles of the statistical distributions	(Carilli et al. 2012; Donner and Carilli 2019)
	Thermal habitat variability	5°C	10°C	15°C	Comparable to those defined in (Albouy et al. 2020) for the vulnerability of cetaceans.	(Guest et al. 2012; Carilli et al. 2012; Xu et al. 2016; Nadeau et al. 2017; Donner and Carilli 2019; Albouy et al. 2020)

Sensitivity risk thresholds

TH_M of thermal safety margins was set at 2°C, TH_L at 1°C and TH_U at 5°C. Their establishment was guided by observed and projected surface warming rates. For example, TH_M of 2°C is comparable to the warmest surface warming rates globally over the past century (Boyce et al. 2010), whereas 5°C compares to projected warming to 2100 (Gattuso et al. 2015a).

Since most species conservation statuses were classified as 'least concern, this category was adopted as a natural threshold for both TH_M and TH_L. TH_U was set at 'vulnerable,' with all species classified within or above this classification defined as very high sensitivity.

Thresholds for sensitivity by cumulative impacts were guided by the categories in Halpern *et al.* (Halpern et al. 2008) and the upper and lower 10% quantiles of its distribution. TH_M was set at 1.4, the level Halpern et al. (Halpern et al. 2008) defined as their low/very low impact threshold. TH_U was set at 2 (90th percentile), while TH_L was set at 0.6 (10th percentile).

Thresholds for vertical habitat use were set individually for the maximum depth of occupancy and vertical habitat range. TH_M, TH_U and TH_L by maximum depth were set at 100, 50, and 200m, respectively. By these thresholds, sensitivity is high within the upper 100m, where warming is greatest. It only becomes very low at depths exceeding the epipelagic zone (200m).

Exposure risk thresholds

The projected time of climate emergence is newly developed (Trisos et al. 2020), and there are not yet objective guidelines to define risk. We set TH_M, TH_L and TH_U by projected ensemble time of thermal niche emergence at 50, 75, and 25 years, respectively. These thresholds were, to an extent, guided by the IUCN RedList categories and criteria for listing. Under the RedList criteria for a listing of vulnerable under Criterion E, species must have a 10% chance of extinction within 100 years (IUCN 2021). Assuming that the instantaneous probability of local species extinction is a function of the death rate (d), our TH_U of 25 years would yield a d of 138×10^{-5} ; following this, our TH_M and TH_L values (50 and 75 years) would then yield extinction probabilities of 7% and 3% respectively by 2116 (100 years). Therefore, exposure to hazardous climate by 2040 (TH_U of 25 years) is very likely to lead to at least a 10% chance of extinction under a RedList assessment criterion of vulnerable.

While the loss in thermally suitable habitat has been used in climate vulnerability studies (Stortini et al. 2015), there were few objective thresholds to define risk from it in marine systems. However, modelling studies and reviews suggest that the maximum permissible habitat loss threshold for species is 10-50% (Swift and Hannon 2010; Yin et al. 2017), comparable to estimates of minimum habitat required for species persistence estimated in freshwater (Homan et al. 2004) or terrestrial (Lange et al. 2010; Arroyo-Rodríguez et al. 2020) systems. Following this,

TH_M, TH_L and TH_U by projected ensemble change in suitable thermal habitat of species were set at 10, 5, and 20%, respectively.

TH_M, TH_L and TH_U by the projected fraction of species lost due to warming were set at 10%, 5%, and 20%, respectively. There is considerable uncertainty regarding the safe operating space for ecosystems and species loss (Scholes and Biggs 2005; Brose and Hillebrand 2016; Newbold et al. 2016; Oliver 2016). However, our thresholds were guided by meta-analytic studies that have suggested a 20% loss of species as one possible threshold (Hooper et al. 2012; Newbold et al. 2016; Trisos et al. 2020).

TH_M, TH_L and TH_U by projected climate velocity were set at 15, 6, and 30 km yr⁻¹, respectively. Lacking a clear basis for their ecological interpretation, these thresholds were set by the 50th, 10th, and 90th quantiles of the distribution of global velocity values.

Adaptivity risk thresholds

Thresholds of adaptivity defined by maximum species body size were referenced by the relationship between maximum body size and the intrinsic rate of population increase, which is linear on a log-log scale. TH_L adaptivity was set when the change in intrinsic population increase became negligible (100cm), and TH_U was set where its change became rapid (10cm). TH_M, denoting the high/low adaptivity threshold, was set at 30cm, the point at which the intrinsic rate of population increase was moderate; this threshold was also the median of all body lengths in our database.

Thresholds of adaptivity defined by geographic range extent were referenced to the size of large marine ecosystems (LMEs) (Frye 1986). TH_U of range extent vulnerability was defined by the size of the largest large marine ecosystems (LME; Arabian Sea=3.84M km²=1% of the global area), TH_M by the median area of all LMEs (1.2M km²~0.4% of the global area) and TH_L by the size of the smallest LME (Faroe Plateau=151,005km²=0.04% of the global ocean).

TH_M, TH_U and TH_L by latitude spanned were set at 45°, 60°, and 20°, respectively. These values approximate the latitude span of marine biogeographic provinces (e.g. tropical, temperate, polar) that have been identified from analyses of large-scale climatological (e.g. winds), oceanographic (e.g. mixing, currents, nutrient availability), and ecological (e.g. primary production) features (Mann and Lazier 1991; e.g. Longhurst 2007; Boyce et al. 2017).

TH_M of adaptivity as defined by habitat fragmentation was set at 10%, TH_U at 20%, and TH_L at 1%. These values are comparable to those described for the vulnerability of marine mammals, except our midpoint threshold is slightly higher (10%) than that defined by Albouy *et al.* (2020); (2-4%).

Thresholds for thermal habitat variability were set individually for the entire temperature range and proportion of available thermal habitat occupied by the species across its geographic

range. TH_M , TH_U and TH_L sensitivity by temperature range were set at 15°, 5°, and 10°C, respectively. TH_M of temperature range is identical to that used to define the vulnerability of marine mammals according to thermal habitat range (Albouy et al. 2020). TH_M , TH_U and TH_L adaptivity by thermal habitat occupancy was set at 95%, 99%, and 80%, respectively.

These climate adaptivity risk thresholds were propagated through the standardization analyses described previously, enabling the relative adaptivity scores to be translated into absolute adaptivity risk categories (Figure 11).

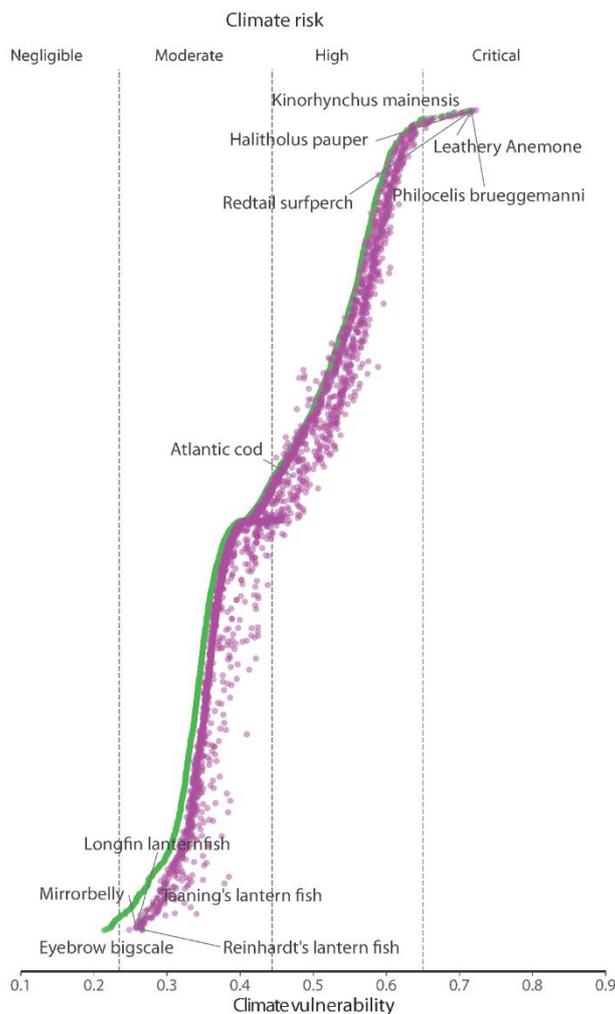


Figure 11 | Climate vulnerability and risk for 2,959 marine species across the Canadian EEZ. Vulnerability and risk scores for species averaged across their geographic ranges within the Canadian EEZ under high (purple) and low (green) emission scenarios. Vertical lines depict the corresponding climate risk categories.

