Supplementary Information

Operationalizing climate risk in a global warming hotspot

The complete CRIB methodology and global implementation are described in Boyce et al. [1]. This Supplementary Information describes how the CRIB methodology was downscaled to evaluate risk across the Northwest Atlantic Ocean. The climate vulnerability and risk for Atlantic cod (*Gadus morhua*) are presented here as an illustrative example of the process and workflow.

Data layers

The CRIB indices are in Table S1, and the data used to calculate them are in Table S2; both are fully described in Boyce et al. [1]. Following most previous CCVAs [2–6,*e.g.* 7–9], the CRIB uses sea surface temperature (SST) as the primary indicator of climate change, even though it may not capture every aspect of climate risk[10]. SST is widely available over historical and future projections at high spatial and temporal resolutions, and there is a greater understanding of SST's effects on species relative to other climate change variables[11,12]. Because surface temperatures could weakly define their vulnerability, species that did not inhabit the upper 100m of the ocean were excluded from the analyses, as were those whose maximum depth of occurrence exceeded 1000m.

Species native geographic distribution

The native geographic distributions of each marine species were obtained from the AquaMaps website[13] and are described in Boyce et al. [1]. 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 bilinear interpolation was suitable through sensitivity analyses by comparing the interpolated probabilities of occurrence from bilinear, nearest neighbour, and spatially averaged approaches and the native 0.5° resolution data.

Thermal niches

The realized thermal niche of marine species was obtained from AquaMaps[13] and described in Boyce et al. [1]. The upper-temperature tolerance values are relevant to this study as they are used to calculate several of the climate indices; these values represent the species realized, rather than fundamental, 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[2,14,15]. The upper realized thermal tolerances reported in AquaMaps were compared against the fundamental thermal tolerances for 60 matching species in the GlobTherm database[15], 76 species reported in Pinsky *et al.* [14], 58 species reported in Comte *et al.* [2], and 767 species that were imputed in Comte *et al.* [2]. 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. The difference in the duration of thermal exposure may drive this discrepancy. 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). Were we to use the hottest hourly or daily temperature in a year, we expect the realized and fundamental tolerances would be equivalent.

Species conservation status

Species conservation statuses' that were specifically relevant to different regions within Canada were obtained from the Wild Species General Status of Species in Canada reports[16]. The Wild Species reports are produced by a National General Status Working Group composed of representatives from each Canadian province and territory and of the three federal agencies (Canadian Wildlife Service of Environment and Climate Change Canada, Fisheries and Oceans Canada, and Parks Canada). The assessments are completed using the best available knowledge, including museum collections, scientific literature, scientists and specialists, Aboriginal traditional and community knowledge, and conservation and government data centres. The Working Group assesses the status of species in Canada using strategies contingent on the amount of information available. The working group usually evaluates information-rich species. In contrast, those for information-poor species are conducted by experts hired to support the working group. The government with the final signoff on the ranks varies depending on the type of species. For aquatic species, DFO has the final signoff on the ranks. The information is then used to produce the *Wild Species* reports and is updated every five years. Species within the Wild Species reports are assessed regionally and/or nationally. We selected species' conservation statuses hierarchically based on their availability: we prioritized Wild Species regional species assessments over National, and for species that were not assessed in Wild Species, their global conservation status, as extracted from the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species[17] in Boyce *et al.* [1] were used. The full methodology for extracting or calculating species' global extinction risk is described in Boyce *et al.* [1].

Maximum body lengths

The maximum body sizes of species were estimated from the FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.ca) databases using methods described in Boyce et al. [1].

Temperature

Temperature conditions were evaluated using daily SST estimates from the NOAA 0.25° daily Optimum Interpolation Sea Surface Temperature dataset (OISST)[18]. 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 was developed in Halpern *et al.* [19,20]. The HI index integrates 17 global anthropogenic drivers of ecological change, including fishing pressure, pollution, invasive species, eutrophication, climate change, and others. The HI estimates were available at a global 1km^2 native resolution. These values were rescaled to a global 0.25° grid using bilinear interpolation.

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 regular global 0.25 x 0.25° grid. An ensemble of SST projections was obtained from four published Global Climate (GCM) or Earth System Models (ESMs) within the CMIP6 archive (Table S3). 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[21,22].

Methods

The Climate Risk Index for Biodiversity (CRIB) is holistic: climate change impacts on species are complex and synergistic[11]. Therefore, the climate vulnerability of species can't be adequately defined by a single index or dimension. Building on this idea, the CRIB represents vulnerability hierarchically: vulnerability is calculated from its three accepted dimensions (sensitivity, exposure, adaptivity)[23], each of which is derived from four climate indices (12 indices total), which in turn are calculated using data and ecological theory (Table S1). Indices related to species climate sensitivity included species' thermal safety margins[2,14,24,25], vertical habitat variability and use[26–29], conservation status[30], and cumulative impacts[19,20,31–36]. Indices of species climate exposure were calculated from ensemble climate projections. They included the species' time of climate emergence from their thermal niche[37–40], the extent of suitable thermal habitat loss[41–43], climate-related ecosystem disruption[44–47], and the projected climate velocity[23,48–50]. Indices related to species adaptivity to climate change included the species' geographic range extent[26,48,50,51,53–55], geographic habitat fragmentation[3,56–

[60], maximum body length[3,5,58,61–65], and historical thermal habitat variability and use[3,66–69]. 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[14,17,20,37,39,e.g. 48,50,70]. Indices were also chosen to maximize their unique information content and minimize redundancies; their uniqueness was evaluated by testing their collinearity and through sensitivity analyses described in Boyce *et al.* [1]. Indices that are easy to interpret and calculate are given priority. The CRIB constitutes a 'combined approach'[4–6]; 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 mapped onto a standardized scale (range: 0-1), using hyperbolic functions described in Boyce et al. [1]. 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.

The 12 indices were used to calculate each species' sensitivity, exposure, and adaptivity in each grid cell across its native geographic range. Species' climate vulnerability was estimated 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. Finally, the CRIB defines climate risk thresholds that enable climate vulnerability to be translated into risk categories according to the ecological interpretation of each of the 12 climate indices. These procedures are described below, and the Atlantic cod's climate vulnerability and risk are presented as illustrative examples.

Climate sensitivity

The species' sensitivity quantifies their responsiveness to climate change and is comparable to reactivity in community ecology[71,72].

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[2,14,24]. 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). Climate risk 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 rapidly declines 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.* [1] for full details and sensitivity analyses.

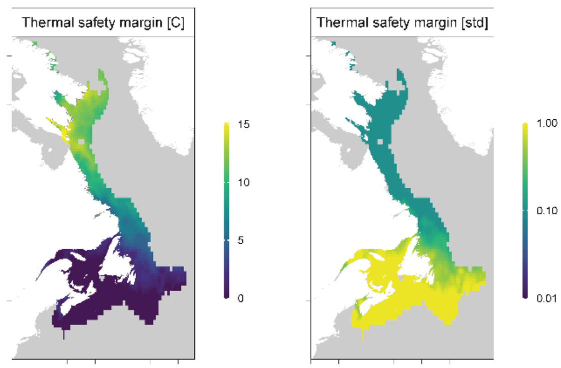

Figure S1 | Thermal safety margins for Atlantic cod. Raw (left) and standardized (right) thermal safety margins across cods' native geographic distribution. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

Conservation status

Species' conservation status makes them more or less 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.* [19,20] was used as an index of cumulative impacts on marine ecosystems. The $1km^2$ HI values were re-interpolated using nearest neighbour methods to a 0.25° grid. For further details and sensitivity analyses, refer to Boyce et al. (1).

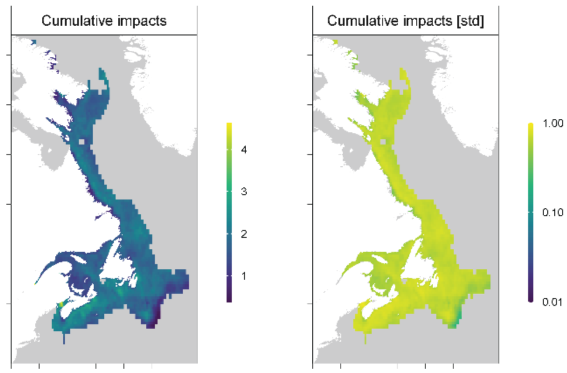

Figure S2 | Cumulative human impacts across the native geographic distribution of Atlantic cod.
Raw (left) and standardized (right) HII across cods' native geographic distribution. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

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 0.25x0.25° grid. Each exposure index (see below) was first calculated separately for each ESM projection; then, the multi-model ensemble average for each exposure index was calculated. Each exposure index was standardized by a normalization constant 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 the species' exposure to dangerous climate conditions[39,40]. This index assesses whether exposure to hazardous climate change is an imminent or distant threat. The time of initial climate emergence (ToE) for each species was estimated as the year in which the projected annual maximum monthly SST emerges from the species' thermal tolerance niche for two consecutive years. ToE calculations were made using the methods described in Boyce et al. [1] 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.* [1] for further details and sensitivity analyses.

