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Global assessment of marine and freshwater recreational fish reveals mismatch in climate change vulnerability and conservation effort

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Abstract

Recreational fisheries contribute substantially to the sociocultural and economic well-being of coastal and riparian regions worldwide, but climate change threatens their sustainability. Fishery managers require information on how climate change will impact key recreational species; however, the absence of a global assessment hinders both directed and widespread conservation efforts. In this study, we present the first global climate change vulnerability assessment of recreationally targeted fish species from marine and freshwater environments (including diadromous fishes). We use climate change projections and data on species' physiological and ecological traits to quantify and map global climate vulnerability and analyze these patterns alongside the indices of socioeconomic value and conservation effort to determine where efforts are sufficient and where they might fall short. We found that over 20% of recreationally targeted fishes are vulnerable to climate change under a high emission scenario. Overall, marine fishes had the highest number of vulnerable species, concentrated in regions with sensitive habitat types (e.g., coral reefs). However, freshwater fishes had higher proportions of species at risk from climate change, with concentrations in northern Europe, Australia, and southern Africa. Mismatches in conservation effort and vulnerability were found within all regions and life-history groups. A key pattern was that current conservation effort focused primarily on marine fishes of high socioeconomic value rather than on the freshwater and diadromous fishes that were predicted to be proportionately more vulnerable. While several marine regions were notably lacking in protection (e.g., Caribbean Sea, Banda Sea), only 19% of vulnerable marine species were without conservation effort. By contrast, 72% of freshwater fishes and 33% of diadromous fishes had no measures in place, despite their high vulnerability and cultural value. The spatial and taxonomic analyses presented here provide guidance for the future conservation and management of recreational fisheries as climate change progresses.

KEYWORDS
climate change, conservation planning, diadromous fish, game fish, socioeconomic value, sport fish, trait-based assessment

1 | INTRODUCTION

Marine and freshwater recreational fisheries are important to the sociocultural, ecological, and economic fabric of riparian and coastal regions worldwide. Estimates suggest that ~220–700 million people engage in recreational fishing globally (Arlinghaus et al., 2013), catching as many as 40 billion fish per year (Cooke & Cowx, 2004), and generating ~$190 billion US annually (Coleman et al., 2004; FAO, 2012; Hyder et al., 2018). Although most of this economic benefit is realized in industrialized countries (Arlinghaus et al., 2015), recreational fishing is of growing importance in developing nations, and increasingly contributes to livelihoods in these regions (Arlinghaus & Cooke, 2009; Barnett et al., 2016; Gupta et al., 2015). Recreational fisheries hold great sociocultural value as a leisure activity that connects people to the natural world (Tufts et al., 2015), and many of the most popular recreational species hold significant traditional and cultural value to Indigenous communities (e.g., Pacific salmon, Arapaima, Murray cod, etc.; Noble et al., 2016). Although release rates of angled fish can be high (Cooke & Cowx, 2004), some are harvested and contribute to nutritional security (Cooke et al., 2018).

Climate change presents a serious threat to the productivity and sustainability of recreational fisheries (Hunt et al., 2016; Paukert et al., 2016; Townhill et al., 2019). Atmospheric temperatures have increased by ~1°C over the past 50 years, and the global hydrological cycle has shifted causing widespread unpredictability in rainfall patterns (IPCC, 2013). These changes have led to several biophysical alterations to marine and freshwater environments (Cohen et al., 2016; IPCC, 2014; NOAA, 2018; Osman, 2018), creating uncertainty and variability in water temperatures, nutrient cycling, sea levels, ocean acidity/salinity, dissolved oxygen concentrations, ice cover, and much more (IPCC, 2013). The cascading effects of such changes have effects on fish recruitment, growth, and survival (Dutil & Brander, 2003; Rätz & Lloret, 2003; Simpson et al., 2011), along with changes to species distributions, community composition, and phenology (Ellis et al., 2019; Lynch et al., 2016). Other anthropogenic stressors such as habitat modification, land-use change, water pollution, and eutrophication can compound climatic stressors (Holder et al., 2020; IPBES, 2019; Lynch et al., 2016), and recent analyses have suggested that intensive recreational fishing can exert pressures on stocks that are comparable to commercial fisheries, or even precipitate fisheries collapse (Embke et al., 2019; Lewin et al., 2006, 2019; Post et al., 2002). Fishery managers and the recreational fishing industry are collectively interested in understanding how climate change will impact key fish species so that effective adaptative governance strategies can be implemented (Creighton et al., 2013; Hunt et al., 2016; Potts et al., 2020); however, the absence of a global assessment hinders widespread conservation efforts (Townhill et al., 2019).

The degree to which species are susceptible to climatic stressors (i.e., their vulnerability) will depend on their exposure to environmental changes, and on the biological, ecological, and genetic traits that allow them to adjust to those changes (Nadeau et al., 2017). Climate change vulnerability assessments (CCVAs) that integrate climatic effects with species' ecological and evolutionary characteristics are known as "trait-based" assessments (Chessman, 2013; Foden et al., 2018; Pacifici et al., 2015), and are powerful tools for improving forecasts of species and regions that might be at risk. Although trait-based CCVAs do not provide empirical predictions of population range expansion, these studies can be performed rapidly, tend to be robust to missing data or uncertainty in data sources, and can cover large numbers of species to provide estimates of relative vulnerabilities within taxonomic groups. Trait-based approaches are thus important tools to lay the groundwork for future research and conservation efforts (Foden et al., 2018; Pacifici et al., 2015).

Recreational fishes are highly diverse and comprise representatives from a variety of life-history types (Donaldson et al., 2011; Sutton & Ditton, 2001). These include migratory and resident inland fishes, reef-dependent and pelagic marine species, and diadromous fishes that use both marine and freshwater habitats. This diversity makes a trait-based approach especially appropriate for understanding the vulnerability of this group as it accounts for their unique advantages and challenges for coping with climate change (Lin et al., 2017). Marine fishes tend to have fewer dispersal restrictions, increasing the potential to find suitable habitats as climatic changes occur (Comte & Olden, 2017). However, if changes occur too quickly, both the species and the environments they inhabit may be unable to adjust (Ruckelshaus et al., 2008), and large-bodied marine fishes (including many recreational species) tend to be under greater threat of extinction due, in part, to overexploitation (Olden et al., 2007). Freshwater fishes are generally restricted in their dispersal capacity relative to marine fish and inhabit ecosystems that are heavily altered by humans (Murdoch et al., 2019; Reid et al., 2018; Sousa et al., 2014). The effects of these habitat alterations can be complex and difficult to predict (Olden et al., 2007), especially if they interact with climate change. Diadromous fishes benefit from having access to a wide variety of habitat types (Gill et al., 2012; Sharma et al., 2007); however, some elements of their life history (e.g., upstream spawning migrations) present unique physiological challenges that are likely to become more difficult as water temperatures rise (Crossin et al., 2008). Most studies investigating climate change effects on diadromous species have focused on impacts in either freshwater or marine environments. However, both the degree of threat and the capacity for fish to cope with those threats can differ between the two habitat types. Integrating impacts across habitats and life stages is key for understanding the vulnerability of diadromous fishes (Lin et al., 2017).

In this study, we determined the vulnerability of 415 recreational fish species to climate change by performing a trait-based CCVA that focused on three dimensions of vulnerability—sensitivity, adaptive capacity, and exposure—and included representatives from marine, freshwater, and diadromous life-history groups. To address the socioecological context of recreational fisheries, we considered the cultural and economic significance of species (i.e., *socioeconomic value*), and determined the conservation actions or management plans currently in place (i.e., *conservation effort*). The specific objectives of this study were to (a) develop species-specific predictions about vulnerability to climatic change; (b) identify geographic regions of conservation priority by comparing the climate change vulnerability of species with their socioeconomic value and conservation efforts; and (c) compare differences among marine, freshwater, and diadromous life-history groups in terms of their vulnerability, socioeconomic value, and conservation effort. We discuss our findings in the context of the overall vulnerability of the recreational fishing sector, as well as management needs to build resilience and enable adaptation of the sector (as per Elmer et al., 2017).

2 | MATERIALS AND METHODS

2.1 | Fish species selection

A list of all recreationally harvested species was obtained from the International Game Fish Association (IGFA), which is a globally relevant, international organization providing support for recreational fishery studies, practices, regulations, and legislation. The full IGFA list is the most comprehensive listing of recreationally targeted species in the world and comprises >1500 species with a recreational catch record; however, a large proportion of these species are not common targets of recreational fisheries. To pare down this list, we first selected all fishes that are classified by IGFA as targets of angling (i.e., "line class and tackle" fishes; 226 species). However, to ensure that we did not exclude recreational species targeted by other types of gears (e.g., spears, bows, traps), five recreational fishing experts within and external to the authorship team independently reviewed the extended list of >1500 species and handpicked other common recreational fishery targets that were not included in the "line class and tackle" category, resulting in the addition of 189 species. Currently, the recreational fishing industry is more prevalent in developed countries, so a large proportion of species in this dataset are from these regions.