Ecosystem climate risk

Since the CRIB is spatially explicit, species climate risk maps can be superimposed to evaluate risk for marine ecosystems across the ocean. While climate risk was evaluated for species across various taxonomies, including plants, algae, bacteria, fungi, vertebrates and invertebrates, it should be noted that the number of assessed species and length of the food web varies across the Canadian EEZ (Figure 12).

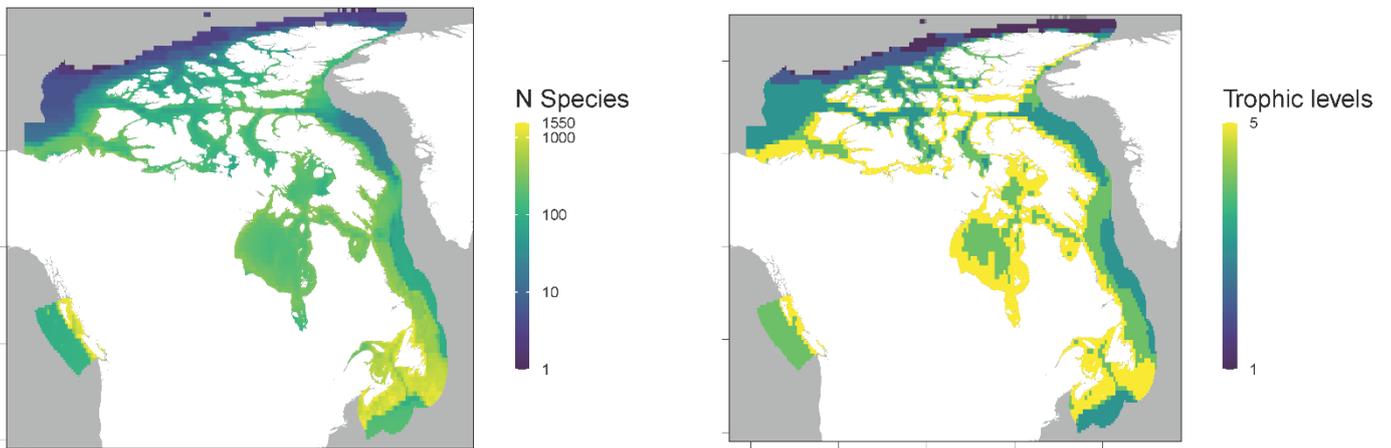


Figure 12 | Geographic patterns of ecosystem biodiversity and structure.
 The number of species evaluated at each location (left) and across the food web (right) across the Canadian marine territory.

In each grid cell under each emission scenario, the proportion of species at low, moderate, high, and critical risk was calculated to obtain a risk measure for the aggregate ecosystem across the Canadian marine territory (Figure 13); this procedure was also undertaken to evaluate the proportion of species that are at low, moderate, high, and critical risk in climate sensitivity, exposure, and adaptive capacity. The mean climate vulnerability of all species in each grid cell was also calculated under both emission scenarios to obtain a relative measure of ecosystem climate vulnerability.

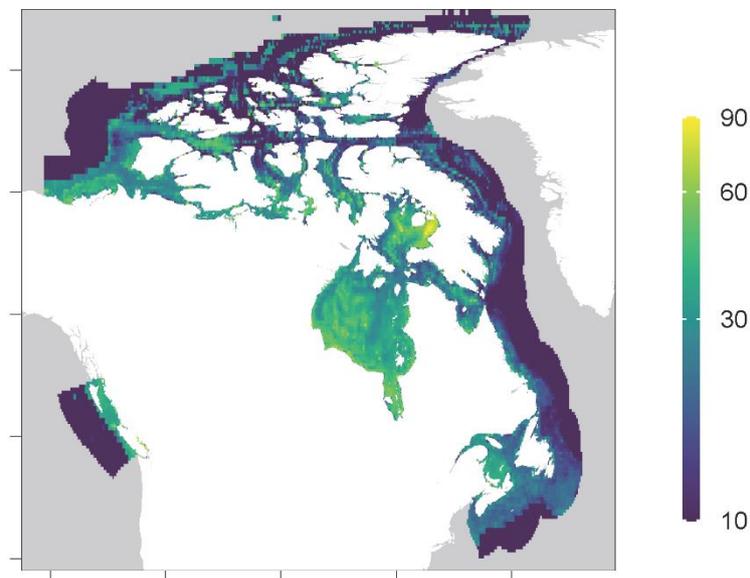


Figure 13 | Geographic patterns of ecosystem climate risk.
 The percent of species at high or critical climate risk across the Canadian marine territory under the SSP5-8.5 emission scenario.

Applications and next steps

The CRIB framework was designed to provide a freely available, transparent, and flexible framework for climate risk estimation in marine systems; it is not intended to be an endpoint but

rather an initial platform to build and improve as information and knowledge of climate risks evolve. Moving forward, several pathways are being explored as pathways to improving the CRIB. Increasing the spatial resolution of the estimates could enhance their usefulness in spatial conservation, especially in nearshore locations; the ability to employ higher-resolution regional climate and species distribution models to achieve this is ongoing. To reduce or better quantify the uncertainty in the risk estimates associated with the data sources, we are also exploring ensemble approaches and multimodel inference, which could allow a broader range of input data sources to be used. The CRIB uses surface temperature to assess climate risk because it is widely available, and its impacts on species have been broadly evaluated; they are best understood relative to other climate variables. However, moving forward, incorporating additional variables, such as dissolved oxygen or bottom temperature, into the risk assessment could provide greater confidence in them.

At the same time, it's critical to move beyond knowledge generation and explore if and how the CRIB could inform and support climate-informed marine conservation and management. To date, the operationalization of CRIB for conservation has primarily been investigated in fisheries (Boyce et al. 2022c), and spatial planning (Bryndum-Buchholz et al. 2022), yet other application areas are also being explored. Lewis *et al.* (2023) used the CRIB to identify high-risk conservation priorities and species of interest across the Canadian marine conservation network. Keen *et al.* (2023) assessed the climate resilience of the Canadian marine conservation network in terms of its ability to capture the complete spectrum of ecosystem climate risk across Canada's marine territory. The Climate Adaptation Framework for Fisheries (CAFF) brings the CRIB outputs together with information about the climate risks to coastal small craft infrastructure (Cogswell et al. 2018; Greenan et al. 2018, 2019) and fisheries management approaches to better understand and support climate adaptation in Canada's fisheries (Boyce et al. 2023). The CRIB is currently being adapted to explore the climate risk for freshwater and diadromous fish species in Atlantic Canada (Stortini *et al.* in prep) to inform habitat restoration efforts and species-at-risk recovery planning.

References

- Albouy, C., Delattre, V., Donati, G., Frölicher, T.L., Albouy-boyer, S., Ru, M., Pellissier, L., and Mouillot, D. 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., Faria, D., Leal, I.R., Melo, F.P.L., Morante-Filho, J.C., Santos, B.A., Arasa-Gisbert, R., Arce-Peña, N., Cervantes-López, M.J., Cudney-Valenzuela, S., Galán-Acedo, C., San-José, M., Vieira, I.C.G., Slik, J.W.F., Nowakowski, A.J., and Tschardtke, T. 2020. Designing optimal human-modified landscapes for forest biodiversity conservation. *Ecol. Lett.*