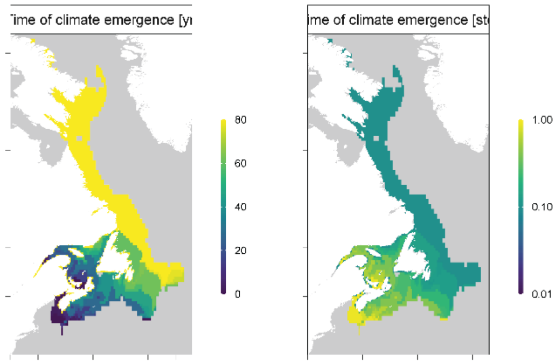

Figure S3 | Projected time of climate exposure for Atlantic cod.
The multi-model projected time of climate exposure (left) was calculated across the native geographic distribution of Atlantic cod and standardized (right). Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

Projected ecosystem disruption

Intact ecosystems are generally more resilient and resistant to stressors, including climate change[73]. Stressors such as climate change can erode the structure and function of an ecosystem through several pathways. In addition to the direct effects of temperature on species via their physiological tolerances, climate change can also indirectly affect species by altering their predators, prey, and competitors[44–47]. 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[74–76]. 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[31]. The 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 (2100). 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.* [1] for further details and sensitivity analyses.

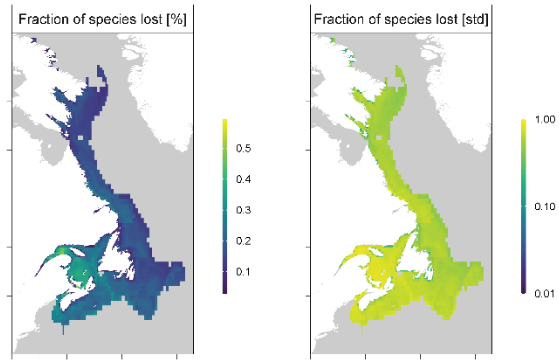

Figure S4 | The magnitude of ecological change across the native geographic distribution of Atlantic cod.
Raw (left) and the standardized (right) fraction of species projected to be lost in each grid cell across cods' native geographic distribution. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

Projected loss of suitable thermal habitat

Climate exposure was evaluated as the extent of each species' estimated native geographic distribution within the study area 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 based on 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. 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 their present-day suitable thermal habitats. For further details and sensitivity analyses, refer to Boyce et al. (1).

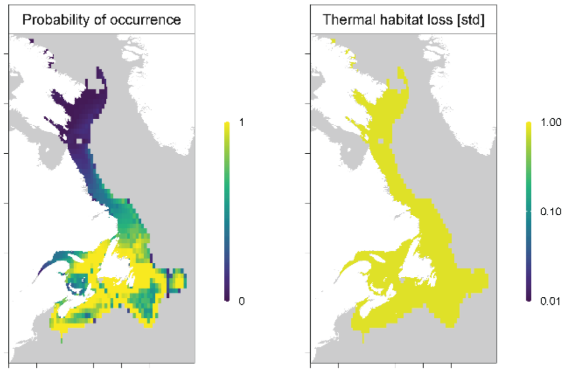

Figure S5 | Thermal habitat loss for Atlantic cod. Proportion of the entire native geographic distribution of Atlantic cod (left) was used to evaluate the projected thermal habitat loss due to climate change (right). Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

Projected climate velocity

The velocity of climate change (VoCC) represents climatic isotherms' geographic movement over time. It is a widely used measure of climate exposure[23,48,49,77,78]. 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. 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 (Figure S6). These calculations were made in the R statistical computing platform using the *VoCC* package[49,79]. For further details and sensitivity analyses, refer to Boyce et al. (1).

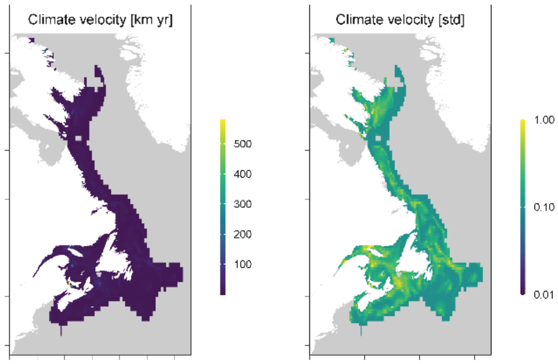

Figure S6 | Velocity of climate change for Atlantic cod. Raw (left) and standardized (right) velocity of climate change across cods' native geographic distribution. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

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 [80]. 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.* 81].

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[26,54,55,82,83]. 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[48,50–53]. The total geographic range area (km)[3,29,62,81] and the latitude range of species[3,58,81] 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 from the geographic range area (km^2) and latitude spanned by their native geographic distributions across the study area, relative to the maximum possibly globally (361,900,000 km^2). 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.* [1] for further details and sensitivity analyses. The range area for cod is 0.005, and the latitude range is 36.5°.

Geographic habitat fragmentation

Species with 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' [84]) and increasing the amount of edge habitat in those patches. As such, terrestrial and marine systems studies suggest that species with fragmented geographic ranges are more sensitive to and less resilient to climate change impacts[3,56–59,83,85], by affecting their extinction and colonization[*e.g.* 60]. 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[86,87], 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[87]. For further details and sensitivity analyses, refer to Boyce et al. (1). 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[88–90]. 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[66–68] and to be less sensitive to it[3]. 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[69]. 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. 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.* [1] for full details and sensitivity analyses.

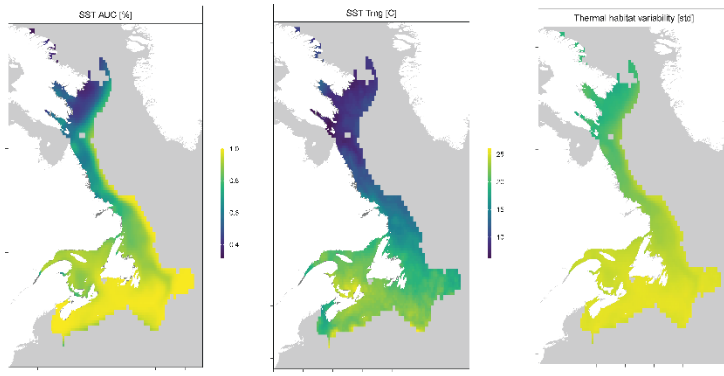

Figure S7 | Thermal habitat variability and use for Atlantic cod.
The total SST habitat variability across its geographic distribution and fraction of the time the SST habitat is within the species' (left & middle) defines cods' thermal habitat variability index (right). Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

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[3,5,58,61–63,81,91]. 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[64,65,81,91,92]. 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[3,5,58,61–63,81,83,91]. The maximum body length of species (cm) was estimated from the FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.ca) databases, and a standardized adaptivity index was calculated. Much change in adaptivity occurred for changes in maximum body length between 0 and 100 cm (0-3.3ft). Given the dramatic 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, with the lowest adaptivity occurring 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 sensitivity analyses, refer to Boyce et al. (1). The maximum body size for cod is 200 cm.

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. 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. Because the sensitivity analyses suggested that omitting any of the 12 climate indices in any grid cell could affect the vulnerability scores, the analysis was restricted to cells containing all 12 indices. Conversely, the sensitivity analyses suggested that the vulnerability scores for species were relatively insensitive to missing values across their geographic distributions; guided by this result, it was determined that species could have upwards of 10% of grid cells across their native geographic distribution missing with minimal effect on the resulting vulnerability scores.

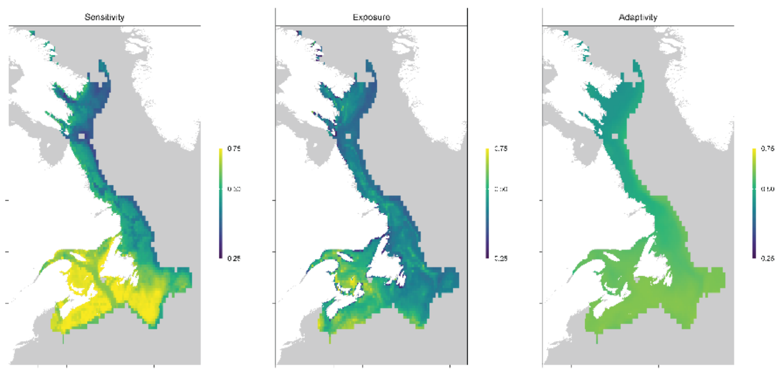

Figure S8 | Dimensions of vulnerability for Atlantic cod.
The sensitivity (left), exposure (middle) and adaptivity (right) of Atlantic cod are calculated from the 12 indices across its native geographic distribution. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

Climate vulnerability

Species' climate vulnerability was calculated in each grid cell across its native range from sensitivity, exposure, and adaptivity while statistically accounting for both their variability and the statistical uncertainty associated with the indices of climate exposure calculated from ensemble climate projections. The greater uncertainty associated with unknown future states (e.g., climate exposure) was statistically accounted for through discounting[34]. With all else being equal, exposure indices derived from single ESMs that make longer-term climate projections are less reliable[52,93–95] 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. Vulnerability was calculated as a weighted average of adaptivity and discounted sensitivity and exposure. 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.* [1]

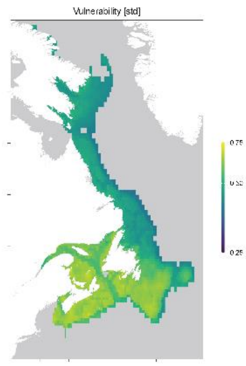

Figure S9 | Geographic patterns of climate vulnerability for Atlantic cod.
The vulnerability of Atlantic cod across its native geographic distribution. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

The vulnerability for each species was calculated as a variance-weighted mean of the vulnerabilities in each grid cell across its geographic distribution. 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 defines climate risk thresholds that enable climate vulnerability to be translated into risk categories according to the ecological interpretation of each of the 12 climate indices. Despite the challenges in reliably defining such risk thresholds[96], they are increasingly being used to help guide conservation strategies and actions[82,97–99]. The risk thresholds are defined in their native units and propagated through the analysis, preserving their meaning and interpretation yet informing the understanding of the dimensionless vulnerability scores. Defining thresholds to define risk is notoriously challenging[96,100] due to various factors, including a lack of knowledge needed to define them, uncertainties in climate model projections, and differences in value judgments regarding what constitutes dangerous risk[96,100–103]. However, 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. It is, however, essential to define risk thresholds using transparent and, where possible, empirically supported approaches[104–106]. Table S4 lists the risk thresholds and their rationale, while full details and descriptions are in Boyce et al. [1]. These thresholds represent waypoints to guide the definition and communication of climate risk. To the extent possible, they were guided by empirical information. Nonetheless, some thresholds were unavoidably defined using less objective criteria. We anticipate that some of these thresholds may be refined as our knowledge of ecological thresholds continues to improve.