2.2 | Assessing vulnerability, socioeconomic value, and conservation effort—A brief overview

Climate change vulnerability was assessed based on scores in three broad dimensions, including exposure, sensitivity, and adaptive capacity. Exposure was estimated from climate change projections across a species' range, derived from general circulation models (GCMs). Sensitivity and adaptive capacity were estimated from species' traits. In the context of this study, sensitivity refers to a species' capacity to cope with environmental changes *in situ*, and adaptive capacity refers to a species' ability to escape unfavorable conditions (Foden et al., 2013). Socioeconomic value was assessed based on cultural and economic importance. Conservation effort was assessed by tallying the number of conservation measures currently in place for each species and by estimating the extent of a species' range that overlapped with a protected area (PA). Species were given binary scores of "high" or "low" for each trait based on scoring regimes developed via literature search. For sensitivity and exposure, a high score indicated high vulnerability to climate change, and for adaptive capacity, a low score indicated high vulnerability to climate change. If a species scored high (or low for adaptive capacity) for one trait within a dimension, it was given a high score overall in that dimension. A species was considered vulnerable to climate change if it was: (a) highly sensitive, (b) of low adaptive capacity, and (c) highly exposed. If a species scored high for one trait within socioeconomic value or conservation effort, it was given a high score overall for that dimension. Continuous indices were also calculated for vulnerability, socioeconomic value, and conservation effort (see Section 2.4). A flow chart is provided to outline all steps in the CCVA, including a worked example of one species (Marbled grouper, *Epinephelus fuscoguttatus*) from our dataset (Figure 1).

2.3 | Data collection

2.3.1 | Trait data

Trait data were collected from the IUCN Red List species information service (IUCN, 2019) and FishBase (Froese & Pauly, 2019) using R packages *rfishbase* (Boettiger et al., 2019) and *rredlist* (Chamberlain, 2018) performed in R v. 3.4.1 (R Core Team, 2019).

2.3.2 | Distribution data

Distribution data were obtained from the IUCN Red List spatial data service (IUCN, 2019) and AquaMaps (Kaschner et al., 2019; Figure 1). AquaMaps data are formatted as point shapefiles, with each point having an estimated probability of occurrence. Most studies using AquaMaps data select probability thresholds that fall between 0% and 50% (e.g., Davies et al., 2017; Hooker et al., 2011; Zhao et al., 2020). We selected a 30% threshold as a middle ground based on the analyses by O'Hara et al., (2017) who showed that 0% might overestimate and 50% might underestimate range size compared to IUCN ranges. When maps were available from both sources for a given species, we performed comparisons of range area and overlap between AquaMaps and IUCN Red List distributions and compared the estimates of climate change calculated from each range for a subset of randomly selected species from both marine ($n = 10$) and freshwater ($n = 10$) environments. In brief, we found 71% alignment among ranges (on the high end according to O'Hara et al., 2017; see Supplementary Methods 1.4.1). Comparisons of climate change estimates revealed no

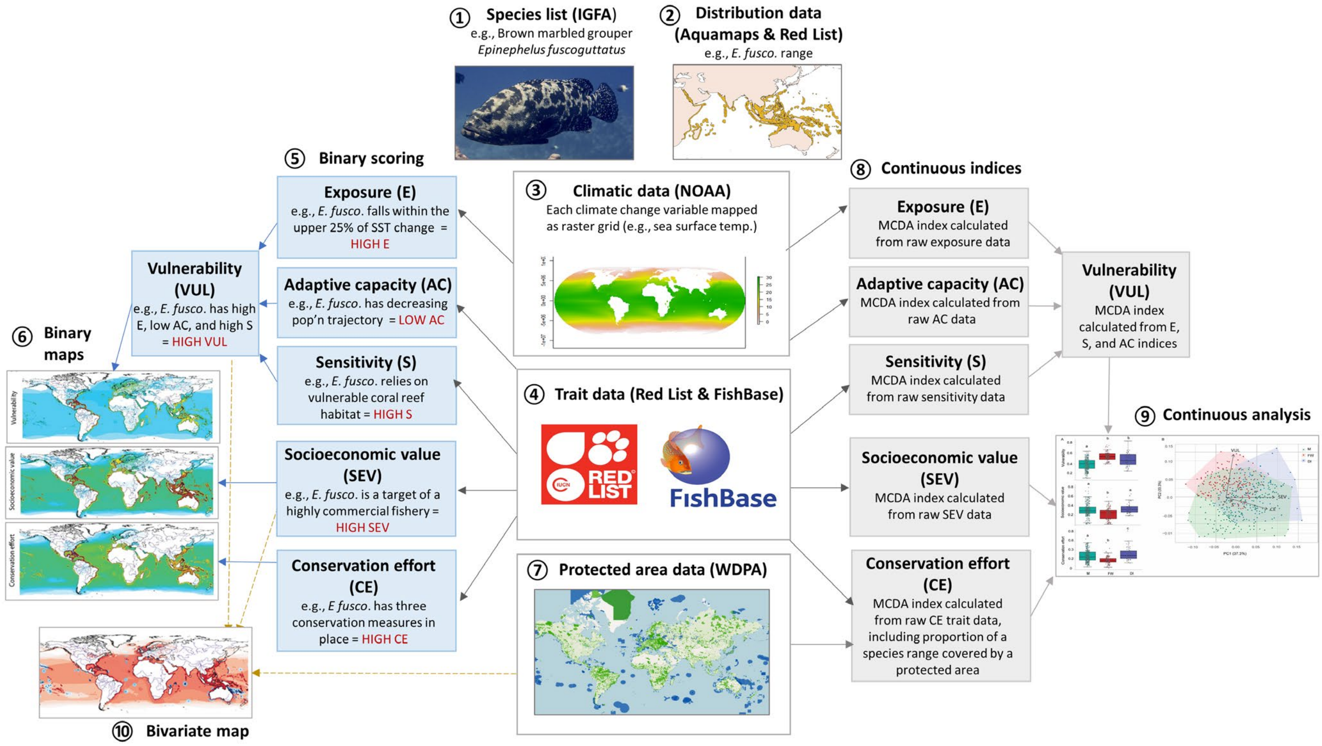

FIGURE 1 Flow chart of the CCVA methodology using the brown-marbled grouper (*Epinephelus fuscoguttatus*) as a worked example. (1) Compiled a species list from the International Game Fish Association (both angled and other recreational species); (2) Downloaded distribution data from the IUCN Red List (RL) and AquaMaps (AM). This figure shows the united AM and RL range for *E. fuscoguttatus*. See Section 2.3.2 and Supplementary Methods 1.4.1 for further details. (3) Calculated historical and projected climatic data using an ensemble of all available models for marine and freshwater climate variables under two RCPs (4.5 and 8.5) and two future time periods (2030 and 2075) from the NOAA climate portal. This figure shows global projected change in sea surface temperature for RCP8.5 in 2075. Average and standard deviation of climatic change was calculated within each species range and used to estimate exposure. (4) IUCN Red List and FishBase databases were accessed to extract data on traits relating to the dimensions of sensitivity (S), adaptive capacity (AC), socioeconomic value (SEV), and conservation effort (CE) for all species; species that score high in S and E, and low in AC get a high score in vulnerability (VUL). (5) Binary scoring methods were developed for each trait to assign each species a high or low score in each dimension. Examples of traits that caused *E. fuscoguttatus* to score "high" (or "low" in the case of AC) under each dimension have been provided. Because *E. fuscoguttatus* scored "high" for S and E, and "low" for AC, they were given a "high" score for vulnerability. (6) After all species were scored for each trait and dimension, species distributions were stacked to create the univariate maps presented in Figure 3. (7) The World Database on Protected Areas (WDPA) was accessed from Protected Planet. (8) Continuous indices were developed using multi-criteria decision analysis (MCDA) for E, AC, S, and SEV from raw data from the IUCN Red List and FishBase. A continuous index of VUL was developed by using indices of E, AC, and S as criteria in the MCDA. For CE, we used the raw conservation effort data from IUCN Red List and united this (using MCDA) with estimates of the proportion of each species' range that overlaps with a protected area (PA). (9) Continuous indices were used to perform ANOVA and PCA (Figure 6). (10) Binary VUL and SEV scores were overlaid with the PA data to highlight regions in need of spatial protection (Figure 5) [Colour figure can be viewed at wileyonlinelibrary.com]

differences for freshwater fish (Figures S11–S13). There were some differences in dissolved oxygen concentration [DO] and pH variability for marine fish (Figures S15–S16); however, none of these changes resulted in alterations to binary exposure scores. Nevertheless, we took a precautionary approach by uniting the AquaMaps and IUCN Red List distribution data when maps were available from both sources. Spatial data were lacking for seven Australian species, so occurrence data were accessed from the Atlas of Living Australia spatial portal (ALA, 2020). If a diadromous species had range data for both marine and freshwater environments, ranges were separated for analysis within each environment (Supplementary Methods 1.4.1). Freshwater ranges were refined by creating a detailed global map of freshwater systems and by clipping the ranges to remove terrestrial areas (Supplementary Methods 1.4.1; Nyboer et al., 2019). Marine and refined freshwater ranges were projected in the World Eckert IV equal area projection to eliminate any latitude-based area distortions and used to calculate the measures of distribution (e.g., extent of occurrence). These ranges were also used as boundaries to estimate exposure to climatic change (see Section 2.4.2).