- 23**(9): 1404–1420. doi:10.1111/ele.13535.
- Bennett, J.M., Calosi, P., Clusella-Trullas, S., Martínez, B., Sunday, J., Algar, A.C., Araújo, M.B., Hawkins, B.A., Keith, S., Kühn, I., Rahbek, C., Rodríguez, L., Singer, A., Villalobos, F., Ángel Olalla-Tárraga, M., and Morales-Castilla, I. 2018. GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. *Sci. Data* **5**(1): 180022. doi:10.1038/sdata.2018.22.
- 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**(2): 257–272. doi:10.1007/BF00344996.
- Boyce, D.G., Frank, K.T., and Leggett, W.C. 2015a. From mice to elephants: overturning the ‘one size fits all’ paradigm in marine plankton food chains. *Ecol. Lett.* **18**: 504–515. doi:10.1111/ele.12434.
- Boyce, D.G., Frank, K.T., Worm, B., and Leggett, W.C. 2015b. Spatial patterns and predictors of trophic control across marine ecosystems. *Ecol. Lett.* **18**(10): 1001–1011.
- Boyce, D.G., Fuller, S., Karbowski, C., Schleit, K., and Worm, B. 2021a. Leading or lagging: How well are climate change considerations being incorporated into Canadian fisheries management? *Can. J. Fish. Aquat. Sci.* **78**(8): 1120–1129. doi:10.1139/cjfas-2020-0394.
- Boyce, D.G., Lewis, M.L., and Worm, B. 2010. Global phytoplankton decline over the past century. *Nature* **466**(7306): 591–596. Nature Publishing Group. doi:10.1038/nature09268.
- Boyce, D.G., Lotze, H.K., Tittensor, D.P., Carozza, D.A., and Worm, B. 2020. Future ocean biomass losses may widen socioeconomic equity gaps. *Nat. Commun.*
- Boyce, D.G., Petrie, B., Frank, K.T., Worm, B., and Leggett, W.C. 2017. Environmental structuring of marine plankton phenology. *Nat. Ecol. Evol.*: 0–1. Springer US. doi:10.1038/s41559-017-0287-3.
- Boyce, D.G., Schleit, K., and Fuller, S. 2021b. Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic. Halifax, Nova scotia, Canada. Available from <https://www.oceansnorth.org/wp-content/uploads/2021/05/Incorporating-climate-change-into-fisheries-management-in-Atlantic-Canada-and-the-Eastern-Arctic.pdf>.
- 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. doi:10.1139/facets-2022-0164.
- Boyce, D.G., Tittensor, D.P., Garilao, C., Henson, S., Kaschner, K., Kesner-Reyes, K., Pigot, A., Reyes, R.B., Reygondeau, G., Schleit, K.E., Shackell, N., Sorongon-Yap, P., and Worm, B. 2022a. A climate risk index for marine life. *Dryad Dataset*. Available from <https://doi.org/10.5061/dryad.7wm37pvwr>.
- Boyce, D.G., Tittensor, D.P., Garilao, C., Henson, S., Kaschner, K., Kesner-Reyes, K., Pigot, A., Reyes, R.B., Reygondeau, G., Schleit, K.E., Shackell, N.L., Sorongon-Yap, P., and Worm, B. 2022b. A climate risk index for marine life. *Nat. Clim. Chang.* **12**(9): 854–862. doi:10.1038/s41558-022-01437-y.
- Boyce, D.G., Tittensor, D.P., S., F., Henson, S., Kaschner, K., Reygondeau, G., Schleit, K.E., Saba, V., Shackell, N., Stanley, R., and Worm, B. 2022c. Operationalizing climate risk for fisheries in a global warming hotspot. *bioRxiv*. doi:<https://doi.org/10.1101/2022.07.19.500650>.
- Boyce, D.G., Tittensor, D.P., and Worm, B. 2008. Effects of temperature on global patterns of tuna and billfish richness. *Mar. Ecol. Ser.* **355**: 267–276. doi:10.3354/meps07237.
- Le Bris, A., Mills, K.E., Wahle, R.A., Chen, Y., Alexander, M.A., Allyn, A.J., Schuetz, J.G., Scott, J.D., and Pershing, A.J. 2018. Climate vulnerability and resilience in the most valuable North American fishery. *Proc. Natl. Acad. Sci. U. S. A.* **115**(8): 1831–1836. doi:10.1073/pnas.1711122115.
- Brito-Morales, I., Molinos, J.G., Schoeman, D.S., Burrows, M.T., Poloczanska, E.S., Brown, C.J., Ferrier, S., Harwood, T.D., Klein, C.J., Pandolfi, J.M., Watson, J.E.M., Wenger, A.S., and Richardson, A.J. 2018. Climate Velocity Can Inform Conservation in a Warming World Simple Climate Metrics Could Help Conservation in a Changing Climate. *Trends Ecol. Evol.* **33**(6): 1–17. doi:10.1016/j.tree.2018.03.009.

- 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. *Ecol. Lett.* **17**(12): 1518–1525. doi:10.1111/ele.12354.
- Brose, U., and Hillebrand, H. 2016. Biodiversity and ecosystem functioning in dynamic landscapes. *Philos. Trans. R. Soc. B Biol. Sci.* **371**(1694): 20150267. doi:10.1098/rstb.2015.0267.
- Brown, J.H., and Kodric-Brown, A. 1977. Turnover Rates in Insular Biogeography: Effect of Immigration on Extinction. *Ecology* **58**(2): 445–449. doi:10.2307/1935620.
- Bruno, J.F., Bates, A.E., Cacciapaglia, C., Pike, E.P., Amstrup, S.C., Van Hooidek, R., Henson, S.A., and Aronson, R.B. 2018. Climate change threatens the world's marine protected areas. *Nat. Clim. Chang.* **8**(6): 499–503. Springer US. doi:10.1038/s41558-018-0149-2.
- Bryndum-Buchholz, A., Boerder, K., Stanley, R.R.E., Hurley, I., Boyce, D.G., Dunmall, K.M., Hunter, K.L., Lotze, H.K., Shackell, N.L., Worm, B., and Tittensor, D.P. 2022. A climate-resilient marine conservation network for Canada. *FACETS* **7**: 571–590. doi:10.1139/facets-2021-0122.
- Bryndum-Buchholz, A., Prentice, F., Tittensor, D.P., Blanchard, J.L., Cheung, W.W.L., Christensen, V., Galbraith, E.D., Maury, O., and Lotze, H.K. 2020. Differing marine animal biomass shifts under 21st century climate change between Canada's three oceans. *Facets* **5**(1): 105–122. doi:10.1139/facets-2019-0035.
- Budescu, D. V., Por, H.H., and Broomell, S.B. 2012. Effective communication of uncertainty in the IPCC reports. *Clim. Change* **113**(2): 181–200. doi:10.1007/s10584-011-0330-3.
- Burek, K.A., Gulland, F.M.D., and O'Hara, T.M. 2008. Effects of climate change on Arctic marine mammal health. *Ecol. Appl.* **18**(sp2): S126–S134. doi:10.1890/06-0553.1.
- Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C. V, Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., and Richardson, A.J. 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science* (80-.). **334**(6056): 652–655. doi:10.1126/science.1210288.
- Busch, D.S., Griffis, R., Link, J., Abrams, K., Baker, J., Brainard, R.E., Ford, M., Hare, J.A., Himes-Cornell, A., Hollowed, A., Mantua, N.J., McClatchie, S., McClure, M., Nelson, M.W., Osgood, K., Peterson, J.O., Rust, M., Saba, V., Sigler, M.F., Sykora-Bodie, S., Toole, C., Thunberg, E., Waples, R.S., and Merrick, R. 2016. Climate science strategy of the US National Marine Fisheries Service. *Mar. Policy* **74**: 58–67. doi:10.1016/j.marpol.2016.09.001.
- Butt, N., Halpern, B.S., O'Hara, C.C., Allcock, A.L., Polidoro, B., Sherman, S., Byrne, M., Birkeland, C., Dwyer, R.G., Frazier, M., Woodworth, B.K., Arango, C.P., Kingsford, M.J., Udyawer, V., Hutchings, P., Scanes, E., McClaren, E.J., Maxwell, S.M., Diaz-Pulido, G., Dugan, E., Simmons, B.A., Wenger, A.S., Linardich, C., and Klein, C.J. 2022. A trait-based framework for assessing the vulnerability of marine species to human impacts. *Ecosphere* **13**(2). doi:10.1002/ecs2.3919.
- Canadian Endangered Species Conservation Council. 2016. Wild Species 2015: The General Status of Species in Canada. *Natl. Gen. Status Work. Gr.*: 128.
- Carilli, J., Donner, S.D., and Hartmann, A.C. 2012. Historical Temperature Variability Affects Coral Response to Heat Stress. *PLoS One* **7**(3): e34418. doi: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**(7820): 238–243. doi:10.1038/s41586-020-2531-2.
- Chessman, B.C. 2013. Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes. *Biol. Conserv.* **160**: 40–49. doi:10.1016/j.biocon.2012.12.032.
- Cheung, W.W.L., and Oyinlola, M.A. 2018. Vulnerability of flatfish and their fisheries to climate change. *J. Sea Res.* **140**(January): 1–10. doi:10.1016/j.seares.2018.06.006.
- Cheung, W.W.L., Pauly, D., and Sarmiento, J.L. 2013. How to make progress in projecting climate change impacts. *ICES J. Mar. Sci.* **70**(6): 1069–1074. doi:10.1093/icesjms/fst133.