Sensitivity

TH_M of thermal safety margins was set at 2ºC, TH_L at 1ºC and TH_U at 5ºC and their establishment was guided by observed and projected surface warming rates. For example, TH_M of 2ºC is comparable to the warmest surface warming rates globally over the past century[53], whereas 5ºC compares to projected warming to 2100[107].

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.* [19] and by the upper and lower 10% quantiles of its distribution. TH_M was set at 1.4, the level Halpern et al. 19 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, and only becomes very low at depths exceeding the epipelagic zone (200m).

Exposure

The projected time of climate emergence is newly developed[39], and there are no 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. To an extent, these thresholds were 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[17]. 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 $138x10^{-5}$; 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 of thermally suitable habitat has been used in climate vulnerability studies8, there were few objective thresholds to define the risk of it in marine systems. However, modelling studies and reviews suggest that species' maximum permissible habitat loss threshold is 10-50%[108,109], comparable to estimates of minimum habitat required for species persistence estimated in freshwater[110] or terrestrial[99,111] 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[112–115]. However, our thresholds were guided by meta-analytic studies that have suggested a 20% loss of species as one possible threshold[39,114,116].

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 50^{th}, 10^{th}, and 90^{th} quantiles of the distribution of global velocity values.

Adaptivity

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)[117]. TH_U of range extent vulnerability was defined by the size of the largest large marine ecosystems (LME; Arabian Sea=3.84M km^2=1% of the global area), TH_M by the median area of all LMEs (1.2M km^2=~4% of the global area) and TH_L by the size of the smallest LME (Faroe Plateau=151,005km^2=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[*e.g.* 118–120].

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.* [3] (2-4%).

Thresholds for thermal habitat variability were set individually for the full 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 [3]. 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 (Table S4).

Climate-driven range expansions

Range expansion into favourable habitats is an important aspect of climate adaptation. However, we did not assess the net change in the geographic distribution of species (e.g. the difference between the habitat gained and lost due to climate) for several reasons. While range contractions can be driven by a single variable (e.g. temperature), species expansions into new habitats will depend on the favorability of several environmental and biotic factors that we did not evaluate (e.g. bathymetry, oxygen, acidity, ocean mixing, predators, prey, competition, dispersal). Evaluating species range expansions would require future projections in many of these environmental and biotic factors, which are often unavailable. Even if such projections were available, using them to forecast species range expansions would introduce considerable uncertainty into our analysis. Further, this study aims to assess the risk to current marine biodiversity rather than trying to project how biodiversity may shift in the future, which has been the focus of other studies[*e.g.* 121]. Whereas many factors are needed to determine range expansions, the lethality of temperature alone can mediate range contractions. Therefore, our approach is conservative but possibly simplistic for some species, as it predicts that most species will lose habitat, but none will gain. Nonetheless, this index provides a valuable assessment of how the native geographic distribution of species could contract in response to climate change while avoiding the assumptions, complexities, and data requirements required to evaluate the net distributional responses.

Supplemental Figures

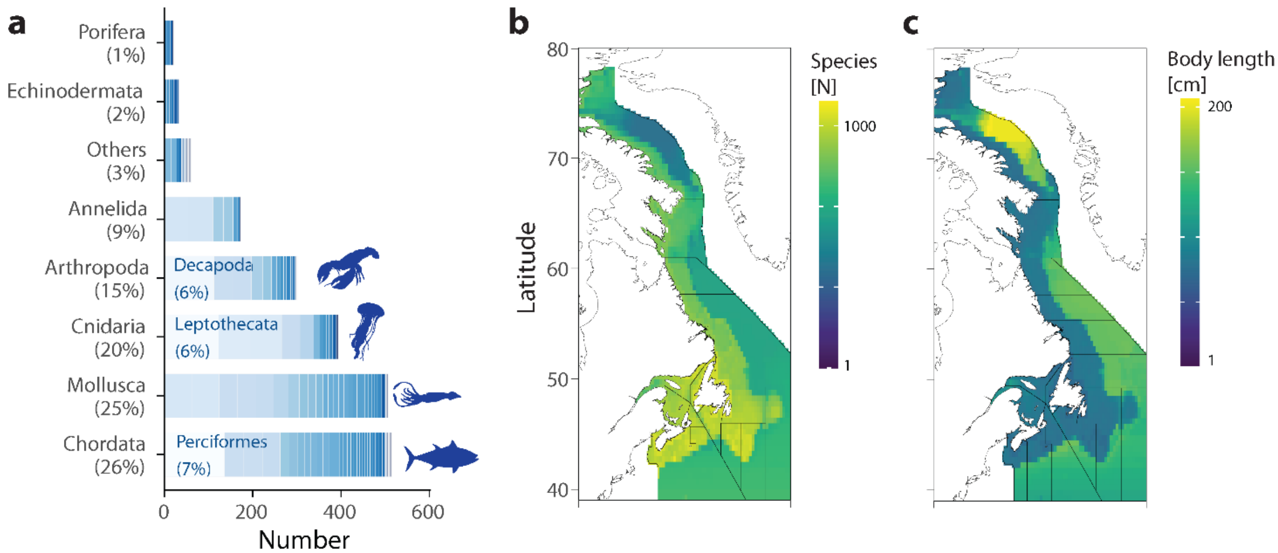

Figure S10 | Data availability.
a) Bars show the proportion of assessed species within each animal phylum, and shading within the bars shows the number of species in each taxonomic class. Spatial distribution in b) the number of assessed species and c) the average body size of all assessed species. Colours depict the number of (b) species assessed or (c) the average maximum body length (cm) of all assessed species per cell. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

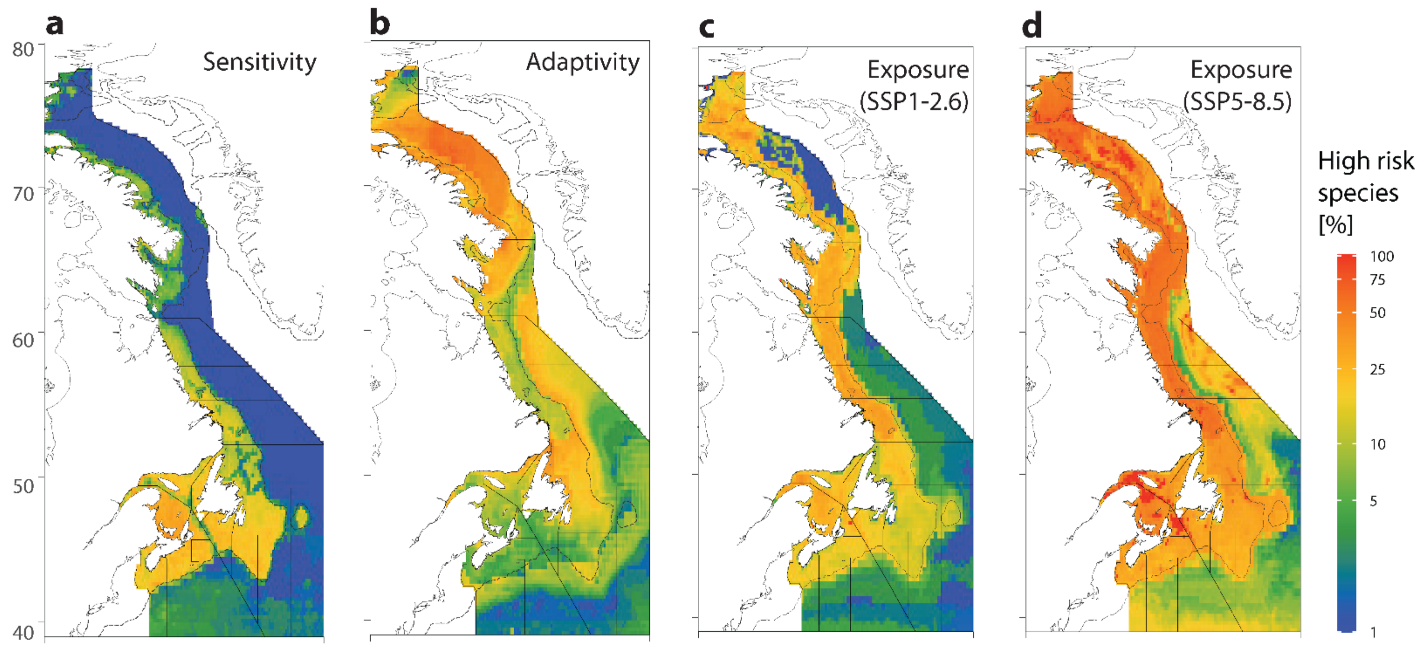

Figure S11 | Climate vulnerability and risk dimensions.
(a-d) The proportion of species at high or critical risk in a) sensitivity, b) adaptivity, c) exposure under low emissions, and d) exposure under high emissions in each grid cell to 2100. Black lines denote the NAFO divisions; the dotted line is the 200m isobath. Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