2.3.3 | Climate data

Marine and freshwater environmental variables that represent key ecosystem drivers for fish species were downloaded from NOAA's Climate Change Web Portal as raster grids (NOAA, 2019) (Figure 1).

The same variables were used in considering both historical and future climate parameters. For freshwater ecosystems, the variables were air temperature (AT) and precipitation (PR). For marine ecosystems, the variables were sea surface or bottom temperature (SST or BT, depending on the species' occurrence in the water column; see Supplementary Methods 1.3), acidity (pH), and [DO]. Means of all available GCMs were used to estimate each environmental variable (Supplementary Methods 1.4.2). All variables were measured for one historical period (1980: mean of 1956–2005) and two projected periods (2030: mean of 2006—2055, 2075: mean of 2050–2099) under the Representative Concentration Pathway (RCP) 4.5 and 8.5. RCP4.5 represents a scenario where global carbon emissions stabilize (Thomson et al., 2011), while RCP8.5 represents a scenario where emissions remain high without intervention (Riahi et al., 2011). We downscaled these data to 10 × 10 arc minute grids using the bilinear interpolation method.

2.3.4 | Protected area data

Spatial PA data were accessed from the World Database of Protected Areas (WDPA) website, which contains the world's most complete database of terrestrial and marine protected areas (MPAs) (Figure 1). Protected area data are collected and vetted by the United Nations Environmental Program (UNEP) and the IUCN, and are categorized based on the type of protection they receive. Although there is likely to be variation in effectiveness of management among the different PAs, we opted to retain all categories given the global scale of the analysis and potential variation in categorization among countries (UNEP-WCMC, 2019). All PAs <5 km^2 were removed from the dataset to minimize calculation errors (Jones, 2018). This resulted in the removal of 65987 km^2, representing a 0.15% decrease in total area mostly from inland regions in Europe and North America. Protected area data were converted from polygon shapefiles to a raster format where all regions covered by a PA have a value of +1 and those without have a value of −1 (±maps).

2.4 | Assigning binary scores for vulnerability, socioeconomic value, and conservation effort

2.4.1 | Vulnerability: Sensitivity and adaptive capacity

The sensitivity dimension is based on traits that affect a species' capacity to cope with environmental changes *in situ* (Foden et al., 2013). Sensitivity was split into the following five trait sets: (a) range size (based on the area of occupancy and extent of occurrence); (b) specialized habitat requirements (based on habitat specificity, microhabitat requirements, and depth range); (c) narrow environmental tolerances (based on historical variance in climatic conditions); (d) specificity of ecological requirements (based on diet specificity and reliance on environmental triggers); and (e) exposure to other disturbances (based on the number and intensity of anthropogenic threats within a species' range).

The adaptive capacity dimension aimed to quantify a species' ability to cope with environmental change through dispersal or micro-evolutionary change (Foden et al., 2013). Adaptive capacity was split into the following three trait sets: (f) potential for dispersal (based on species' intrinsic capacity to disperse across all life-history stages); (g) species abundance (based on rarity and population growth estimates); and (h) reproductive capacity (based on r- vs. K-selected life-history traits).

Species were assigned binary "high" or "low" scores for each trait based on thresholds and scoring regimes that were determined via literature searches (described in detail in the Supplementary Methods Section 1.3). If a species scored high for one sensitivity trait, it was given a high overall score in that dimension. If a species scored low for one trait in adaptive capacity, it was given a low overall score in that dimension (Figure 1). Scoring regimes varied among traits, but generally indices and scoring thresholds were chosen based on the distribution of trait values in our dataset (Supplementary Methods 1.3). For most traits, we used the same thresholds for marine and freshwater fishes. However, "depth range" (in trait set B) and "historical variance in climatic conditions" (in trait set C) required different scoring regimes. For depth range, different thresholds were used because of the greater depth of most marine environments compared to freshwater environments (Supplementary Methods 1.3). For historical variance in climatic conditions, we used different climatic measures for marine (SST/BT, pH, [DO]) and freshwater (AT, PR) ecosystems necessitating different thresholds. Environmental variables from both environments were used for vulnerability of diadromous fishes. Thresholds used to score traits are available in Table 1, and descriptions of trait scoring methods, the justification for inclusion of each trait in the study, and additional considerations can be found in Supplementary Methods 1.3.

2.4.2 | Vulnerability: Exposure

The exposure dimension is based on the degree to which a species is projected to be exposed to climate change and was encompassed by one trait set called "predicted exposure to the effects of climate change." This was split into (I) freshwater and (J) marine environments. For freshwater, four variables were used to assess exposure, including changes in average AT and AT variability, and changes in average PR and PR variability. For marine fishes, exposure was assessed based on six variables, including changes in average SST/BT and SST/BT variability, changes in average pH and pH variability, and changes in average [DO] and [DO] variability. Zonal statistics were applied to find the average change within each species' range using range polygons as zonal boundaries (Figure 1). These calculations were performed for all year and RCP combinations. Justifications and further details can be found in Supplementary Methods 1.3 and 1.4. A species within the highest 25% of environmental change was classified as highly exposed (Foden et al., 2013). We calculated overall exposure scores based on the proportion of high scores out of the four variables for freshwater

TABLE 1 Trait sets and scoring regimes. Descriptions of trait sets, variables, and thresholds qualifying species as high or low for three vulnerability dimensions (sensitivity, low adaptive capacity, and exposure) and for socioeconomic value and conservation effort. The number and proportion of species classified as “high” and “low” for each dimension and trait are provided for all species together, and split by freshwater (FW), marine (M), and diadromous (DI)

Trait Set	Trait	Description	High vs Low	All	FW	M	DI	%All	%FW	%M	%DI
DIMENSION 1: SENSITIVITY				248	97	112	39	59.8	78.9	45.7	83.0
A. Range size	1. Extent of occurrence	EOO: Extent of taxon distribution across landscape	High =EOO <2,000,000km2	26	17	8	1	6.3	13.8	3.3	2.1
			Low =EOO >2,000,000km2	389	106	237	46	93.7	86.2	96.7	97.9
	2. Area of occupancy	AOO: Area occupied by the species	High =AOO <100,000km2	88	68	1	19	21.2	0.8	7.8	40.4
			Low =AOO >100,000km2	327	55	244	28	78.8	44.7	99.6	59.6
B. Specialized habitat or microhabitat requirements	3. Microhabitat specificity	Taxon is restricted to one rare habitat at some point of life cycle	High =Score ≥2	8	2	2	4	1.9	1.6	0.8	8.5
			Low =Score ≤2	407	121	243	43	98.1	98.4	99.2	91.5
	4. Habitat specialization	Taxon is a habitat specialist	High =taxon listed in only one biological habitat	36	0	35	1	8.7	0.0	14.3	2.1
			Low =all other taxa	379	123	210	46	91.3	100.0	85.7	97.9
	5. Depth range	Taxon is restricted to shallow depths or shallow habitat	High =taxon is restricted to depths ≤7m (freshwater) or ≤20m (marine)	44	7	9	28	10.6	5.7	3.7	59.6
			Low =all other taxa	371	116	236	19	89.4	94.3	96.3	40.4
C. Narrow environmental tolerance	6. Tolerance to changes in precipitation (freshwater)	Historical variability in precipitation across taxon's range	High =lowest 15% in precip variability	23	19		4	5.5	15.4		11.4
			Low =highest 85% in precip variability	135	104		31	32.5	84.6		88.6
	7. Tolerance to changes in temperature (freshwater)	Historical variability in temperature across taxon's range	High =lowest 15% in temp variability	23	18		5	5.5	14.6		14.3
			Low =highest 85% in temp variability	135	105		30	32.5	85.4		85.7
	8. Tolerance to changes in temperature (marine)	Historical variability in temperature across taxon's range	High =lowest 15% in temp variability	43		39	4	10.4		15.9	9.3
			Low =highest 85% in temp variability	245		206	39	59.0		84.1	90.7
	9. Tolerance to changes in pH (marine)	Historical variability in pH across taxon's range	High =lowest 15% in pH variability	41		37	4	9.9		15.1	9.3
			Low =highest 85% in pH variability	247		208	39	59.5		84.9	90.7
	10. Tolerance to changes in DO (marine)	Historical variability in DO across taxon's range	High =lowest 15% in DO variability	43		38	5	10.4		15.5	11.6
			Low =highest 85% in DO variability	245		207	38	59.0		84.5	88.4
D. Specificity of ecological requirements	11. Diet specificity	Taxon is reliant on limited number of prey items	High =taxon consumes one “food II” and <10 unique food items	24	10	14	0	5.8	8.1	5.7	0.0
			Low =all other taxa	391	113	231	47	94.2	91.9	94.3	100
	12. Relies on environmental trigger	Taxon is reliant on specific environmental trigger for reproduction /growth / development	High =taxon relies on ≥3 temperature, flow or light trigger	17	7	4	6	4.1	5.7	1.6	12.8
			Low =all other taxa	398	116	241	41	95.9	94.3	98.4	87.2

(Continues)