- Cheung, W.W.L., Watson, R., Morato, T., Pitcher, T.J., and Pauly, D. 2007. Intrinsic vulnerability in the global fish catch. *Mar. Ecol. Prog. Ser.* **333**: 1–12.
- Cogswell, A., Greenan, B.J.W., and Greyson, P. 2018. Evaluation of two common vulnerability index calculation methods. *Ocean Coast. Manag.* **160**(6–7): 46–51.
- Cole, L.E.S., Bhagwat, S.A., and Willis, K.J. 2014. Recovery and resilience of tropical forests after disturbance. *Nat. Commun.* **5**(1): 3906. doi:10.1038/ncomms4906.
- Comte, L., and Olden, J.D. 2017. Climatic vulnerability of the world's freshwater and marine fishes. *Nat. Clim. Chang.* **7**(10): 718–722. doi:10.1038/nclimate3382.
- 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. *Proc. Natl. Acad. Sci.* **114**(29): 7635–7640.
- Davidson, A.D.D., Boyer, A.G., Kim, H., Pompa-Mansilla, S., Hamilton, M.J., Costa, D.P., Ceballos, G., and Brown, J.H. 2012. Drivers and hotspots of extinction risk in marine mammals. *Proc. Natl. Acad. Sci.* **109**(9): 3395–3400. 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. *Sci. Rep.* **7**(1): 1–7. Springer US. doi:10.1038/s41598-017-08758-5.
- DFO. 2012a. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Atlantic Large Aquatic Basin. *Can. Sci. Advis. Secr. Sci. Response* **2013/011**: 43.
- DFO. 2012b. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within fisheries and oceans Canada's mandate — Pacific large aquatic basin. *Can. Sci. Advis. Secr. Sci. Response* **2013/011**.
- Donner, S.D., and Carilli, J. 2019. Resilience of Central Pacific reefs subject to frequent heat stress and human disturbance. *Sci. Rep.* **9**(1): 3484. doi:10.1038/s41598-019-40150-3.
- Dunne, J.P., John, J.G., Adcroft, A.J., Griffies, S.M., Hallberg, R.W., Shevliakova, E., Stouffer, R.J., Cooke, W., Dunne, K.A., Harrison, M.J., Krasting, J.P., Malyshev, S.L., Milly, P.C.D., Phillipps, P.J., Sentman, L.T., Samuels, B.L., Spelman, M.J., Winton, M., Wittenberg, A.T., and Zadeh, N. 2012. GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. *J. Clim.* **25**(19): 6646–6665. doi:10.1175/JCLI-D-11-00560.1.
- Dunne, J.P., John, J.G., Shevliakova, E., Stouffer, R.J., Krasting, J.P., Malyshev, S.L., Milly, P.C.D., Sentman, L.T., Adcroft, A.J., Cooke, W., Dunne, K.A., Griffies, S.M., Hallberg, R.W., Harrison, M.J., Levy, H., Wittenberg, A.T., Phillips, P.J., and Zadeh, N. 2013. GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics. *J. Clim.* **26**(7): 2247–2267. doi:10.1175/JCLI-D-12-00150.1.
- Estes, J. a., Tinker, M.T., Williams, T.M., and Doak, D.F. 1998. Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. *Science* (80-.). **282**(5388): 473–476. doi:10.1126/science.282.5388.473.
- 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. *Geosci. Model Dev.* **9**(5): 1937–1958. doi:10.5194/gmd-9-1937-2016.
- Eyring, V., Cox, P.M., Flato, G.M., Gleckler, P.J., Abramowitz, G., Caldwell, P., Collins, W.D., Gier, B.K., Hall, A.D., Hoffman, F.M., Hurtt, G.C., Jahn, A., Jones, C.D., Klein, S.A., Krasting, J.P., Kwiatkowski, L., Lorenz, R., Maloney, E., Meehl, G.A., Pendergrass, A.G., Pincus, R., Ruane, A.C., Russell, J.L., Sanderson, B.M., Santer, B.D., Sherwood, S.C., Simpson, I.R., Stouffer, R.J., and Williamson, M.S. 2019. Taking climate model evaluation to the next level. *Nat. Clim. Chang.* **9**(2): 102–110. Springer US. doi:10.1038/s41558-018-0355-y.
- Fahrig, L. 2002. Effect of habitat fragmentation on the extinction threshold: A synthesis. *Ecol. Appl.* **12**(2): 346–353. doi:10.1890/1051-0761(2002)012[0346:eohfot]2.0.co;2.
- 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. *Edited by* M. Barange, T. Bahiri, M.C.M. Beveridge, K.L. Cochrane, S. Funge-Smith, and F. Poulain. Rome. p. 628.
- Fenchel, T. 1974. Intrinsic rate of natural increase: The relationship with body size. *Oecologia* **14**(4): 317–326. doi: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 (Cop.)*. **32**(6): 1075–1084. doi:10.1111/j.1600-0587.2009.05571.x.
- Fischlin, A. 2009. Do We Have Sufficient Safety Margins in Climate Policy? *GAIA-ECOLOGICAL Perspect. Sci. Soc.* **18**(3): 193–199. doi:10.14512/gaia.18.3.3.
- Foden, W.B., Butchart, S.H.M., Stuart, S.N., Vié, J.-C., Akçakaya, H.R., Angulo, A., DeVantier, L.M., Gutsche, A., Turak, E., Cao, L., Donner, S.D., Katariya, V., Bernard, R., Holland, R.A., Hughes, A.F., O’Hanlon, S.E., Garnett, S.T., Şekercioğlu, Ç.H., and Mace, G.M. 2013. Identifying the World’s Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS One* **8**(6): e65427. doi: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., Wheatley, C.J., Bickford, D., Carr, J.A., Hole, D.G., Martin, T.G., Pacifici, M., Pearce-Higgins, J.W., Platts, P.J., Visconti, P., Watson, J.E.M., and Huntley, B. 2019. Climate change vulnerability assessment of species. *Wiley Interdiscip. Rev. Clim. Chang.* **10**(1): 1–36. doi:10.1002/wcc.551.
- Frank, K.T., Petrie, B., Fisher, J.A.D., and Leggett, W.C. 2011. Transient dynamics of an altered large marine ecosystem. *Nature* **477**(7362): 86–89. Nature Publishing Group, London, UK. doi:10.1038/nature10285.
- Frank, K.T., Petrie, B., and Shackell, N.L. 2007. The ups and downs of trophic control in continental shelf ecosystems. *Trends Ecol. Evol.* **22**(5): 236–242. doi:10.1016/j.tree.2007.03.002.
- Frank, K.T., Petrie, B., Shackell, N.L., and Choi, J.S. 2006. Reconciling differences in trophic control in mid-latitude marine ecosystems. *Ecol. Lett.* **9**(10): 1096–1105. doi:10.1111/j.1461-0248.2006.00961.x.
- Frank, K.T.T., Petrie, B., Choi, J.S.S., and Leggett, W.C.C. 2005. Trophic cascades in a formerly cod-dominated ecosystem. *Science (80-)*. **308**(5728): 1621–1623. doi:10.1126/science.1113075.
- Froese, R., and Pauly, D. (*Editors*). 2000. *FishBase 2000: concepts, design and data sources*. Los Banos, Laguna, Philippines.
- Frye, R. 1986. Variability and management of large marine ecosystems - Sherman, K, Alexander, LM. *Nat. Resour. J.* **26**(3): 653–654.
- Gallagher, R. V., Allen, S., and Wright, I.J. 2019. Safety margins and adaptive capacity of vegetation to climate change. *Sci. Rep.* **9**(1): 8241. doi:10.1038/s41598-019-44483-x.
- García Molinos, J., Schoeman, D.S., Brown, C.J., and Burrows, M.T. 2019. VoCC: An R package for calculating the velocity of climate change and related climatic metrics. *Methods Ecol. Evol.* **10**(12): 2195–2202. doi:10.1111/2041-210X.13295.
- 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. *J. Biogeogr.* **41**: 724–735.
- Garner, G., Reed, P., and Keller, K. 2016. Climate risk management requires explicit representation of societal trade-offs. *Clim. Change* **134**(4): 713–723. doi:10.1007/s10584-016-1607-3.
- Gattuso, J.-P.J.-P.P., Magnan, A., Billé, R., Cheung, W.W.L.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Pörtner, H.O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., Bille, R., Cheung, W.W.L.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Portner, H.-O., Rogers,