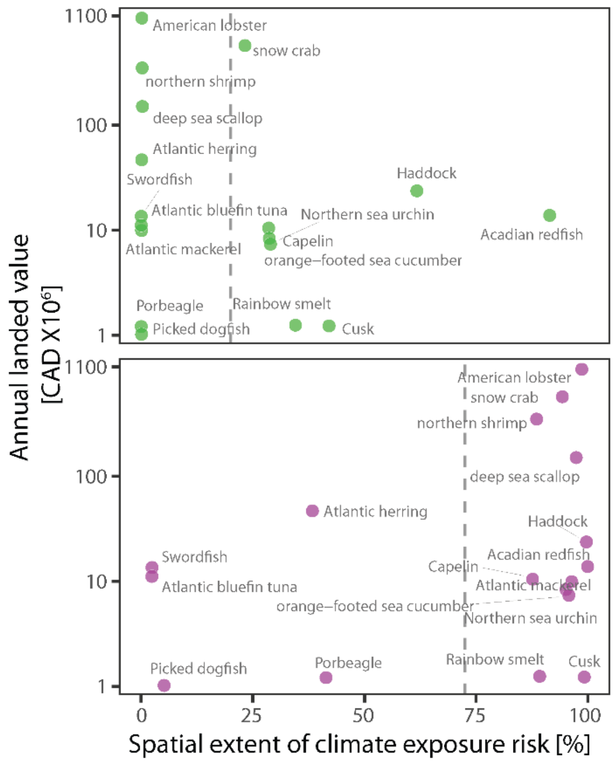

Figure S12 | Climate exposure of economically valued species. Relationships between the spatial extent of climate exposure risk of economically valuable species (n=17) and their average annual landed value (2010-2019) under low (a) and high (b) emission scenarios. Gray dotted lines are the average spatial extents of climate exposure risk for all valued species.

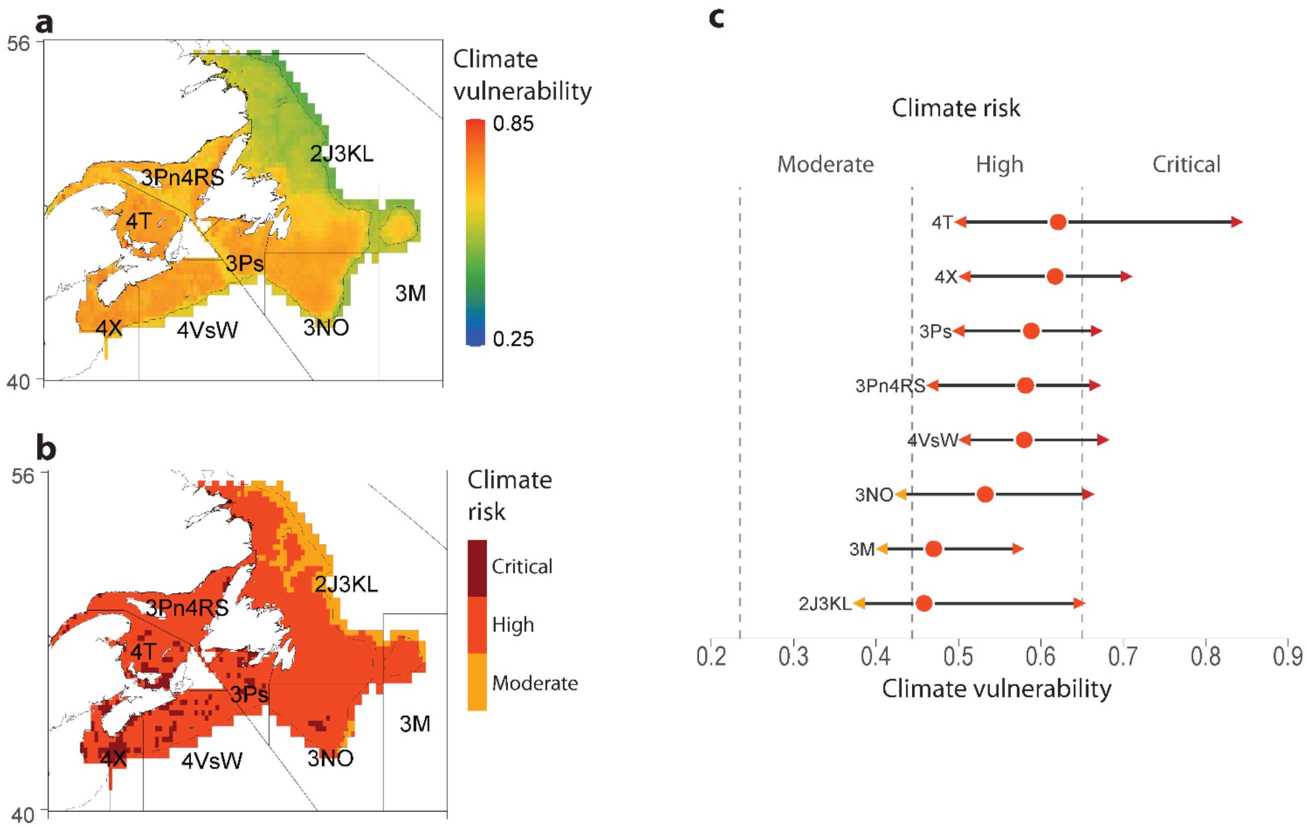

Figure S13 | Example of climate vulnerability and risk intersection with Atlantic cod stocks. (a-b) Climate vulnerability (a) and risk (b) for cod are evaluated across the geographic domain of commercial cod stocks. The stock management areas are displayed as thick black lines and are labelled. c) Within each stock domain, the climate vulnerability and risk of each cod fishery are calculated. c) The average climate vulnerability and risk of each cod stock are displayed as points (circles). The arrows show the minimum and maximum climate vulnerability that exists across the geographic domain of each cod stock. Dotted lines and colours depict the climate risk, with the colour legend in b). Maps were made with Natural Earth using the R statistical computing platform (version 4.3.0).

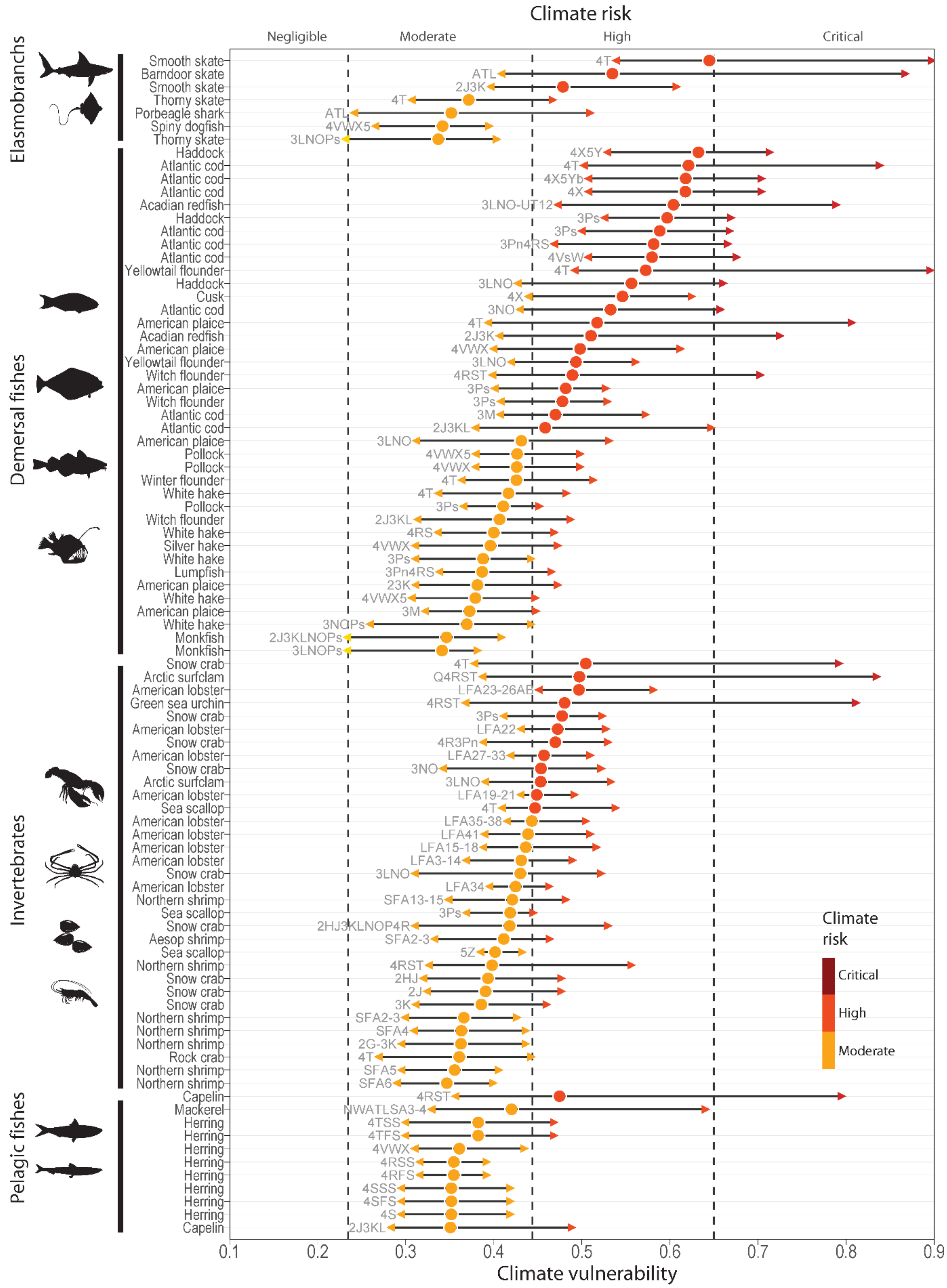

Figure S14 | Climate risk for fisheries.