TABLE 1 (Continued)

Trait Set	Trait	Description	High vs Low	All	FW	M	DI	%All	%FW	%M	%DI
E. Exposure to other disturbances	13. Number and intensity of threats	Taxon is already subjected to threats	High =score ≥6	43	18	9	16	10.4	14.6	3.7	34.0
			Low =all other taxa	372	105	236	31	89.6	85.4	96.3	66.0
DIMENSION 2: ADAPTIVE CAPACITY				156	48	93	15	37.6	39.0	38.0	31.9
F. Potential for dispersal	1. Dispersal capacity	Taxon's intrinsic dispersal capabilities at larval, juvenile, and adult stages	High =Score ≥3	26	23	0	3	6.3	18.7	0.0	6.4
			Low =Score ≤3	389	100	245	44	93.7	81.3	100.0	93.6
G. Abundance	2. Rarity	Estimated rarity of species	High =taxon listed as rare or uncommon	38	10	26	2	9.2	8.1	10.6	4.3
			Low =taxon listed as moderately common or common	377	113	219	45	90.8	91.9	89.4	95.7
	3. Population growth trajectory	Trajectory of population (increasing vs. decreasing)	High =taxon population decreasing	110	22	79	9	26.5	17.9	32.2	19.1
			Low =taxon population increasing or stable	305	101	166	38	73.5	82.1	67.8	80.9
H. Reproductive capacity	4. Relative fecundity / Reproductive capacity	Taxon's mean annual relative fecundity	High =taxon possesses ≥3 K-selected traits	28	9	14	5	6.7	7.3	5.7	10.6
			Low =taxon possesses ≤3 K-selected traits	387	114	231	42	93.3	92.7	94.3	89.4
DIMENSION 3: EXPOSURE				368	117	207	44	88.7	95.1	84.5	93.6
I. Predicted exposure to the effects of climate change (freshwater)	1. Changes in mean temperature—RCP8.5	Average change in mean temp. (1980–2075) across range	High =top 25%	158	123		35	38.1	100.0		100
			Low =bottom 75%	0	0		0	0.0	0.0		0.0
	2. Changes in temperature variability—RCP8.5	Average change in temp. variability (1980–2075) across range	High =top 25%	61	56		5	14.7	45.5		14.3
			Low =bottom 75%	97	67		30	23.4	54.5		85.7
	3. Changes in mean precipitation—RCP8.5	Average change in mean precip. (1980–2075) across range	High =top 25%	73	55		18	17.6	44.7		51.4
			Low =bottom 75%	85	68		17	20.5	55.3		48.6
	4. Changes in precipitation variability—RCP8.5	Average change in precip. variability (1980–2075) across range	High =top 25%	112	89		23	27.0	72.4		65.7
			Low =bottom 75%	46	34		12	11.1	27.6		34.3
J. Predicted exposure to the effects of climate change (marine)	5. Changes in mean acidity—RCP8.5	Average change in mean acidity (1980–2075) across range	High =top 25%	208		186	22	50.1		75.9	51.2
			Low =bottom 75%	80		59	21	19.3		24.1	48.8
	6. Changes in acidity variability—RCP8.5	Average change in acidity variability (1980–2075) across range	High =top 25%	131		109	22	31.6		44.5	51.2
			Low =bottom 75%	157		136	21	37.8		55.5	48.8
	7. Changes in mean temperature—RCP8.5	Average change in mean temp (1980–2075) across range	High =top 25%	268		226	42	64.6		92.2	97.7
			Low =bottom 75%	20		19	1	4.8		7.8	2.3

(Continues)

TABLE 1 (Continued)

Trait Set	Trait	Description	High vs Low	All	FW	M	DI	%All	%FW	%M	%DI
	8. Changes in temperature variability—RCP8.5	Average change in temp variability (1980–2075) across range	High =top 25%	69		49	20	16.6		20.0	46.5
			Low =bottom 75%	219		196	23	52.8		80.0	53.5
	9. Changes in mean DO—RCP8.5	Average change in mean DO (1980–2075) across range	High =top 25%	257		220	37	61.9		89.8	86.0
			Low =bottom 75%	31		25	6	7.5		10.2	14.0
	10. Changes in DO variability—RCP8.5	Average change in DO variability (1980–2075) across range	High =top 25%	49		31	18	11.8		12.7	41.9
			Low =bottom 75%	239		214	25	57.6		87.3	58.1
CLIMATE CHANGE VULNERABILITY (with scenario comparison)											
Vulnerability with lenient trait scores	RCP4.5	1980–2030	top 25%	40	9	23	8	9.6	7.3	9.4	17.0
		1980–2075	top 25%	41	7	25	9	9.9	5.7	10.2	19.1
	RCP8.5	1980–2030	top 25%	77	25	41	11	18.6	20.3	16.7	23.4
		1980–2075	top 25%	91	36	42	13	21.9	29.3	17.1	27.7
Vulnerability with strict trait scores	RCP4.5	1980–2030	top 25%	86	27	46	13	20.7	22.0	18.8	27.7
		1980–2075	top 25%	88	27	45	16	21.2	22.0	18.4	34.0
	RCP8.5	1980–2030	top 25%	204	82	95	27	49.2	66.7	38.8	57.4
		1980–2075	top 25%	244	100	111	33	58.8	81.3	45.3	70.2
DIMENSION 5: SOCIOECONOMIC VALUE				124	30	76	18	29.9	24.4	31.0	38.3
K. Importance for human use	1. Fishing pressure	Degree to which a species is commercially targeted	High =highly commercial	258	59	161	38	62.2	48.0	65.7	80.9
			Low =subsistence	157	64	84	9	37.8	52.0	34.3	19.1
	2. Other uses	Taxon is used for aquaculture, bait, or aquarium trade	High =taxon has >2 other uses	126	43	67	16	30.4	35.0	27.3	34.0
			Low =taxon has ≤2 other uses	289	80	178	31	69.6	65.0	72.7	66.0
L. Cultural significance	3. Cultural significance	Number of languages and common names used to identify taxon	High =top 15%	63	4	51	8	15.2	3.3	20.8	17.0
			Low =bottom 85%	352	119	194	39	84.8	96.7	79.2	83.0
DIMENSION 6: CONSERVATION EFFORT											
M. Conservation effort	1. Conservation measures in place	Number of conservation measures currently implemented for taxa	High =no/minimal measures <1.5	147	11	120	16	35.4	8.9	49.0	34.0
			Low =moderate/exceptional measures >1.5	268	112	125	31	64.6	91.1	51.0	66.0

fish and the six variables for marine fish. If a species scored high in ≥50% of exposure variables, they were given a high overall score.

2.4.3 | Overall climate change vulnerability

A species was given a high score for overall vulnerability if it had all three of high sensitivity, low adaptive capacity, and high exposure (Figure 1).

2.4.4 | Scenario analyses

We tested the degree to which different scenarios influenced our findings by shifting the thresholds to different cutoff points with lenient scenarios resulting in fewer species with high scores and strict scenarios resulting in more species with high scores. We also calculated scores based on the top 15% and 35% of climate change exposure. Certain traits within the sensitivity and adaptive capacity dimensions had unknown values for some species (Supplementary Methods 1.3). Thus, we calculated indices with all unknowns coded as low for sensitivity and high for adaptive capacity for the lenient scenario, and *vice versa* for the strict scenario. For the main analysis, we present vulnerability scores based on a lenient scoring regime, a 25% exposure threshold, and the RCP8.5–2075 emission scenario. The comparisons of scenarios can be found in Supplementary Results, Table S1, and Figures S3–S8.

2.4.5 | Socioeconomic value and conservation effort

Socioeconomic value was split into the following two trait sets: (K) importance for human use and (L) cultural significance (based on the number of languages and common names associated with a species; Garibaldi & Turner, 2004). Conservation effort has one trait set, namely (M) based on the number of conservation measures currently in place for each species. Data on conservation measures were obtained from the IUCN Red List and include information on species-specific management or recovery plans, legislation on species protection, and harvest and trade regulations, among others. IUCN conservation measure data were tested for accuracy and completeness by crosschecking against species protection legislation for Canada (Species at Risk Act), the USA (Endangered Species Act), and the European Union's Habitats Directive. The IUCN data were found to capture 70% of species listed in the abovementioned Acts.

2.5 | Calculating continuous indices for vulnerability, socioeconomic value, and conservation effort

Composite indices were calculated for sensitivity (S), adaptive capacity (AC), exposure (E), vulnerability (VUL), socioeconomic value (SEV), and conservation effort (CE) directly from the raw trait data using multi-criteria decision analysis (MDCA) and the TOPSIS method (Technique for Order Preference by Similarity to an Ideal Solution) (Hwang & Yoon, 1981; Figure 1). Multi-criteria decision analysis using TOPSIS ranks each component (in our case, species) according to their relative geometric distance from the positive and negative ideal solution (El Amine et al.,2014; Penadés-Plà et al., 2016) with scales ranging from 0 (minimum VUL, SEV, CE) to 1 (maximum VUL, SEV, CE). This approach is used in many domains to enhance the quality of decision-making procedures and can account for both qualitative and quantitative variables (Mendoza & Martins, 2006). The VUL index was created using S, AC, and E as criteria in the MCDA. For CE, we calculated the proportion of each species' range covered by a PA by overlaying species range polygons with the WDPA raster dataset (Davies et al., 2017; Zhao et al., 2020) and included these proportions as a criterion in the MCDA alongside tallies of conservation measures (Figure 1).