- A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., Billé, R., Cheung, W.W.L.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Pörtner, H.O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C., Bille, R., Cheung, W.W.L.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Poertner, H.-O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., and Turley, C. 2015a. Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science* (80-). **349**(6243): aac4722-1-aac4722-10. doi:10.1126/science.aac4722.
- Gattuso, J.P., Magnan, A., Billé, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Pörtner, H.O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., and Turley, C. 2015b. Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science* (80-). **349**(6243). doi:10.1126/science.aac4722.
- 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., Cogswell, A., Greyson, P., Kilpatrick, D.J., Cloutier, M., Bird, E., Losier, R., Marceau, E., and Fan, W. 2018. Small Craft Harbours Coastal Infrastructure Vulnerability Index Pilot Project. *Can. Tech. Rep. Fish. Aquat. Sci.* **3245**: 87.
- Greenan, B.J.W., Shackell, N.L., Ferguson, K., Greyson, P., Cogswell, A., Brickman, D., Wang, Z., Cook, A., Brennan, C.E., and Saba, V.S. 2019. Climate Change Vulnerability of American Lobster Fishing Communities in Atlantic Canada. *Front. Mar. Sci.* **6**: 1–18. Frontiers Media, Lausanne, Switzerland. doi:10.3389/fmars.2019.00579.
- Guest, J.R., Baird, A.H., Maynard, J.A., Muttaqin, E., Edwards, A.J., Campbell, S.J., Yewdall, K., Affendi, Y.A., and Chou, L.M. 2012. Contrasting Patterns of Coral Bleaching Susceptibility in 2010 Suggest an Adaptive Response to Thermal Stress. *PLoS One* **7**(3): e33353. doi:10.1371/journal.pone.0033353.
- Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J.S., Rockwood, R.C., Selig, E.R., Selkoe, K.A., and Walbridge, S. 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* **6**(May): 1–7. Nature Publishing Group. doi:10.1038/ncomms8615.
- Halpern, B.S., Longo, C., Hardy, D., McLeod, K.L., Samhuri, J.F., Katona, S.K., Kleisner, K., Lester, S.E., O'Leary, J., Ranelletti, M., Rosenberg, A.A., Scarborough, C., Selig, E.R., Best, B.D., Brumbaugh, D.R., Chapin, F.S., Crowder, L.B., Daly, K.L., Doney, S.C., Elfes, C., Fogarty, M.J., Gaines, S.D., Jacobsen, K.I., Karrer, L.B., Leslie, H.M., Neeley, E., Pauly, D., Polasky, S., Ris, B., St Martin, K., Stone, G.S., Sumaila, U.R., and Zeller, D. 2012. An index to assess the health and benefits of the global ocean. *Nature* **488**(7413): 615–620. Nature Publishing Group. doi:10.1038/nature11397.
- Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, K. V, Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., Kappel, C. V, Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., C.D'Agrosa, Fox, F.E., Kappel, K. V, Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., C.D'Agrosa, Fox, F.E., Kappel, K. V, Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., C.D'Agrosa, Fox, F.E., Kappel, K. V, Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., and Watson, R. 2008. A global map of human impact on marine

- ecosystems. *Science* (80-.). **319**(5865): 948–952. doi:10.1126/science.1149345.
- Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., Kocik, J.F., Lucey, S.M., McCandless, C.T., Milke, L.M., Richardson, D.E., Robillard, E., Walsh, H.J., McManus, M.C., Marancik, K.E., and Griswold, C.A. 2016. A vulnerability assessment of fish and invertebrates to climate change on the northeast u.s. continental shelf. *PLoS One* **11**(2): 1–30. doi:10.1371/journal.pone.0146756.
- Healy, K., Guillerme, T., Finlay, S., Kane, A., Kelly, S.B.A., McClean, D., Kelly, D.J., Donohue, I., Jackson, A.L., and Cooper, N. 2014. Ecology and mode-of-life explain lifespan variation in birds and mammals. *Proc. R. Soc. B Biol. Sci.* **281**(1784): 20140298. doi:10.1098/rspb.2014.0298.
- Henson, S.A., Beaulieu, C., Ilyina, T., John, J.G., Long, M., Séférian, R., Tjiputra, J., and Sarmiento, J.L. 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nat. Commun.* **8**(5020): 1–9. doi:10.1038/ncomms14682.
- Hesselbarth, M.H.K., Sciaini, M., With, K.A., Wiegand, K., and Nowosad, J. 2019. Landscapemetrics: an open-source R tool to calculate landscape metrics. *Ecography (Cop.)*. **42**: 1648–57.
- Hewitt, H.T., Copey, D., Culverwell, I.D., Harris, C.M., Hill, R.S.R., Keen, A.B., McLaren, A.J., and Hunke, E.C. 2011. Design and implementation of the infrastructure of HadGEM3: the next-generation Met Office climate modelling system. *Geosci. Model Dev.* **4**(2): 223–253. doi:10.5194/gmd-4-223-2011.
- Hill, M.F., and Caswell, H. 1999. Habitat fragmentation and extinction thresholds on fractal landscapes. *Ecol. Lett.* **2**(2): 121–127. doi:10.1046/j.1461-0248.1999.22061.x.
- Hillebrand, H., Donohue, I., Harpole, W.S., Hodapp, D., Kucera, M., Lewandowska, A.M., Merder, J., Montoya, J.M., and Freund, J.A. 2020. Thresholds for ecological responses to global change do not emerge from empirical data. *Nat. Ecol. Evol.* **4**(11): 1502–1509. doi:10.1038/s41559-020-1256-9.
- van der Hoek, Y., Zuckerberg, B., and Manne, L.L. 2015. Application of habitat thresholds in conservation: Considerations, limitations, and future directions. *Glob. Ecol. Conserv.* **3**: 736–743. doi:10.1016/j.gecco.2015.03.010.
- Holling, C.S. 1973. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **4**(1): 1–23. doi:10.1146/annurev.es.04.110173.000245.
- Homan, R.N., Windmiller, B.S., and Reed, J.M. 2004. Critical thresholds associated with habitat loss for two vernal pool-breeding amphibians. *Ecol. Appl.* **14**(5): 1547–1553. doi: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., Duffy, J.E., Gamfeldt, L., and O’Connor, M.I. 2012. A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* **486**(7401): 105–8. Nature Publishing Group. doi:10.1038/nature11118.
- Horton, T., Kroh, A., Ahyong, S., Bailly, N., Boyko, C.B., Brandão, S.N., Gofas, S., Hooper, J.N.A., Hernandez, F., Holovachov, O., Mees, J., Molodtsova, T.N., Paulay, G., Decock, W., Dekeyzer, S., Poffyn, G., Vandepitte, L., Vanhoorne, B., Adlard, R., Agatha, S., Ahn, K.J., Akkari, N., Alvarez, B., Anderberg, A., Anderson, G., Angel, M. V, Antic, D., Arango, C., Artois, T., Atkinson, S., Auffenberg, K., Baldwin, B.G., Bank, R., Barber, A., Barbosa, J.P., Bartsch, I., Bellan-Santini, D., Bergh, N., Bernot, J., Berta, A., Bezerra, T.N., Bieler, R., Blanco, S., Blasco-Costa, I., Blazewicz, M., Bock, P., de León, M., Böttger-Schnack, R., Bouchet, P., Boury-Esnault, N., Boxshall, G., Bray, R., Bruce, N.L., Cairns, S., Calvo Casas, J., Carballo, J.L., Cárdenas, P., Carstens, E., Chan, B.K., Chan, T.Y., Cheng, L., Churchill, M., Coleman, C.O., Collins, A.G., Collins, G.E., Corbari, L., Cordeiro, R., Cornils, A., Coste, M., Costello, M.J., Crandall, K.A., Cremonte, F., Cribb, T., Cutmore, S., Dahdouh-Guebas, F., Daly, M., Daneliya, M., Dauvin, J.C., Davie, P., De Broyer, C., De Grave, S., de Mazancourt, V., de Voogd, N.J., Decker, P., Decraemer, W., Defaye, D., d’Hondt, J.L., Dippenaar, S., Dohrmann, M., Dolan, J., Domning, D., Downey, R., Ector, L., Eisendle-Flöckner, U., Eitel, M.,