Points are the average vulnerability scores for 95 fish stocks that operate across with area of study available within the RAM stock assessment database, estimated under the high emission scenario to 2100. Coloured points represent the climate risk category for the stock, and lines with arrows are the minimum and maximum climate vulnerability and risk experienced by across the stock geographic domain.

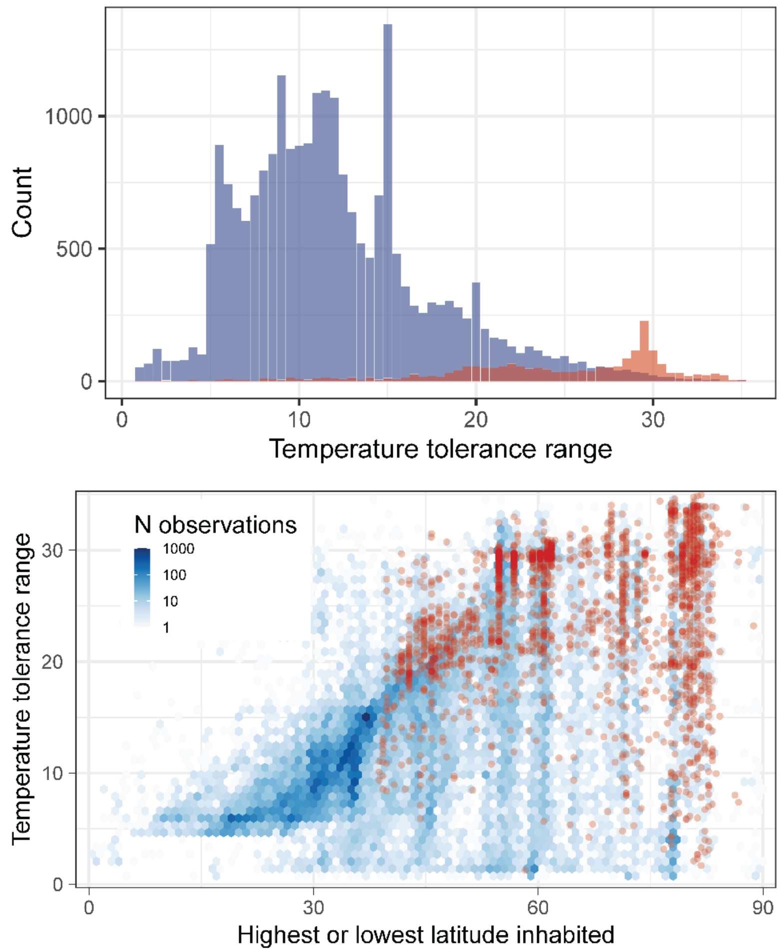

Figure S15 | Variation in species' thermal niche breadth along latitude.

(a) Statistical distribution of the thermal tolerance niches for species in the global species pool (blue) and in our study (red). b) Relationship between the thermal tolerance niche of species and the maximum absolute latitude they inhabit. (a-b) Blue are species in the global species pool and red are those across the area of study (AOS).

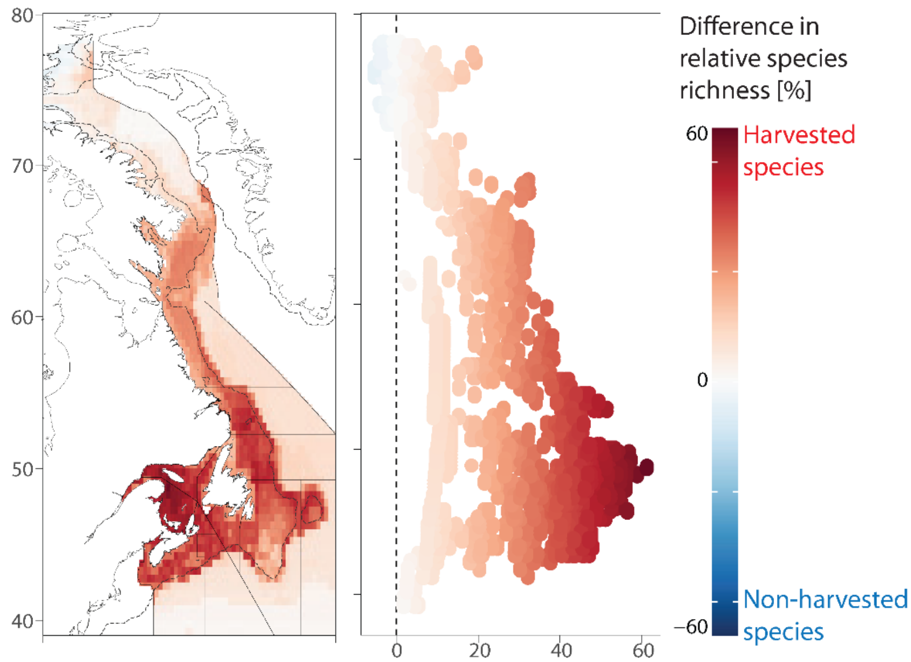

Figure S16 | Relative geographic distribution of fished and unfished species. Colours depict geographic patterns in relative species richness of harvested versus non-harvested species ([n harvested species in cell/n harvested species total] / ([n non-harvested species in cell/n non-harvested species total]). Red depicts locations where the relative number of harvested species is higher than that of non-harvested species, and blue the opposite. Map was made with Natural Earth using the R statistical computing platform (version 4.3.0).

Table S1. Indices used in this study.

Index	Description	Data sources	Rationale	References
Sensitivity (S)				
Thermal safety margin (spatiotemporal)	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.	2,14,24,25
Conservation status (taxonomic)	Assessed species extinction risk (categorical).	IUCN red list status	Climate effects on species can be more severe when species are or have been impacted by additional stressors (*e.g.* fishing, pollution, and nutrient loading) and are at low conservation status.	30
Cumulative impacts (spatial)	Multivariate index of human impacts.	Human impact index	Species exposed to multiple impacts are more sensitive to additional stressors, tipping points, and synergistic impacts.	19,20,31–36
Vertical habitat variability and use (taxonomic, spatial)	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 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.	26–29
Adaptivity (AC)				
Geographic range extent (taxonomic)	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.	3,26,29,54,55,58,62,81,82
Geographic habitat fragmentation (taxonomic)	The proportion of species' native geographic distribution that is fragmented.	AquaMaps	Species with less fragmented habitat ranges have greater access to potentially favourable habitats (*e.g.* climate refugia), migration corridors, and larval dispersal. Consequently, studies in terrestrial and marine systems have reported that species with fragmented geographic ranges are more sensitive to and less resilient to climate change impacts	3,56,125,57–60,84,122–124
Maximum body length (taxonomic)	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 for extinction risks and the vulnerability of species to climate change. Smaller species that tend to be r-selected are viewed as more resilient than larger, k-selected ones.	3,5,91,92,58,61–65,68,81
Thermal habitat variability and use (spatiotemporal, taxonomic)	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	3,66–69,88,90,126
Exposure (E)				
Projected climate velocity (spatiotemporal)	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	23,48,49,78
Projected ecosystem disruption (spatiotemporal, taxonomic)	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, and competition.	39,44–47,73
Projected time of climate emergence from species' thermal niche (spatiotemporal, taxonomic)	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 a species' exposure to dangerous climate conditions.	37,39,40,50,127
Projected loss of suitable thermal habitat (spatiotemporal, taxonomic)	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.	41–43,128

Table S2. Data sources used in this study.

Type	Variable	Source	Temporal	Spatial	References
Taxonomic, spatial	Species native geographic distribution	AquaMaps	2000-2014	0.5°	[13]
Taxonomic	Conservation status	Wild Species, IUCN Red List	-	-	[17]
Taxonomic, spatial	Vertical habitat variability and use	FishBase, SeaLifeBase, AquaMaps	-	-	[13,129,130]
Taxonomic	Maximum body length	FishBase, SeaLifeBase	-	-	[129,130]
Taxonomic	Thermal niche	AquaMaps	2000-2014	-	[13]
Spatial	Cumulative impacts	Cumulative human impact index	-	$1km^2$	[19,20,34]
Spatial	Bathymetry	General Bathymetric Chart of the Oceans (GEBCO)	-	$4km^2$	[131]
Spatiotemporal	Sea surface temperature	NOAA daily Optimum Interpolation Sea Surface Temperature dataset	1981-2020	0.25°	[18]
Spatiotemporal	Projected sea surface temperature	Coupled model intercomparison project phase 6 (CMIP6)	1850-2100	0.25°	[132]

Table S3. List of models from the CMIP6 multi-model ensemble archive (https://pcmdi.llnl.gov/CMIP6/) used in this study.