2.6 | Mapping concentrations of vulnerable species

The distributions of species that are highly vulnerable, of high socioeconomic value, and targets of conservation effort were mapped to identify regions where they are concentrated. Each map is displayed as both total count of all species, and as proportions of species within each grid cell (Figure 1). Bivariate maps were used to determine the regions of coincidence between climate change vulnerability and PAs (Figure 1). These maps were created by summing the ± WDPA maps and the vulnerability and socioeconomic value maps creating a new layer where regions with PAs are positive and regions without PAs are negative. Fish that are vulnerable to climate change but are not targets of conservation effort were summarized to complement the spatial analysis (Table S2).

2.7 | Trait and life-history group analysis

We summarized trait data to determine which traits contributed most to vulnerability, socioeconomic value, and conservation effort. The analyses were conducted for all fish together, and for freshwater, marine, and diadromous fish separately. First, we calculated the traits that had the most high scores in each category and ranked them. Second, we examined the number of species that received a high score within each dimension based exclusively on one trait. This indicated the sensitivity of the analysis to the selected traits.

To assess differences among life-history groups in vulnerability, socioeconomic value, and conservation effort, we used one-way ANOVA with the continuous indices as the response variables and life-history group as the fixed factor. Principal component analysis (PCA) was used to reduce the continuous indices to major axes, and a PCA biplot was used to visualize the associations among variables and determine how species and groups relate to each axis. All analyses were conducted in R v. 3.4.1.

3 | RESULTS

3.1 | Recreational species distributions and data availability

We obtained range maps and trait data for 415 fish species from marine (*n* = 245), freshwater (*n* = 123), and diadromous (*n* = 47) life-history groups representing most recreational fish species globally. Generally, marine areas contained a higher species richness of recreational fish than freshwater areas (Figure 2). In marine environments, recreational fish were concentrated in the Caribbean Sea, the Gulf of Mexico, the East Pacific Ocean, the eastern Indian Ocean, and the Timor Sea (Figure 2). Although freshwaters contained only a fraction of the species richness relative to marine, notable areas included the North American Great Lakes, the Amazon basin, and the river systems in northern Europe (Figure 2). Trait data were highly available with 100% representation of all traits except for depth range (403 species; 97% representation), diet (373 species; 90%), fishery value (370 species; 89%), population growth trajectory (319 species; 77%), and rarity (285 species, 69%).

3.2 | Climate change vulnerability

3.2.1 | Overall vulnerability

Of all species in our dataset, 21.9% (*n* = 91) were considered highly vulnerable to climate change (Table 1). Marine fishes had the highest total count qualifying as vulnerable (*n* = 42), followed by freshwater (n = 36) and diadromous fishes (n = 13; Table 1; Figure 3a,b). Based on proportions, freshwater and diadromous groups were higher at 29.3% and 27.7%, respectively, compared to their marine counterparts at 17.1% (Table 1; Figure 3a,b). Analyses comparing different combinations of RCP (4.5 vs. 8.5), year (2030 vs. 2075), exposure threshold (15%, 25%, 35%), and scoring threshold (strict vs. lenient) revealed that 18 scenarios (75% of all scenarios) found similar patterns as described above (Table 1; Table S1; Figure S18). However, there were six scenarios under the lenient scoring regime where the proportion of vulnerable marine species outweighed the proportion of vulnerable freshwater species (Figure S18). Detailed results of the scenario analyses can be found in the Supplementary Results, Table S1 and Figures S3–S8.

Out of the 415 species, 248 (60%) scored high for sensitivity (Table 1; Figures S1, S2). For adaptive capacity, 156 species (38%) were given a low score (Table 1; Figures S1, S2). Exposure in the RCP8.5–2075 emission scenario resulted in 368 species (89%) being highly exposed (Table 1; Figures S1, S2). For sensitivity and adaptive capacity, the strict scenario resulted in a 48% and 99% increase in high scores compared to the lenient scenario, respectively. For exposure, the 15% threshold resulted in a 42% decrease in high scores, while the 35% threshold resulted in a 33% increase in high scores (Supplementary Results, Table S1; Figures S1 and S2). Comparisons of the different emission scenarios (RCP4.5 vs RCP8.5), years (2030 vs. 2078), and thresholds of exposure (15%, 25%, 35%) can be found in the Supplementary Results, Table S1, and Figures S3–S8.

3.2.2 | Trait breakdowns: Family and life-history group analysis

The most important traits within each vulnerability dimension are presented in Figure 4a–d, and examples of vulnerable families within each life-history group are provided in Table 2. Highly vulnerable marine families included the Epinephelidae

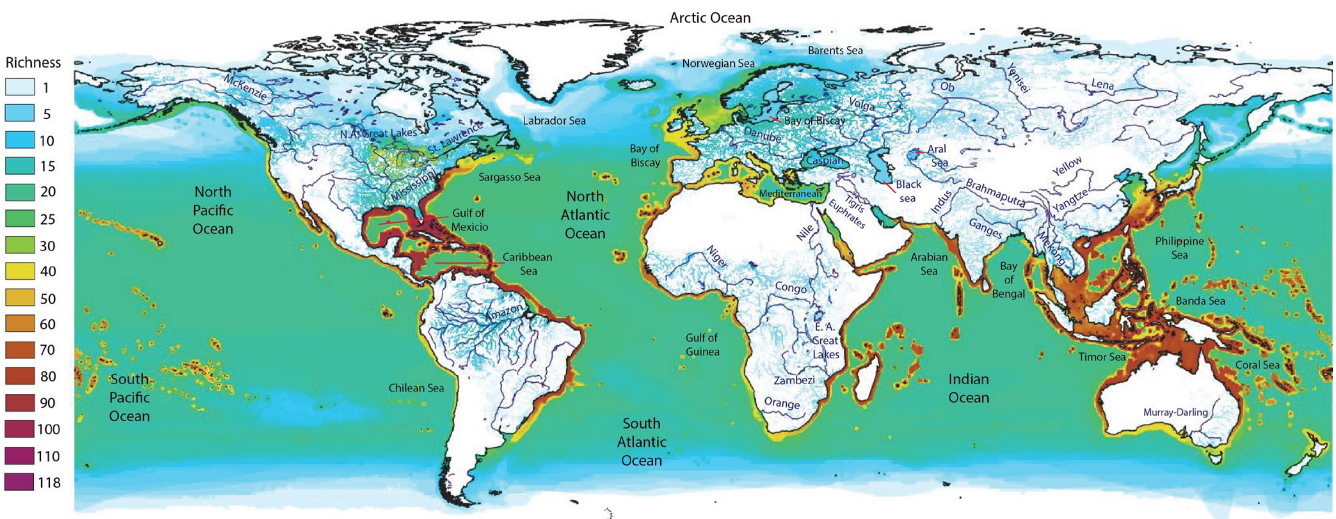

FIGURE 2 Map showing the global distribution of species richness of recreationally harvested fishes from marine and freshwater environments, with labels for major oceans, seas, lakes, and rivers. Scale bar indicates the number of species [Colour figure can be viewed at wileyonlinelibrary.com]