- Encarnação, S.C. d., Enghoff, H., Epler, J., Ewers-Saucedo, C., Faber, M., Figueroa, D., Finn, J., Fišer, C., Fordyce, E., Foster, W., Frank, J.H., Fransen, C., Freire, S., Furuya, H., Galea, H., Gao, T., Garcia-Alvarez, O., Garcia-Jacas, N., Garic, R., Garnett, S., Gasca, R., Gaviria-Melo, S., Gerken, S., Gibson, D., Gibson, R., Gil, J., Gittenberger, A., Glasby, C., Glover, A., Gómez-Noguera, S.E., González-Solís, D., Gordon, D., Gostel, M., Grabowski, M., Gravili, C., Guerra-García, J.M., Guidetti, R., Guiry, M.D., Gutierrez, D., Hadfield, K.A., Hajdu, E., Hallermann, J., Hayward, B.W., Heiden, G., Hendrycks, E., Herbert, D., Herrera Bachiller, A., Ho, J. s., Hodda, M., Høeg, J., Hoeksema, B., Houart, R., Hughes, L., Hyžný, M., Iniesta, L.F.M., Iseto, T., Ivanenko, S., Iwataki, M., Janssen, R., Jarms, G., Jaume, D., Jazdzewski, K., Jersabek, C.D., Józwiak, P., Kabat, A., Kantor, Y., Karanovic, I., Karthick, B., Katinas, L., Kim, Y.H., King, R., Kirk, P.M., Klautau, M., Kociolek, J.P., Köhler, F., Kolb, J., Kotov, A., Kremenetskaia, A., Kristensen, R.M., Kulikovskiy, M., Kullander, S., Kupriyanova, E., Lambert, G., Lazarus, D., Le Coze, F., LeCroy, S., Leduc, D., Lefkowitz, E.J., Lemaitre, R., Lichter-Marck, I.H., Lindsay, D., Liu, Y., Loeuille, B., Lörz, A.N., Lowry, J., Ludwig, T., Lundholm, N., Macpherson, E., Madin, L., Mah, C., Mamo, B., Mamos, T., Manconi, R., Mapstone, G., Marek, P.E., Marshall, B., Marshall, D.J., Martin, P., Mast, R., McFadden, C., McInnes, S.J., Meidla, T., Meland, K., Merrin, K.L., Messing, C., Mills, C., Moestrup, Ø., Mokievsky, V., Monniot, F., Mooi, R., Morandini, A.C., da Rocha, R., Morrow, C., Mortelmans, J., Mortimer, J., Musco, L., Nesom, G., Neubauer, T.A., Neubert, E., Neuhaus, B., Ng, P., Nguyen, A.D., Nielsen, C., Nishikawa, T., Norenburg, J., O'Hara, T., Opresko, D., Osawa, M., Osigus, H.J., Ota, Y., Páll-Gergely, B., Panero, J.L., Pasini, E., Patterson, D., Paxton, H., Pelsler, P., Peña-Santiago, R., Perrier, V., Petrescu, I., Pica, D., Picton, B., Pilger, J.F., Pisera, A.B., Polhemus, D., Poore, G.C., Potapova, M., Pugh, P., Read, G., Reich, M., Reimer, J.D., Reip, H., Reuscher, M., Reynolds, J.W., Richling, I., Rimet, F., Ríos, P., Rius, M., Rodríguez, E., Rogers, D.C., Roque, N., Rosenberg, G., Rützler, K., Sabbe, K., Saiz-Salinas, J., Sala, S., Santagata, S., Santos, S., Sar, E., Satoh, A., Saucède, T., Schatz, H., Schierwater, B., Schilling, E., Schmidt-Rhaesa, A., Schneider, S., Schönberg, C., Schuchert, P., Senna, A.R., Serejo, C., Shaik, S., Shamsi, S., Sharma, J., Shear, W.A., Shenkar, N., Shinn, A., Short, M., Sicinski, J., Sierwald, P., Simmons, E., Sinniger, F., Sivell, D., Sket, B., Smit, H., Smit, N., Smol, N., Souza-Filho, J.F., Spelda, J., Sterrer, W., Stienen, E., Stoev, P., Stöhr, S., Strand, M., Suárez-Morales, E., Summers, M., Suppan, L., Susanna, A., Suttle, C., Swalla, B.J., Taiti, S., Tanaka, M., Tandberg, A.H., Tang, D., Tasker, M., Taylor, J., Taylor, J., Tchesunov, A., Temereva, E., ten Hove, H., ter Poorten, J.J., Thomas, J.D., Thuesen, E. V., Thurston, M., Thuy, B., Timi, J.T., Timm, T., Todaro, A., Turon, X., Tyler, S., Uetz, P., Urbatsch, L., Uribe-Palomino, J., Urtubey, E., Utevsky, S., Vacelet, J., Vachard, D., Vader, W., Väinölä, R., de Vijver, B., van der Meij, S.E., van Haaren, T., van Soest, R.W., Vanreusel, A., Venekey, V., Vinarski, M., Vonk, R., Vos, C., Walker-Smith, G., Walter, T.C., Watling, L., Wayland, M., Wesener, T., Wetzels, C.E., Whipps, C., White, K., Wieneke, U., Williams, D.M., Williams, G., Wilson, R., Witkowski, A., Witkowski, J., Wyatt, N., Wylezich, C., Xu, K., Zanol, J., Zeidler, W., and Zhao, Z. 2020. World Register of Marine Species (WoRMS). WoRMS Editorial Board. Available from <https://www.marinespecies.org>.
- 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. *Edited By* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IUCN. 2012. IUCN Red List Categories and Criteria: Version 3.1. *In* 2nd edition. IUCN, Gland, Switzerland and Cambridge, UK.
- IUCN. 2021. The IUCN Red List of Threatened Species. Available from <https://www.iucnredlist.org>.
- Kaschner, K., Kesner-Reyes, K., Garilao, C., Segschneider, J., Rius-Barile, J., Rees, T., and Froese, R. 2019. Aquamaps: Predicted range maps for aquatic species.

- 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. *Mar. Ecol. Prog. Ser.* **316**: 285–310. doi:10.3354/meps316285.
- Keen, L., Stortini, C., Boyce, D.G., and Stanley, R. 2023. Representing Climate Change Vulnerabilities in Canadian Marine Conservation Networks. Submitted.
- Laidre, K.L., Stirling, I., Lowry, L.F., Wiig, O., Heide-Jorgensen, M.P., and Ferguson, S.H. 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol. Appl.* **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. *Mol. Ecol.* **19**(22): 4936–4948. doi:10.1111/j.1365-294X.2010.04877.x.
- Layton, K.K.S., Snelgrove, P.V.R., Dempson, J.B., Kess, T., Lehnert, S.J., Bentzen, P., Duffy, S.J., Messmer, A.M., Stanley, R.R.E., DiBacco, C., Salisbury, S.J., Ruzzante, D.E., Nugent, C.M., Ferguson, M.M., Leong, J.S., Koop, B.F., and Bradbury, I.R. 2021. Genomic evidence of past and future climate-linked loss in a migratory Arctic fish. *Nat. Clim. Chang.* **11**(2): 158–165. doi:10.1038/s41558-020-00959-7.
- Leemans, R., and Vellinga, P. 2017. The scientific motivation of the internationally agreed “well below 2 degrees C” climate protection target: a historical perspective. *Curr. Opin. Environ. Sustain.* **26–27**: 134–142. doi:10.1016/j.cosust.2017.07.010.
- Lehtinen, R.M., Galatowitsch, S.M., and Tester, J.R. 1999. Consequences of habitat loss and fragmentation for wetland amphibian assemblages. *Wetlands* **19**(1): 1–12. doi: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. 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. *Glob. Chang. Biol.* **24**(9): 4095–4106. doi:10.1111/gcb.14327.
- 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. *Ecol. Modell.* **268**: 9–17. doi:10.1016/j.ecolmodel.2013.07.021.
- 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**(7276): 1052–1056. doi:10.1038/nature08649.
- Longhurst, A. 2007. *Ecological geography of the sea*. Elsevier Inc., Burlington, MA.
- 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. *Glob. Ecol. Conserv.* **15**. doi:10.1016/j.gecco.2018.e00412.
- Lotze, H.K., Tittensor, D.P., Bryndum-Buchholz, A., Eddy, T.D., Cheung, W.W., Galbraith, E.D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J.L., Bopp, L., Buechner, M., Bulman, C., Carozza, D.A., Christensen, V., Coll, M., Dunne, J., Fulton, E.A., Jennings, S., Jones, M., Mackinson, S., Maury, O., Niiranen, S., Oliveros-Ramos, R., Roy, T., Fernandes, J.A., Schewe, J., Shin, Y.-J., Silva, T.A., Steenbeek, J., Stock, C.A., Verley, P., Volkholz, J., and Walker, N.D. 2019a. Ensemble projections of global ocean animal biomass with climate change. *Proc. Natl. Acad. Sci.*: 1–6. doi:doi.org/10.1073/pnas.1900194116.
- Lotze, H.K., Tittensor, D.P., Bryndum-Buchholz, A., Eddy, T.D., Cheung, W.W.L., Galbraith, E.D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J.L., Bopp, L., Büchner, M., Bulman, C.M., Carozza, D.A., Christensen, V., Coll, M., Dunne, J.P., Fulton, E.A., Jennings, S., Jones, M.C., Mackinson, S., Maury, O., Niiranen, S., Oliveros-Ramos, R., Roy, T., Fernandes, J.A., Schewe, J., Shin, Y.-J., Silva, T.A.M., Steenbeek, J., Stock, C.A., Verley, P., Volkholz, J., Walker, N.D., and Worm, B. 2019b. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc. Natl. Acad. Sci.* **116**(26): 12907–12912. doi:10.1073/pnas.1900194116.
- Mackenzie, B.R., Payne, M.R., Boje, J., Hoyer, J.L., Siegstad, H., Hoyer, J.L., and Siegstad, H.