N	Model	Modeling Center (or Group)	References
1	GFDL-CM4	Geophysical Fluid Dynamics Laboratory	[133,134]
2	HadGEM3	Met Office Hadley Centre	[135]
3	AWI-CM-1-1-MR	Helmholtz Centre for Polar and Marine Research	[136]

Table S4 | Thresholds used to define climate risk categories.

Dimension	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[53]. 5° to projected warming [107].	14,24,53,138,139
Sensitivity	Conservation status	LC	LC	V, E, CR	Defined by the IUCN RedList categories and criteria[17]: any category at or above 'vulnerable' is considered at high risk.	17
Sensitivity	Cumulative impacts	0.6	1.4	2	Guided by [19].	19,140
Sensitivity	Vertical habitat variability and use					
Sensitivity	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.	
Sensitivity	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.	
Exposure	Projected time of climate emergence from the thermal niche	75yrs	50yrs	25yrs	Guided by the IUCN RedList assessment criteria[17].	17,39
Exposure	Projected loss of suitable thermal habitat	5%	10%	20%	Guided by [99,108–111].	98,99,108–111,141–144.
Exposure	Projected ecosystem disruption	5%	10%	20%	Guided by thresholds in [39,114,116].	39,98,112,114–116,145
Adaptivity	Geographic range extent					
Adaptivity	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[118–120]	118–120,142
Adaptivity	Total geographic area	0.04%	1%	4%	Referenced to the size spectrum of large marine ecosystems[117].	55,99,108–110,117,142–145
Adaptivity	Geographic habitat fragmentation	20%	10%	1%	Guided by and comparable to those defined in [3] for the vulnerability of cetaceans.	3,99,111,123,124,142,144–147
Adaptivity	Maximum body length	100cm	30cm	10cm	Empirically guided by the relationship with the intrinsic rate of population increase.	64,92,148
Adaptivity	Thermal habitat variability and use					
Adaptivity	Thermal habitat occupancy	8%	95%	99%	Guided by the quantiles of the statistical distributions	66,68
Adaptivity	Thermal habitat variability	5°C	10°C	15°C	Comparable to those defined in [3] for the vulnerability of cetaceans.	3,66–68,90,149

Table S5. List of harvested and commercial species across the study area. Notes: T=true; F=false.

Species	Common Name	Harvested	Commercial
Limanda ferruginea	Yellowtail flounder	T	F
Glyptocephalus cynoglossus	Witch flounder	T	F
Molva molva	Ling	T	F
Katsuwonus pelamis	Skipjack tuna	T	F
Thunnus albacares	Yellowfin tuna	T	F
Thunnus obesus	Bigeye tuna	T	F
Menidia menidia	Atlantic silverside	T	F
Merluccius bilinearis	Silver hake	T	F
Microgadus tomcod	Atlantic tomcod	T	F
Morone americana	White perch	T	F
Morone saxatilis	Striped bass	T	F
Urophycis chuss	Red hake	T	F
Urophycis tenuis	White hake	T	F
Carcharhinus obscurus	Dusky shark	T	F
Scophthalmus aquosus	Windowpane flounder	T	F
Paralichthys dentatus	Summer flounder	T	F
Pollachius virens	Saithe	T	F
Hippoglossoides platessoides	American plaice	T	F
Tautogolabrus adspersus	Cunner	T	F
Cyclopterus lumpus	Lumpfish	T	F
Gadus morhua	Atlantic cod	T	F
Lophius americanus	American angler	T	F
Macrourus berglax	Roughhead grenadier	T	F
Anarhichas lupus	Atlantic wolffish	T	F
Anarhichas minor	Spotted wolffish	T	F
Scomberesox saurus	Atlantic saury	T	F
Malacoraja senta	Smooth skate	T	F
Pandalus montagui	Aesop shrimp	T	F
Cancer borealis	Jonah crab	T	F
Cancer irroratus	Atlantic rock crab	T	F
Arctica islandica	Ocean quahog	T	F
Mytilus edulis	Blue mussel	T	F
Crassostrea virginica	American cupped oyster	T	F
Mactromeris polynyma	Arctic surfclam	T	F

Supplemental references

1. Boyce, D. G. *et al.* A climate risk index for marine life. *Nat. Clim. Chang.* **12**, 854–862 (2022).
2. Comte, L. & Olden, J. D. Climatic vulnerability of the world's freshwater and marine fishes. *Nat. Clim. Chang.* **7**, 718–722 (2017).
3. Albouy, C. *et al.* Global vulnerability of marine mammals to global warming. 1–12 (2020).
4. Pacifici, M. *et al.* Assessing species vulnerability to climate change. *Nat. Clim. Chang.* **5**, 215–225 (2015).
5. Foden, W. B. *et al.* Climate change vulnerability assessment of species. *Wiley Interdiscip. Rev. Clim. Chang.* **10**, 1–36 (2019).
6. de los Ríos, C., Watson, J. E. M. & Butt, N. Persistence of methodological, taxonomical, and geographical bias in assessments of species' vulnerability to climate change: A review. *Glob. Ecol. Conserv.* **15**, (2018).
7. Foden, W. B. *et al.* Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS One* **8**, e65427 (2013).
8. Stortini, C. H. C. H., Shackell, N. L. N. L., Tyedmers, P. & Beazley, K. Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. *ICES J. Mar. Sci.* **72**, 1713–1743 (2015).
9. Greenan, B. J. W. *et al.* Climate Change Vulnerability of American Lobster Fishing Communities in Atlantic Canada. *Front. Mar. Sci.* **6**, 1–18 (2019).
10. McHenry, J., Welch, H., Lester, S. E. & Saba, V. Projecting marine species range shifts from only temperature can mask climate vulnerability. *Glob. Chang. Biol.* **25**, 4208–4221 (2019).
11. Scheffers, B. R. *et al.* The broad footprint of climate change from genes to biomes to people. *Science (80-.).* **354**, (2016).
12. Boyce, D. G., Schleit, K. & Fuller, S. *Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic*. (2021).
13. Kaschner, K. *et al.* Aquamaps: Predicted range maps for aquatic species. (2019).
14. Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L. & Sunday, J. M. Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature* (2019) doi:10.1038/s41586-019-1132-4.
15. Bennett, J. M. *et al.* GlobTherm, a global database on thermal tolerances for aquatic and terrestrial organisms. *Sci. Data* **5**, 180022 (2018).
16. Canadian Endangered Species Conservation Council. Wild Species 2015: The General Status of Species in Canada. *Natl. Gen. Status Work. Gr.* 128 (2016).

17. IUCN. The IUCN Red List of Threatened Species. *Version 2021-1* https://www.iucnredlist.org (2021).

18. Reynolds, R. W. *et al.* Daily high-resolution-blended analyses for sea surface temperature. *J. Clim.* **20**, 5473–5496 (2007).

19. Halpern, B. S. *et al.* A global map of human impact on marine ecosystems. *Science (80-.).* **319**, 948–952 (2008).

20. Halpern, B. S. *et al.* Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* **6**, 1–7 (2015).

21. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).

22. Meinshausen, M. *et al.* The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605 (2020).

23. IPCC. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2014).

24. Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Kininmonth, S. J. & Bates, A. E. Thermal biases and vulnerability to warming in the world's marine fauna. *Nature* **528**, 88+ (2015).

25. Sunday, J. M., Bates, A. E. & Dulvy, N. K. Thermal tolerance and the global redistribution of animals. *Nat. Clim. Chang.* **2**, 686–690 (2012).

26. Laidre, K. L. *et al.* Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol. Appl.* **18**, S97-125 (2008).

27. Rosset, V. & Oertli, B. Freshwater biodiversity under climate warming pressure: Identifying the winners and losers in temperate standing waterbodies. *Biol. Conserv.* **144**, (2011).

28. Peters, R. L. The Greenhouse Effect and Nature Reserves. *Biosciences* **35**, 707–717 (1985).

29. Garcia, R. A. *et al.* Matching species traits to projected threats and opportunities from climate change. *J. Biogeogr.* **41**, 724–735 (2014).

30. IUCN. *IUCN Red List Categories and Criteria: Version 3.1*. (IUCN, 2012).

31. Worm, B. *et al.* Impacts of biodiversity loss on ocean ecosystem services. *Science (80-.).* **314**, 787–90 (2006).

32. Worm, B., Lotze, H. K., Hillebrand, H. & Sommer, U. Consumer versus resource control of species diversity and ecosystem functioning. *Nature* **417**, 848–851 (2002).

33. Worm, B. & Duffy, J. E. Biodiversity, productivity, and stability in real food webs. *Trends Ecol. Evol.* **18**, 628–632 (2003).