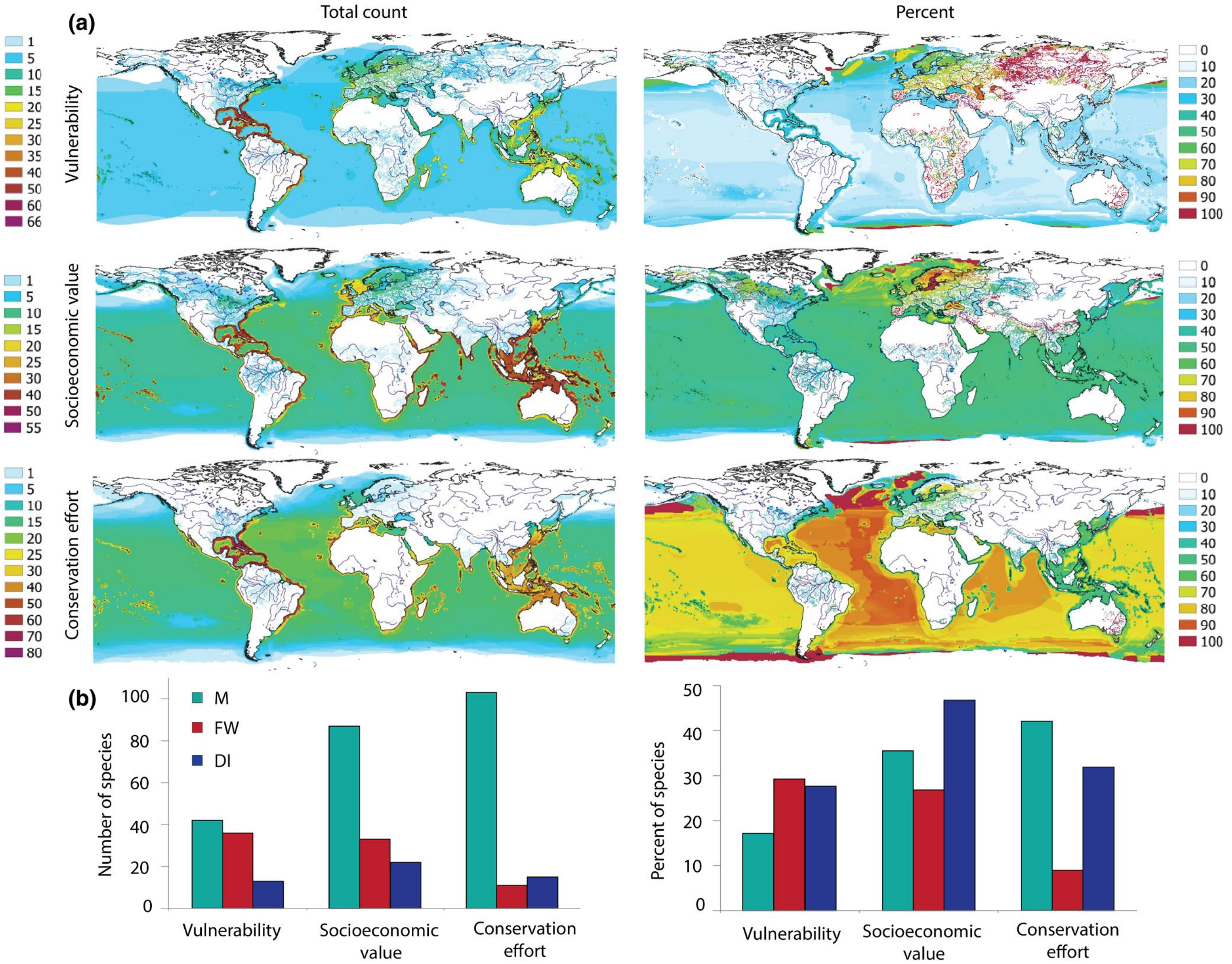

FIGURE 3 Univariate maps showing the global distributions of species that are highly vulnerable to climate change, of high socioeconomic value, and that benefit from current conservation action (panel A). Maps are displayed by total count and by percent. Panel B shows the number and proportion of species from each life-history group—marine (M), freshwater (FW), and diadromous (DI)—that had high scores in each category [Colour figure can be viewed at wileyonlinelibrary.com]

(groupers), Lutjanidae (snappers), and Labridae (Wrasses). Vulnerable freshwater families included the Cichlidae (cichlids), Cyprinidae (carps and minnows), Percichthyidae (temperate perches), and Pangasiidae (shark catfish). Vulnerable diadromous families included the Salmonidae (salmonids), Anguillidae (eels), Acipenseridae (sturgeon), and Clupeidae (shads and herrings; Table 2). Across all life-history groups, many other less speciose families also had high vulnerability to climate change (Supplementary Results, Table S2).

Key traits that made recreational fish sensitive to climate change included dependence on environmental triggers, small range sizes, and microhabitat specificity (Figure 4a). Each life-history group also possessed unique traits that made them sensitive. Marine species frequently received high scores from having highly specialized habitats and diets, especially those that rely on sensitive habitats such as coral reefs, seagrass beds, mangroves, or estuaries (Table 2). Freshwater fish were sensitive primarily due to the relatively small size of their habitable zones and because they are highly exposed to anthropogenic threats (Table 2). Diadromous fish were sensitive because of their dependence on environmental triggers (e.g., temperatures to cue spawning), their reliance on microhabitats (e.g., spawning grounds), and threats in their freshwater habitats and along migration routes (Table 2).

Key traits that caused low adaptive capacity in recreational species included low population growth rates and small population sizes. Decreasing population sizes were equally common in all three life-history groups (by proportion; Figure 5b). Marine fish generally tended to have higher adaptive capacity than the other groups due to higher dispersal capacity; however, several groups had lower reproductive rates (13 species in the *Carcharhinus* and *Epinephelus* genera). Freshwater fish had the lowest adaptive capacity primarily because of low dispersal capacities relative to marine fish (Table 2). Diadromous fish faced barriers to adaptation due to low dispersal capacity (e.g., Salmonids that spawn in natal streams) and

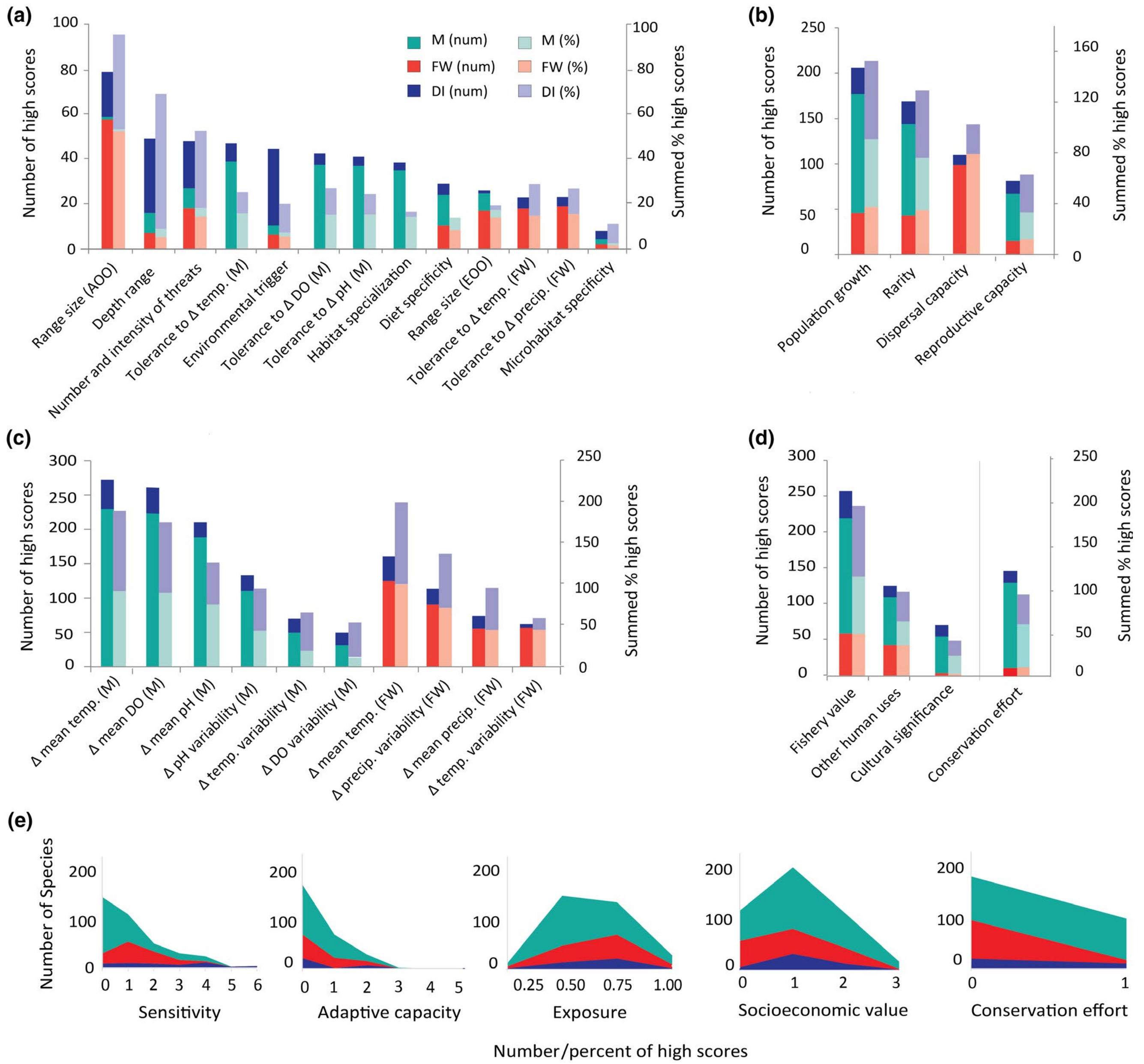

FIGURE 4 Summary of the number (dark bars) and proportion (pale bars) of species from each life-history group—marine (M), freshwater (FW), and diadromous (DI)—to be given high scores (low in the case of adaptive capacity) in each of the traits within the vulnerability dimensions: sensitivity (A), adaptive capacity (B), and exposure (C). Socioeconomic value and conservation effort are both presented in panel D. Panel E shows the number of species within each life-history group that received high scores in multiple traits within each dimension [Colour figure can be viewed at wileyonlinelibrary.com]

low reproductive capacity (e.g., Sturgeon; Table 2). The most important climatic changes to species' environments (exposure) included changes in mean SST/BT, [DO], and pH for marine fishes, and changes in mean AT and variability of PR for freshwater fishes. Diadromous species were affected by these same five physical changes in their marine and freshwater environments (Figure 4).

Most species that scored high for sensitivity and low for adaptive capacity were given these overall scores due to just one or two traits, with fewer species scoring high (or low for adaptive capacity) in three or more traits (Figure 4e). However, most species scored high in 50%–75% of climate change parameters (Figure 4e).