2014. A cascade of warming impacts brings bluefin tuna to Greenland waters. *Glob. Chang. Biol.* **20**(8): 2484–2491. doi:10.1111/gcb.12597.
- Mann, K.H., and Lazier, J.R.N. 1991. *Dynamics of marine ecosystems*. Blackwell, Oxford, UK.
- Martin, T.G., and Watson, J.E.M. 2016. Intact ecosystems provide best defence against climate change. *Nat. Clim. Chang.* **6**(2): 122–124. doi:10.1038/nclimate2918.
- May, R.M. 1973. *Stability and complexity in model ecosystems*. Princeton University Press, Princeton, NJ, USA.
- McGarigal, K., and Cushman, S.A. 2012. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available from <http://www.umass.edu/landeco/research/fragstats/fragstats.html>.
- McHenry, J., Welch, H., Lester, S.E., and Saba, V. 2019. Projecting marine species range shifts from only temperature can mask climate vulnerability. *Glob. Chang. Biol.* **25**(12): 4208–4221. doi:10.1111/gcb.14828.
- Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J.G., Daniel, J.S., John, A., Krummel, P.B., Luderer, G., Meinshausen, N., Montzka, S.A., Rayner, P.J., Reimann, S., Smith, S.J., van den Berg, M., Velders, G.J.M., Vollmer, M.K., and Wang, R.H.J. 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**(8): 3571–3605. doi:10.5194/gmd-13-3571-2020.
- Moore, S.E., and Huntington, H.P. 2008. Arctic marine mammals and climate change: impacts and resilience. *Ecol. Appl.* **18**(sp2): S157–S165. doi:10.1890/06-0571.1.
- Mora, C., Caldwell, I.R., Caldwell, J.M., Fisher, M.R., Genco, B.M., and Running, S.W. 2015. Suitable Days for Plant Growth Disappear under Projected Climate Change: Potential Human and Biotic Vulnerability. *PLoS Biol.* **13**(6): e1002167. doi:10.1371/journal.pbio.1002167.
- 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. *Sci. Rep.* **4**: 5427. doi:10.1038/srep05427.
- Mora, C., Frazier, A.G., Longman, R.J., Dacks, R.S., Walton, M.M., Tong, E.J., Sanchez, J.J., Kaiser, L.R., Stender, Y.O., Anderson, J.M., Ambrosino, C.M., Fernandez-Silva, I., Giuseffi, L.M., and Giambelluca, T.W. 2013a. The projected timing of climate departure from recent variability. *Nature* **502**(7470): 183+. Nature Publishing Group. doi:10.1038/nature12540.
- Mora, C., Wei, C.-L., Rollo, A., Amaro, T., Baco, A.R., Billett, D., Bopp, L., Chen, Q., Collier, M., Danovaro, R., Gooday, A.J., Grube, B.M., Halloran, P.R., Ingels, J., Jones, D.O.B., Levin, L. a, Nakano, H., Norling, K., Ramirez-Llodra, E., Rex, M., Ruhl, H. a, Smith, C.R., Sweetman, A.K., Thurber, A.R., Tjiputra, J.F., Usseglio, P., Watling, L., Wu, T., and Yasuhara, M. 2013b. Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. *PLoS Biol.* **11**(10): 1–14. doi:10.1371/journal.pbio.1001682.
- Munday, P.L., Warner, R.R., Monroe, K., Pandolfi, J.M., and Marshall, D.J. 2013. Predicting evolutionary responses to climate change in the sea. *Ecol. Lett.* **16**(12): 1488–1500. doi:10.1111/ele.12185.
- Nadeau, C.P., Urban, M.C., and Bridle, J.R. 2017. Climates past, present, and yet-to-come shape climate change vulnerabilities. *Trends Ecol. Evol.* **32**(10): 786–800. doi:10.1016/j.tree.2017.07.012.
- Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S., Hill, S.L.L., Hoskins, A.J., Lysenko, I., Phillips, H.R.P., Burton, V.J., Chng, C.W.T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B.I., Whitmee, S., Zhang, H., Scharlemann, J.P.W., and Purvis, A. 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* (80-.). **353**(6296): 288–291. doi:10.1126/science.aaf2201.
- O'Regan, S.M., Archer, S.K., Friesen, S.K., and Hunter, K.L. 2021. A Global Assessment of Climate Change Adaptation in Marine Protected Area Management Plans. *Front. Mar. Sci.* **8**. doi:10.3389/fmars.2021.711085.

- 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. *Conserv. Biol.* **29**(2): 440–451. doi:10.1111/cobi.12446.
- Oliver, T.H. 2016. How much biodiversity loss is too much? *Science* (80-.). **353**(6296): 220–221. doi:10.1126/science.aag1712.
- Oppenheimer, M., Little, C.M., and Cooke, R.M. 2016. Expert judgement and uncertainty quantification for climate change. *Nat. Clim. Chang.* **6**(5): 445–451. doi:10.1038/NCLIMATE2959.
- 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. *Fish. Oceanogr.* **15**(3): 230–243. doi:10.1111/j.1365-2419.2006.00404.x.
- Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M., Scheffers, B.R., Hole, D.G., Martin, T.G., Akçakaya, H.R., Corlett, R.T., Huntley, B., Bickford, D., Carr, J.A., Hoffmann, A.A., Midgley, G.F., Pearce-Kelly, P., Pearson, R.G., Williams, S.E., Willis, S.G., Young, B., and Rondinini, C. 2015. Assessing species vulnerability to climate change. *Nat. Clim. Chang.* **5**(3): 215–225. doi:10.1038/nclimate2448.
- 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**(3): e0230209. doi:10.1371/journal.pone.0230209.
- Palomares, M.L.D., and Pauly, D. 2022. SeaLifeBase. World Wide Web Electron. Publ. 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. *Biol. Conserv.* **105**(2): 217–229. doi:10.1016/S0006-3207(01)00184-7.
- Pearson, R.G., Stanton, J.C., Shoemaker, K.T., Aiello-Lammens, M.E., Ersts, P.J., Horning, N., Fordham, D.A., Raxworthy, C.J., Ryu, H.Y., McNeese, J., and Akçakaya, H.R. 2014. Life history and spatial traits predict extinction risk due to climate change. *Nat. Clim. Chang.* **4**(3): 217–221. doi:10.1038/nclimate2113.
- Pepin, P., King, J., Holt, C., Smith, H., Shackell, N., Hedges, K., and Bundy, A. 2022. Incorporating knowledge of changes in climatic, oceanographic and ecological conditions in Canadian stock assessments. *Fish Fish.* **2019/043**(iv): 66. doi:10.1111/faf.12692.
- Peters, R.L. 1985. The Greenhouse Effect and Nature Reserves. *Biosciences* **35**: 707–717.
- 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. doi:10.1038/s41586-019-1132-4.
- Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L., and Levin, S.A. 2013. Marine Taxa Track Local Climate Velocities. *Science* (80-.). **341**(6151): 1239–1242. doi:10.1126/science.1239352.
- Poloczanska, E.S., Burrows, M.T., Brown, C.J., Garcia Molinos, J., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C. V, Moore, P.J., Richardson, A.J., Schoeman, D.S., Sydeman, W.J., García Molinos, J., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C. V, Moore, P.J., Richardson, A.J., Schoeman, D.S., Sydeman, W.J., Molinos, J.G., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C. V, Moore, P.J., Richardson, A.J., Schoeman, D.S., and Sydeman, W.J. 2016. Responses of Marine Organisms to Climate Change across Oceans. *Front. Mar. Sci.* **3**(May): 62. doi:10.3389/fmars.2016.00062.
- 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. *Ecol. Evol.* **5**(19): 4315–4326. 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. *J. Clim.* **20**(22): 5473–5496. doi:10.1175/2007jcli1824.1.
- Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang,