34. Halpern, B. S. *et al.* An index to assess the health and benefits of the global ocean. *Nature* **488**, 615–620

(2012).
35. Ottersen, G., Hjermann, D. O. & Stenseth, N. C. Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (Gadus morhua) stock. *Fish. Oceanogr.* **15**, 230–243 (2006).
36. Le Bris, A. *et al.* Climate vulnerability and resilience in the most valuable North American fishery. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 1831–1836 (2018).
37. Henson, S. A. *et al.* Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nat. Commun.* **8**, 1–9 (2017).
38. Bates, A. E. *et al.* Climate resilience in marine protected areas and the 'Protection Paradox'. *Biol. Conserv.* **236**, 305–314 (2019).
39. Trisos, C. H., Merow, C. & Pigot, A. L. The projected timing of abrupt ecological disruption from climate change. *Nature* **580**, 1–6 (2020).
40. Xu, C., Kohler, T. A., Lenton, T. M., Svenning, J.-C. & Scheffer, M. Future of the human climate niche. *Proc. Natl. Acad. Sci.* **117**, 11350–11355 (2020).
41. Davies, T. E., Maxwell, S. M., Kaschner, K., Garilao, C. & Ban, N. C. Large marine protected areas represent biodiversity now and under climate change. *Sci. Rep.* **7**, 1–7 (2017).
42. MacKenzie, B. R. *et al.* A cascade of warming impacts brings bluefin tuna to Greenland waters. *Glob. Chang. Biol.* **20**, 2484–2491 (2014).
43. Shackell, N. L., Ricard, D. & Stortini, C. Thermal habitat index of many Northwest Atlantic temperate species stays neutral under warming projected for 2030 but changes radically by 2060. *PLoS One* **9**, (2014).
44. Boyce, D. G., Frank, K. T., Worm, B. & Leggett, W. C. Spatial patterns and predictors of trophic control across marine ecosystems. *Ecol. Lett.* **18**, 1001–1011 (2015).
45. Boyce, D. G., Frank, K. T. & Leggett, W. C. From mice to elephants: overturning the 'one size fits all' paradigm in marine plankton food chains. *Ecol. Lett.* **18**, 504–515 (2015).
46. Frank, K. T., Petrie, B., Shackell, N. L. & Choi, J. S. Reconciling differences in trophic control in mid-latitude marine ecosystems. *Ecol. Lett.* **9**, 1096–1105 (2006).
47. Frank, K. T., Petrie, B. & Shackell, N. L. The ups and downs of trophic control in continental shelf ecosystems. *Trends Ecol. Evol.* **22**, 236–242 (2007).
48. Loarie, S. R. *et al.* The velocity of climate change. *Nature* **462**, 1052–1056 (2009).
49. Burrows, M. T. *et al.* The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science (80-.).* **334**, 652–655 (2011).
50. Mora, C. *et al.* The projected timing of climate departure from recent variability. *Nature* **502**, 183+

(2013).

51. Poloczanska, E. S. *et al.* Responses of Marine Organisms to Climate Change across Oceans. *Front. Mar. Sci.* **3**, 62 (2016).

52. Boyce, D. G., Lotze, H. K., Tittensor, D. P., Carozza, D. A. & Worm, B. Future ocean biomass losses may widen socioeconomic equity gaps. *Nat. Commun.* (2020).

53. Boyce, D. G., Lewis, M. L. & Worm, B. Global phytoplankton decline over the past century. *Nature* **466**, 591–596 (2010).

54. Burek, K. A., Gulland, F. M. D. & O'Hara, T. M. Effects of climate change on Arctic marine mammal health. *Ecol. Appl.* **18**, S126–S134 (2008).

55. Staude, I. R., Navarro, L. M. & Pereira, H. M. Range size predicts the risk of local extinction from habitat loss. *Glob. Ecol. Biogeogr.* **29**, 16–25 (2020).

56. Moore, S. E. & Huntington, H. P. Arctic marine mammals and climate change: impacts and resilience. *Ecol. Appl.* **18**, S157–S165 (2008).

57. Kaschner, K., Watson, R., Trites, A. & Pauly, D. Mapping world-wide distributions of marine mammal species using a relative environmental suitability (RES) model. *Mar. Ecol. Prog. Ser.* **316**, 285–310 (2006).

58. Gonzalez-Suarez, M., Gomez, A. & Revilla, E. Which intrinsic traits predict vulnerability to extinction depends on the actual threatening processes. *Ecosphere* **4**, 1–16 (2013).

59. Rogan, J. E. & Lacher, T. E. Impacts of Habitat Loss and Fragmentation on Terrestrial Biodiversity. in *Reference Module in Earth Systems and Environmental Sciences* (Elsevier, 2018). doi:10.1016/B978-0-12-409548-9.10913-3.

60. Warren, M. S. *et al.* Rapid responses of British butterflies to opposing forces of climate and habitat change. *Nature* **414**, 65–69 (2001).

61. Chessman, B. C. Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes. *Biol. Conserv.* **160**, 40–49 (2013).

62. Davidson, A. D. D. *et al.* Drivers and hotspots of extinction risk in marine mammals. *Proc. Natl. Acad. Sci.* **109**, 3395–3400 (2012).

63. Cheung, W. W. L., Pauly, D. & Sarmiento, J. L. How to make progress in projecting climate change impacts. *ICES J. Mar. Sci.* **70**, 1069–1074 (2013).

64. Fenchel, T. Intrinsic rate of natural increase: The relationship with body size. *Oecologia* **14**, 317–326 (1974).

65. Healy, K. *et al.* Ecology and mode-of-life explain lifespan variation in birds and mammals. *Proc. R. Soc. B Biol. Sci.* **281**, 20140298 (2014).

66. Carilli, J., Donner, S. D. & Hartmann, A. C. Historical Temperature Variability Affects Coral Response to Heat Stress. *PLoS One* **7**, e34418 (2012).
67. Guest, J. R. *et al.* Contrasting Patterns of Coral Bleaching Susceptibility in 2010 Suggest an Adaptive Response to Thermal Stress. *PLoS One* **7**, e33353 (2012).
68. Donner, S. D. & Carilli, J. Resilience of Central Pacific reefs subject to frequent heat stress and human disturbance. *Sci. Rep.* **9**, 3484 (2019).
69. Rehm, E. M., Olivas, P., Stroud, J. & Feeley, K. J. Losing your edge: climate change and the conservation value of range-edge populations. *Ecol. Evol.* **5**, 4315–4326 (2015).
70. Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Kininmonth, S. J. & Bates, A. E. Thermal biases and vulnerability to warming in the world € s marine fauna. *Nature* **528**, 88–92 (2015).
71. Britten, G. L. *et al.* Predator decline leads to decreased stability in a coastal fish community. *Ecol. Lett.* **17**, 1518–1525 (2014).
72. Ves, A. R. I. *et al.* Estimating community stability and ecological interactions from time-series data. *Ecol. Monogr.* **73**, 301–330 (2003).
73. Martin, T. G. & Watson, J. E. M. Intact ecosystems provide best defence against climate change. *Nat. Clim. Chang.* **6**, 122–124 (2016).
74. Frank, K. T. T., Petrie, B., Choi, J. S. S. & Leggett, W. C. C. Trophic cascades in a formerly cod-dominated ecosystem. *Science (80-.).* **308**, 1621–1623 (2005).
75. Frank, K. T., Petrie, B., Fisher, J. A. D. & Leggett, W. C. Transient dynamics of an altered large marine ecosystem. *Nature* **477**, 86–89 (2011).
76. Estes, J. a., Tinker, M. T., Williams, T. M. & Doak, D. F. Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. *Science (80-.).* **282**, 473–476 (1998).
77. Brito-Morales, I. *et al.* Climate Velocity Can Inform Conservation in a Warming World Simple Climate Metrics Could Help Conservation in a Changing Climate. *Trends Ecol. Evol.* **33**, 1–17 (2018).
78. Li, D., Wu, S., Liu, L., Zhang, Y. & Li, S. Vulnerability of the global terrestrial ecosystems to climate change. *Glob. Chang. Biol.* **24**, 4095–4106 (2018).
79. García Molinos, J., Schoeman, D. S., Brown, C. J. & Burrows, M. T. VoCC: An R package for calculating the velocity of climate change and related climatic metrics. *Methods Ecol. Evol.* **10**, 2195–2202 (2019).
80. Holling, C. S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **4**, 1–23 (1973).
81. Cheung, W. W. L., Watson, R., Morato, T., Pitcher, T. J. & Pauly, D. Intrinsic vulnerability in the global fish catch. *Mar. Ecol. Prog. Ser.* **333**, 1–12 (2007).
82. Ficetola, G. F. & Denoel, M. Ecological thresholds: an assessment of methods to identify abrupt changes

in species-habitat relationships. *Ecography (Cop.).* **32**, 1075–1084 (2009).

83. Pearson, R. G. *et al.* Life history and spatial traits predict extinction risk due to climate change. *Nat. Clim. Chang.* **4**, 217–221 (2014).

84. Brown, J. H. & Kodric-Brown, A. Turnover Rates in Insular Biogeography: Effect of Immigration on Extinction. *Ecology* **58**, 445–449 (1977).

85. Crooks, K. R. *et al.* Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proc. Natl. Acad. Sci.* **114**, 7635–7640 (2017).

86. McGarigal, K. & Cushman, S. A. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. (2012).

87. Hesselbarth, M. H. K., Sciaini, M., With, K. A., Wiegand, K. & Nowosad, J. Landscapemetrics: an open-source R tool to calculate landscape metrics. *Ecography (Cop.).* **42**, 1648–57 (2019).

88. Cole, L. E. S., Bhagwat, S. A. & Willis, K. J. Recovery and resilience of tropical forests after disturbance. *Nat. Commun.* **5**, 3906 (2014).

89. Mora, C. *et al.* Suitable Days for Plant Growth Disappear under Projected Climate Change: Potential Human and Biotic Vulnerability. *PLoS Biol.* **13**, e1002167 (2015).