3.3 | Socioeconomic value

3.3.1 | Overall socioeconomic value

Of all species, 30% (n = 124) were of high socioeconomic value (Table 1; Figure 2). Marine fishes had the most species of high socioeconomic value based on total count (n = 76), followed by freshwater (n = 30) and diadromous fish (n = 18; Table 1; Figure 3a,b). However, diadromous fish had the greatest proportion of socioeconomically valuable species at 39%, followed by marine (31%) and freshwater (24%; Table 1; Figure 2a,b; Figures S1, S2).

TABLE 2 Family groups of marine, freshwater, and diadromous fish that contain several species that are likely to be vulnerable to climate change. Descriptions of traits common to each group for vulnerability (including high sensitivity, low adaptive capacity, and high exposure), socioeconomic value, and conservation effort are provided along with total counts and proportions of species in each family group with high scores for each index

			Vulnerability								Socioeconomic value				Conservation effort		
LH Group	Family	Common	Tot	#	%	Sensitivity traits with high scores	Why did the family have high sensitivity?	Ad. Cap. traits with low scores	Why did the family have low Ad. Cap.?	Exposure	#	%	Socioeconomic value traits with high scores	Why did the family have high SEV	#	%	Conservation measures
Marine	Epinephelidae	Groupers	26	13	50	- Habitat and diet specificity -Stable historical conditions	- Coral reefs -Tropical zones w. stable water conditions	- Population trajectory - Rarity	- Decreasing populations	- Δ mean [DO], SST, pH - Δ pH SD	9	34.6	- High fishery value, cultural significance, several other uses	- Heavily exploited commercially	22	84.6	- Size and harvest limits, gear limitations, species-specific measures, protected areas, sale bans
	Lutjanidae	Snappers	18	8	44.4	- Habitat specificity - Stable historical condition - Threats	- Requires biological habitats - Lives in tropical zones with stable water conditions -Overfishing	- Population trajectory	- Decreasing populations	- Δ mean [DO], SST, pH - Δ pH SD	5	27.8	- Commercial fishery value and other uses	- Subsistence fishing, aquarium trade, cultural importance	12	66.7	- Size and harvest limits, gear limitations, protected areas, sale bans
	Labridae	Wrasses	12	3	25	- Diet specificity - Stable historical conditions	- Requires biological habitats and specific diets - Tropical zones w. stable water conditions	- Population trajectory - Rarity	- Decreasing populations	- Δ mean [DO], SST, pH - Δ pH SD	3	25	- Commercial fishery value, cultural significance, other uses	- Subsistence and commercial fishery, aquarium trade	8	66.7	- Size and harvest limits, species-specific measures, protected areas, sale bans
Freshwater	Cichlidae	Cichlids	8	5	62.5	- AOO - Diet specificity	- Small distributions - Highly specified diets	- Dispersal capacity	- Low dispersal due to small body size, and because adults and juveniles are in restricted habitats	- Δ mean AT - Δ AT SD	4	50	- Fishery value and other uses	- Artisanal and commercial fishery, aquarium trade	0	0	- Very little, some habitat protection in place

(Continues)

TABLE 2 (Continued)

			Vulnerability								Socioeconomic value				Conservation effort		
	Cyprinidae	Carps and minnows	21	10	47.6	- AOO - Threats	- Small distributions - Threatened by harvesting, dams, urban run off, altered habitats	- Population trajectory - Dispersal capacity	- Decreasing populations - Low dispersal due to adults and juveniles in restricted habitats	- Δ mean AT - Δ AT, PR SD	6	28.6	- Fishery value and other uses	- Artisanal and commercial fishery, cultural importance	3	14.3	- Species not considered a concern
	Percichthyidae	Temperate perches	4	4	100	- AOO - Threats	- Small distributions - Threatened by dams, invasive species, droughts	- Reproductive capacity	- Relatively slow maturation	- Δ mean AT, PR - Δ AT SD	0	0			2	50	- Some species-specific measures, harvest restriction, breeding programs
	Pangasiidae	Shark catfish	3	3	100	- AOO - Threats	- Small distributions - Threatened by fishing, dams, forestry runoff	- Population trajectory - Rarity	- Decreasing populations - Species are rare	- Δ mean AT - Δ AT, PR SD	2	66.7	- Fishery value and other uses	- Artisanal and commercial fishery, cultural importance	3	100	- Some species-specific measures, harvest restriction, breeding programs
	Acipenseridae	Sturgeon	1	1	100	- AOO - Threats	- Small distributions - Threatened by fishing, dams, forestry and urban runoff	- Population trajectory - Reproductive capacity	- Decreasing population - Relatively slow maturation - Relatively low fecundity	- Δ mean AT - Δ AT SD	0	0			1	100	- Species-specific measures, harvest closures
Diadromous	Salmonidae	Salmonids	16	8	50	- Depth while in freshwater habitat - Environmental triggers	- Shallow depths during freshwater migrations - Specific spawning temperatures required	- Dispersal capacity - Population trajectory	- Low dispersal capacity due to restricted spawning sites - Low relative fecundity	- Δ mean SST [DO], PR, AT - Δ SST, [DO], PR SD	8	50	- Fishery value, other uses, cultural significance	- Cultural importance, commercial and artisanal fishery	0	0	- Few recorded, some habitat protection
	Anguillidae	Eels	5	3	60	- Threats - Depth while in freshwater habitat	- Shallow depths in freshwaters - Threatened by fishing, dams, agricultural, urban and forestry runoff, droughts	- Population trajectory	- Decreasing populations, some are rare	- Δ mean SST, [DO], AT - Δ SST, pH, PR SD.	2	40	- Fishery value, cultural significance	- Cultural importance, commercial and artisanal fishery	4	80	- Many species-specific measures, size and harvest restrictions, permits required, fish passes, breeding

(Continues)

TABLE 2 (Continued)

			Vulnerability							Socioeconomic value				Conservation effort		
Acipenseridae	Sturgeon	4	3	75	- Threats - Depth while in freshwater habitat	- Shallow depths in freshwaters - Threatened by fishing, dams, agricultural, urban and forestry runoff, droughts	-Population trajectory - Rarity - Reproductive capacity	- Decreasing populations, some are rare - Relatively low maturation - Relatively low fecundity	- Δ mean SST, PR, AT - Δ pH, PR SD	1	25	- Fishery value and other uses	- Commercial and artisanal fishery	2	50	- Some species-specific measures, gear and harvest limits / closures, breeding
Clupeidae	Shads and herrings	3	2	66.7	- Threats - Depth while in freshwater habitat	- Shallow depths in freshwaters - Threatened by fishing, dams, invasive species, agricultural, urban and forestry runoff	- Population trajectory - Rarity	- Decreasing populations, some are rare	- Δ mean SST, [DO], PR, AT - Δ PR SD	0	0	- none	-Mostly not high socioeconomic value	1	33.3	- Generally, species not considered a concern; fish passes for some

3.3.2 | Trait breakdowns: Family and life-history group analysis

Marine families that were of high socioeconomic value included the groupers, snappers, and wrasses (as with vulnerability; Table 2), but also included the Scombridae (tunas, mackerels; 12 species), Gadidae (cods; three species), Carcharhinidae (requiem sharks; three species), and Carangidae (jacks, pompanos; 11 species). High scores for these species were largely because of their great monetary value in commercial fisheries. Over half (n = 161) of the marine species in our dataset are targeted commercially as well as recreationally (Figure 4d; Table 2). Freshwater families of high socioeconomic value included the Cichlidae and Cyprinidae (as with vulnerability; Table 2) but also included the Percidae (four species). Freshwater fish had high scores for socioeconomic value because they are often targets of artisanal and commercial fisheries (Figure 4d; Table 2). Diadromous families that scored high for socioeconomic value were the same as those that scored high for vulnerability (Table 2), because they were targets of artisanal and commercial fisheries and because several species are of cultural significance (Figure 4d; Table 2). Most species scored high for socioeconomic value due to one or two traits (Figure 4e).

3.4 | Conservation effort

3.4.1 | Overall conservation effort

Of all species, 35% (n = 147) were shown to be benefitting from at least two conservation initiatives (Table 1; Figure 2). Marine fishes had the highest number and proportion of species with conservation efforts (n = 120, 49%), followed by diadromous fishes (n = 16, 34%) and freshwater species (n = 11, 9%; Table 1; Figure 3a,b; Figures. S1, S2).