- L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., and Tavoni, M. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**: 153–168. doi:10.1016/j.gloenvcha.2016.05.009.
- 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. *Proc. Natl. Acad. Sci.* **114**(40): 10678–10683. doi:10.1073/pnas.1702078114.
- 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. doi:10.1016/B978-0-12-409548-9.10913-3.
- Romppe, 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. *For. Chron.* **86**(5): 589–596. doi:10.5558/tfc86589-5.
- Rosset, V., and Oertli, B. 2011. Freshwater biodiversity under climate warming pressure: Identifying the winners and losers in temperate standing waterbodies. *Biol. Conserv.* **144**(2311–2319).
- 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. *Glob. Ecol. Biogeogr.* **22**(12): 1282–1292. doi:10.1111/geb.12079.
- Scheffer, M., Bascompte, J., Brock, W.A.W.A., Brovkin, V., Carpenter, S.R.S.R., Dakos, V., Held, H., van Nes, E.H.E.H., Rietkerk, M., and Sugihara, G. 2009. Early-warning signals for critical transitions. *Nature* **461**(7260): 53–59. doi:10.1038/nature08227.
- Scheffer, M., and Carpenter, S. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol. Evol.* **18**(12 (Dec)): 648–656.
- Scheffer, M., Carpenter, S.R., Lenton, T.M., Bascompte, J., Brock, W., Dakos, V., van de Koppel, J., van de Leemput, I. a., Levin, S. a., van Nes, E.H., Pascual, M., and Vandermeer, J. 2012. Anticipating Critical Transitions. *Science (80-)*. **338**(6105): 344–348. doi:10.1126/science.1225244.
- 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., Pearce-Kelly, P., Kovacs, K.M., Dudgeon, D., Pacifici, M., Rondinini, C., Foden, W.B., Martin, T.G., Mora, C., Bickford, D., and Watson, J.E.M.M. 2016. The broad footprint of climate change from genes to biomes to people. *Science (80-)*. **354**(6313). doi:10.1126/science.aaf7671.
- Scholes, R.J., and Biggs, R. 2005. A biodiversity intactness index. *Nature* **434**(7029): 45–49. doi:10.1038/nature03289.
- Sein, D. V., Koldunov, N. V., Danilov, S., Sidorenko, D., Wekerle, C., Cabos, W., Rackow, T., Scholz, P., Semmler, T., Wang, Q., and Jung, T. 2018. The Relative Influence of Atmospheric and Oceanic Model Resolution on the Circulation of the North Atlantic Ocean in a Coupled Climate Model. *J. Adv. Model. Earth Syst.* **10**(8): 2026–2041. doi: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**(3). doi:10.1371/journal.pone.0090662.
- Shennan-Farpon, Y., Visconti, P., and Norris, K. 2021. Detecting ecological thresholds for biodiversity in tropical forests: Knowledge gaps and future directions. *Biotropica: btp.12999*. doi:10.1111/btp.12999.
- Stanley, R.R.E., Dibacco, C., Lowen, B., Beiko, R.G., Jeffery, N.W., Wyngaarden, M. Van, Bentzen, P., Brickman, D., Benestan, L., Bernatchez, L., Johnson, C., Snelgrove, P.V.R., Wang, Z., Wringe, B.F., and Bradbury, I.R. 2018. A climate-associated multispecies cryptic cline in the northwest Atlantic. *Sci. Adv.* doi:10.1126/sciadv.aag0929.
- Staudé, I.R., Navarro, L.M., and Pereira, H.M. 2020. Range size predicts the risk of local extinction

- from habitat loss. *Glob. Ecol. Biogeogr.* **29**(1): 16–25. 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 J. Mar. Sci.* **72**(6): 1713–1743. doi:10.1093/icesjms/fst048.
- 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**(7580): 88–92. doi:10.1038/nature16144.
- 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**(7580): 88+. doi:10.1038/nature16144.
- Sunday, J.M., Bates, A.E., and Dulvy, N.K. 2012. Thermal tolerance and the global redistribution of animals. *Nat. Clim. Chang.* **2**(9): 686–690. Nature Publishing Group. doi: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. *Clim. Change* **92**(1–2): 1–29. doi:10.1007/s10584-008-9444-7.
- Swift, T.L., and Hannon, S.J. 2010. Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications. *Biol. Rev.* **85**(1): 35–53. 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., Dunn, D.C., Ghiffary, W., Grant, S.M., Hannah, L., Halpin, P.N., Harfoot, M., Heaslip, S.G., Jeffery, N.W., Kingston, N., Lotze, H.K., McGowan, J., McLeod, E., McOwen, C.J., O’Leary, B.C., Schiller, L., Stanley, R.R.E., Westhead, M., Wilson, K.L., and Worm, B. 2019. Integrating climate adaptation and biodiversity conservation in the global ocean. *Sci. Adv.* **5**(11): 1–16. doi:10.1126/sciadv.aay9969.
- Tittensor, D.P., Mora, C., Jetz, W., Lotze, H.K., Ricard, D., Berghe, E. Vanden, and Worm, B. 2010. Global patterns and predictors of marine biodiversity across taxa. *Nature* **466**(7310): 1098–1101. Nature Publishing Group. doi:10.1038/nature09329.
- Tittensor, D.P., Novaglio, C., Harrison, C.S., Heneghan, R.F., Barrier, N., Bianchi, D., Bopp, L., Bryndum-Buchholz, A., Britten, G.L., Büchner, M., Cheung, W.W.L., Christensen, V., Coll, M., Dunne, J.P., Eddy, T.D., Everett, J.D., Fernandes-Salvador, J.A., Fulton, E.A., Galbraith, E.D., Gascuel, D., Guiet, J., John, J.G., Link, J.S., Lotze, H.K., Maury, O., Ortega-Cisneros, K., Palacios-Abrantes, J., Petrik, C.M., du Pontavice, H., Rault, J., Richardson, A.J., Shannon, L., Shin, Y.-J., Steenbeek, J., Stock, C.A., and Blanchard, J.L. 2021. Next-generation ensemble projections reveal higher climate risks for marine ecosystems. *Nat. Clim. Chang.* **11**(11): 973–981. doi:10.1038/s41558-021-01173-9.
- Trisos, C.H., Merow, C., and Pigot, A.L. 2020. The projected timing of abrupt ecological disruption from climate change. *Nature* **580**(April): 1–6. Springer US. doi:10.1038/s41586-020-2189-9.
- Ves, A.R.I., Ennis, B.D., Ottingham, K.L.C., Ives, A.R., Dennis, B., Cottingham, K.L., and Carpenter, S.R. 2003. Estimating community stability and ecological interactions from time-series data. *Ecol. Monogr.* **73**(2): 301–330.
- Warren, M.S., Hill, J.K., Thomas, J.A., Asher, J., Fox, R., Huntley, B., Toy, D.B., Telfer, M.G., Jeffcoate, S., Harding, P., Jeffcoate, G., Willis, S.G., Greatorex-Daview, J.N., Moss, D., and Thomas, C.D. 2001. Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature* **414**: 65–69.
- Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., and Watson, R. 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science* (80-.). **314**(5800): 787–90. doi:10.1126/science.1132294.
- Worm, B., and Duffy, J.E. 2003. Biodiversity, productivity, and stability in real food webs. *Trends Ecol. Evol.* **18**(12): 628–632.
- 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.

- Xu, C., Kohler, T.A., Lenton, T.M., Svenning, J.-C., and Scheffer, M. 2020. Future of the human climate niche. *Proc. Natl. Acad. Sci.* **117**(21): 11350–11355. doi:10.1073/pnas.1910114117.
- Xu, Y., Shen, Z.-H., Ying, L.-X., Ciais, P., Liu, H.-Y., Piao, S., Wen, C., and Jiang, Y.-X. 2016. The exposure, sensitivity and vulnerability of natural vegetation in China to climate thermal variability (1901–2013): An indicator-based approach. *Ecol. Indic.* **63**: 258–272. doi:10.1016/j.ecolind.2015.12.023.
- Yin, D., Leroux, S.J., and He, F. 2017. Methods and models for identifying thresholds of habitat loss. *Ecography (Cop.)*. **40**(1): 131–143. doi:10.1111/ecog.02557.
- Zommers, Z., Marbaix, P., Fischlin, A., Ibrahim, Z.Z., Grant, S., Magnan, A.K., Pörtner, H.-O., Howden, M., Calvin, K., Warner, K., Thiery, W., Sebesvari, Z., Davin, E.L., Evans, J.P., Rosenzweig, C., O'Neill, B.C., Patwardhan, A., Warren, R., van Aalst, M.K., and Hulbert, M. 2020. Burning embers: towards more transparent and robust climate-change risk assessments. *Nat. Rev. Earth Environ.* **1**(10): 516–529. doi:10.1038/s43017-020-0088-0.