90. Nadeau, C. P., Urban, M. C. & Bridle, J. R. Climates past, present, and yet-to-come shape climate change vulnerabilities. *Trends Ecol. Evol.* **32**, 786–800 (2017).

91. Cheung, W. W. L. & Oyinlola, M. A. Vulnerability of flatfish and their fisheries to climate change. *J. Sea Res.* **140**, 1–10 (2018).

92. Blueweiss, L. *et al.* Relationships between body size and some life history parameters. *Oecologia* **37**, 257–272 (1978).

93. Mora, C. *et al.* Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century. *PLoS Biol.* **11**, 1–14 (2013).

94. Lotze, H. K. *et al.* Ensemble projections of global ocean animal biomass with climate change. *Proc. Natl. Acad. Sci.* 1–6 (2019) doi:doi.org/10.1073/pnas.1900194116.

95. Eyring, V. *et al.* Taking climate model evaluation to the next level. *Nat. Clim. Chang.* **9**, 102–110 (2019).

96. Hillebrand, H. *et al.* Thresholds for ecological responses to global change do not emerge from empirical data. *Nat. Ecol. Evol.* **4**, 1502–1509 (2020).

97. van der Hoek, Y., Zuckerberg, B. & Manne, L. L. Application of habitat thresholds in conservation: Considerations, limitations, and future directions. *Glob. Ecol. Conserv.* **3**, 736–743 (2015).

98. Shennan-Farpón, Y., Visconti, P. & Norris, K. Detecting ecological thresholds for biodiversity in tropical forests: Knowledge gaps and future directions. *Biotropica* btp.12999 (2021) doi:10.1111/btp.12999.

99. Arroyo-Rodríguez, V. *et al.* Designing optimal human-modified landscapes for forest biodiversity conservation. *Ecol. Lett.* **23**, 1404–1420 (2020).

100. Zommers, Z. *et al.* Burning embers: towards more transparent and robust climate-change risk assessments. *Nat. Rev. Earth Environ.* **1**, 516–529 (2020).

101. Leemans, R. & Vellinga, P. 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 (2017).

102. Fischlin, A. Do We Have Sufficient Safety Margins in Climate Policy? *GAIA-ECOLOGICAL Perspect. Sci. Soc.* **18**, 193–199 (2009).

103. Garner, G., Reed, P. & Keller, K. Climate risk management requires explicit representation of societal trade-offs. *Clim. Change* **134**, 713–723 (2016).

104. Oppenheimer, M., Little, C. M. & Cooke, R. M. Expert judgement and uncertainty quantification for climate change. *Nat. Clim. Chang.* **6**, 445–451 (2016).

105. Budescu, D. V, Por, H. H. & Broomell, S. B. Effective communication of uncertainty in the IPCC reports. *Clim. Change* **113**, 181–200 (2012).

106. Swart, R., Bernstein, L., Ha-Duong, M. & Petersen, A. Agreeing to disagree: uncertainty management in assessing climate change, impacts and responses by the IPCC. *Clim. Change* **92**, 1–29 (2009).

107. Gattuso, J.-P. J.-P. P. *et al.* Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science (80-.).* **349**, aac4722-1-aac4722-10 (2015).

108. Yin, D., Leroux, S. J. & He, F. Methods and models for identifying thresholds of habitat loss. *Ecography (Cop.).* **40**, 131–143 (2017).

109. Swift, T. L. & Hannon, S. J. Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications. *Biol. Rev.* **85**, 35–53 (2010).

110. Homan, R. N., Windmiller, B. S. & Reed, J. M. Critical thresholds associated with habitat loss for two vernal pool-breeding amphibians. *Ecol. Appl.* **14**, 1547–1553 (2004).

111. Lange, R., Durka, W., Holzhauer, S. I. J., Wolters, V. & Diekotter, T. Differential threshold effects of habitat fragmentation on gene flow in two widespread species of bush crickets. *Mol. Ecol.* **19**, 4936–4948 (2010).

112. Oliver, T. H. How much biodiversity loss is too much? *Science (80-.).* **353**, 220–221 (2016).

113. Brose, U. & Hillebrand, H. Biodiversity and ecosystem functioning in dynamic landscapes. *Philos. Trans. R. Soc. B Biol. Sci.* **371**, 20150267 (2016).

114. Newbold, T. *et al.* Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science (80-.).* **353**, 288–291 (2016).

115. Scholes, R. J. & Biggs, R. A biodiversity intactness index. *Nature* **434**, 45–49 (2005).

116. Hooper, D. U. *et al.* A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature* **486**, 105–8 (2012).

117. FRYE, R. Variability and management of large marine ecosystems - Sherman, K, Alexander, LM. *Nat. Resour. J.* **26**, 653–654 (1986).

118. Longhurst, A. *Ecological geography of the sea*. (Elsevier Inc., 2007).

119. Boyce, D. G., Petrie, B., Frank, K. T., Worm, B. & Leggett, W. C. Environmental structuring of marine plankton phenology. *Nat. Ecol. Evol.* 0–1 (2017) doi:10.1038/s41559-017-0287-3.

120. Mann, K. H. & Lazier, J. R. N. *Dynamics of marine ecosystems*. (Blackwell, 1991).

121. Garciá Molinos, J. *et al.* Climate velocity and the future global redistribution of marine biodiversity. *Nat. Clim. Chang.* **6**, 83–88 (2016).

122. Lehtinen, R. M., Galatowitsch, S. M. & Tester, J. R. Consequences of habitat loss and fragmentation for wetland amphibian assemblages. *Wetlands* **19**, 1–12 (1999).

123. Fahrig, L. Effect of habitat fragmentation on the extinction threshold: A synthesis. *Ecol. Appl.* **12**, 346–353 (2002).

124. Rueda, M. *et al.* Does fragmentation increase extinction thresholds? A European-wide test with seven forest birds. *Glob. Ecol. Biogeogr.* **22**, 1282–1292 (2013).

125. Palmeirim, A. F., Santos-Filho, M. & Peres, C. A. Marked decline in forest-dependent small mammals following habitat loss and fragmentation in an Amazonian deforestation frontier. *PLoS One* **15**, e0230209 (2020).

126. Mora, C., Danovaro, R. & Loreau, M. 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 (2014).

127. Bruno, J. F. *et al.* Climate change threatens the world's marine protected areas. *Nat. Clim. Chang.* **8**, 499–503 (2018).

128. Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L. & Levin, S. A. Marine Taxa Track Local Climate Velocities. *Science (80-.).* **341**, 1239–1242 (2013).

129. *FishBase 2000: concepts, design and data sources*. (Los Banos, 2000).

130. Palomares, M. L. D. & Pauly, D. SeaLifeBase. *World Wide Web Electron. Publ. www.sealifebase.org, version (11/2014).* (2022).

131. *Gebco gridded global bathymetry data*. (British Oceanographic Data Centre, 2009).

132. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).

133. Dunne, J. P. *et al.* GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics. *J. Clim.* **26**, 2247–2267 (2013).
134. Dunne, J. P. *et al.* GFDL's ESM2 Global Coupled Climate-Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. *J.* **25**, 6646–6665 (2012).
135. Hewitt, H. T. *et al.* Design and implementation of the infrastructure of HadGEM3: the next-generation Met Office climate modelling system. *Geosci. Model Dev.* **4**, 223–253 (2011).
136. Sein, D. V. *et al.* 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**, 2026–2041 (2018).
137. Voldoire, A. *et al.* The CNRM-CM5.1 global climate model: description and basic evaluation. *Clim. Dyn.* **40**, 2091–2121 (2013).
138. Gattuso, J. P. *et al.* Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science (80-.).* **349**, (2015).
139. Gallagher, R. V., Allen, S. & Wright, I. J. Safety margins and adaptive capacity of vegetation to climate change. *Sci. Rep.* **9**, 8241 (2019).
140. Butt, N. *et al.* A trait-based framework for assessing the vulnerability of marine species to human impacts. *Ecosphere* **13**, (2022).
141. Ochoa-Quintero, J. M., Gardner, T. A., Rosa, I., de Barros Ferraz, S. F. & Sutherland, W. J. Thresholds of species loss in Amazonian deforestation frontier landscapes. *Conserv. Biol.* **29**, 440–451 (2015).
142. Rompre, G., Boucher, Y., Belanger, L., Cote, S. & Robinson, W. D. Conserving biodiversity in managed forest landscapes: The use of critical thresholds for habitat. *For. Chron.* **86**, 589–596 (2010).
143. Liao, J. *et al.* 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 (2013).
144. Parker, M. & Mac Nally, R. Habitat loss and the habitat fragmentation threshold: an experimental evaluation of impacts on richness and total abundances using grassland invertebrates. *Biol. Conserv.* **105**, 217–229 (2002).
145. Chase, J. M., Blowes, S. A., Knight, T. M., Gerstner, K. & May, F. Ecosystem decay exacerbates biodiversity loss with habitat loss. *Nature* **584**, 238–243 (2020).
146. Andren, H. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *OIKOS* **71**, 355–366 (1994).
147. Hill, M. F. & Caswell, H. Habitat fragmentation and extinction thresholds on fractal landscapes. *Ecol. Lett.* **2**, 121–127 (1999).

148. Ripple, W. J. *et al.* Extinction risk is most acute for the world's largest and smallest vertebrates. *Proc. Natl. Acad. Sci.* **114**, 10678–10683 (2017).

149. Xu, Y. *et al.* 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 (2016).