3.4.2 | Trait breakdowns: Family and life-history group analysis

Marine families with some form of conservation effort included the groupers, snappers, and wrasses (as with vulnerability and socioeconomic value; Table 2; Figure 4d), but also included the Scombridae (tunas, mackerels; 13 species), Carangidae (jacks, pompanos; eight species), and Sparidae (porgies, seven species). The Carcarhinidae and Gadidae were not recorded by IUCN to have received conservation effort despite being of high socioeconomic value; however, for the Gadidae, this may be inaccurate given several known fisheries management measures that are in place. The Gadidae thus represent one group with regional protective legislation that might not have been recorded in the IUCN database (see Section 2.4.5). Conservation efforts directed toward marine species included restrictions on commercial fisheries (i.e., size and harvest limits; 32%,

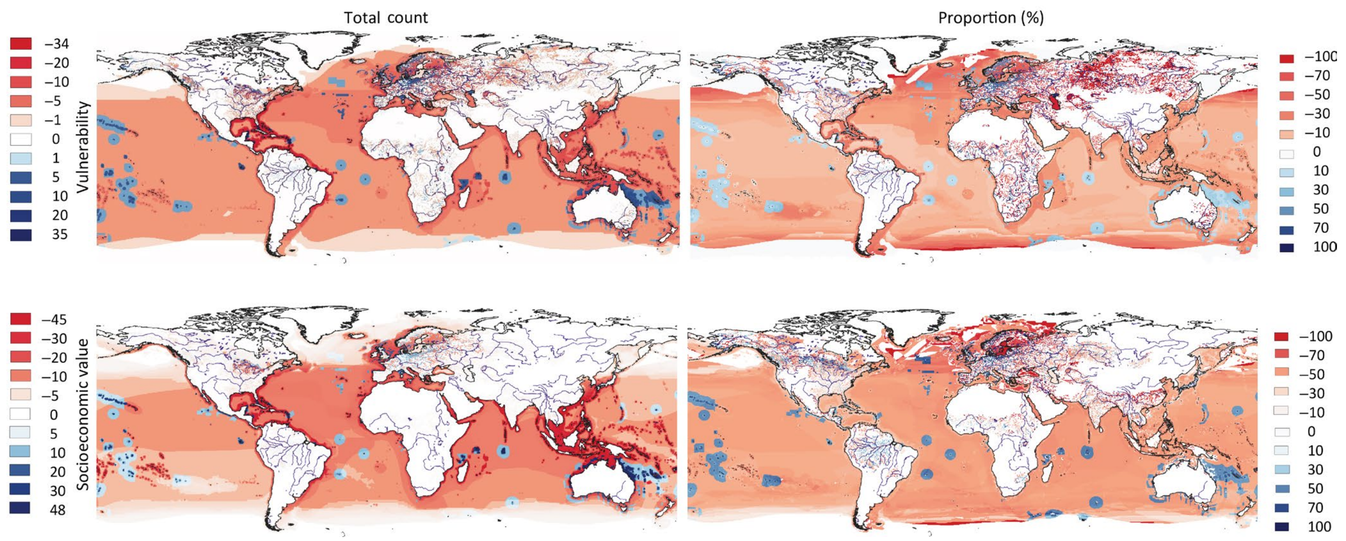

FIGURE 5 Bivariate maps showing total counts and percent of vulnerable species that are covered by protected areas. Regions with protected areas are positive (blue) and regions without protected areas are negative (red), with increasing intensity of color for increasing concentrations of species vulnerability. Dark red areas represent regions of conservation concern [Colour figure can be viewed at wileyonlinelibrary.com]

n = 77) and species-specific initiatives (16%, *n* = 39). Freshwater species that benefit from conservation efforts included the cyprinids, shark catfish, and temperate perch (Table 2; Figure 4d). However, conservation efforts for freshwater fish were quite low. For example, the Cichlidae had few conservation efforts in place despite being both highly vulnerable and of high socioeconomic value. In addition, 27% of recreational freshwater fish were labeled “not of concern” in the IUCN conservation effort data. Of all freshwater fish, five species (4%) had breeding programs and four (3%) had harvest or catch restrictions. Diadromous families that benefit from conservation effort included the Anguillid eels, sturgeon (Table 2; Figure 4d), and the Mugilidae (mullet, two species). Conservation efforts for diadromous fishes included harvest and size limits for commercial fisheries (17%, *n* = 8), construction of fish passages on dams (11%, *n* = 5), and breeding programs (11%, *n* = 5).

3.5 | Regions of vulnerability, socioeconomic value, and conservation effort

3.5.1 | Climate change vulnerability

Based on total counts, vulnerable recreational fish species were concentrated in marine areas with coral reefs and mangroves (Figure 3a), such as the Gulf of Mexico, the Caribbean Sea, and the northern and eastern coasts of South America. Other regions of concern included the Coral Sea (i.e., the Australian Great Barrier reef), the Philippine Sea, and the Banda Sea (Indonesia). Freshwaters contained a lower density of vulnerable recreational fish by total count, with the only notable regions of concern being the northern European river drainages (the Danube, Rhine, Seine, Elbe, and Volga).

These patterns shifted when examined by percentage (Figure 3a). Vulnerable marine areas included the polar regions, and the Labrador and Norwegian Seas. Freshwaters (and inland seas) with high proportions of vulnerable species included the major Russian river basins (the Ob, Yenisei, and Lena), the Black and Aral Seas, the Tigris/Euphrates basin, inland water bodies across Spain, the Murray–Darling River basin in Australia, and the Orange and Zambezi drainages in Africa. Rivers in northern Europe also contained high proportions of vulnerable freshwater fish (Figure 3a).

Patterns for total counts of vulnerability intensified with year (2030, 2075), RCP (4.5, 8.5), threshold (15%, 25%, 35%), and scenario (lenient, strict), but regional patterns were not drastically altered (Supplementary Results, Table S1; Figures S3–S8). When examined by percentage, the year, RCP, and threshold did not change vulnerability patterns; however, under the strict scenario, new vulnerable regions were highlighted, including freshwater bodies throughout India, Southeast Asia, South America, and Canada (Supplementary Results, Figure S8).

3.5.2 | Socioeconomic value

Recreational fishes with high socioeconomic value were concentrated primarily in marine regions (Figure 2a). Key regions included the Philippine Sea, the Banda, Timor, and Coral Seas, coastal regions of the South Pacific Ocean, the East African and Malagasy coasts, the Gulf of Mexico, and the Caribbean Sea. Patterns shifted when based upon percentages (Figure 3a), with high concentrations of socioeconomically valuable species in the Labrador and Norwegian seas, the Bay of Biscay, and the Mediterranean Sea. For freshwaters, regions with high proportions included the Caspian Sea, northern Scandinavia, the Tigris/Euphrates basin, inland water bodies across Spain, the Yangtze River, and the Ganges/Brahmaputra and Indus Rivers in India. Inland water bodies in northern Canada and Alaska (USA) also had notable proportions of high socioeconomic value species.

3.5.3 | Conservation effort

Regions that benefit from conservation effort included the Gulf of Mexico, the Caribbean Sea, and the northern and eastern coasts of South America. Other regions included the Philippine Sea, the Banda, Timor, and Coral Seas, coastal regions of the South Pacific Ocean, and coastal northwestern Africa. By percentage, regions with high concentrations of species with conservation effort included the North and South Atlantic Oceans, the polar regions, the Labrador and Norwegian Seas, and the North Pacific Ocean. For inland waters, regions included the Murray–Darling River, inland waters of New Zealand and Japan, and rivers in northern Europe.

3.6 | Protected areas and climate change vulnerability

Regions with PAs that also contain high numbers of species vulnerable to climate change included the inland waters of northern Europe, many of the small island developing states (SIDS) in the South Pacific and Indian Oceans, and the Australian Great Barrier Reef (GBR). Areas with many vulnerable species in need of PAs included the Gulf of Mexico, the Caribbean Sea, the Philippine seas, and the Banda Sea. Regions with PAs and high proportions of vulnerable species included northern Europe. Inland zones that require additional protection due to a high proportion of vulnerable species included the Russian river basins, the Aral and Black seas, the Ganges River, and some African river basins (Figure 5).

For socioeconomic value, total counts of species showed similar patterns to vulnerability. In terms of the proportion of vulnerable species, additional protection is needed in the Bay of Biscay, the Mediterranean and Caspian seas, and the major southern and eastern Asian rivers (Indus, Ganges, Brahmaputra, Yangtze). Regions where many species of high socioeconomic value received conservation effort included inland zones of North America, the Amazon basin, northern Europe, and Japan (Figure 5), along with several marine regions (i.e., SIDS, GBR).

3.7 | Patterns among life-history groups in vulnerability, socioeconomic value, and conservation effort

The analysis of variance of climate change vulnerability, socioeconomic value, and conservation effort among life-history groups showed that marine fishes had lower vulnerability than freshwater and diadromous fishes (ANOVA: $F_{(df)} = 99.5_{(2,412)}$, $p < 0.0001$; Figure 6a; Table 3), that freshwater fishes had lower socioeconomic value than marine and diadromous species (ANOVA: $F_{(df)} = 19.9_{(2,412)}$, $p < 0.0001$; Figure 6a; Table 3), and that diadromous fish had the highest conservation effort followed by marine and freshwater species (ANOVA: $F_{(df)} = 35.2_{(2,412)}$, $p < 0.0001$; Figure 6a; Table 3). These findings were similar to the proportional trait analysis (Figure 3b).

The PCA analysis extracted two components with eigenvalues >1 (Table 4), which explained 37.2% and 33.3% of the variance in vulnerability, socioeconomic value, and conservation effort, respectively. Socioeconomic value and conservation effort loaded onto PC1 and vulnerability loaded onto PC2 (Table 4; Figure 3b). Scatterplots

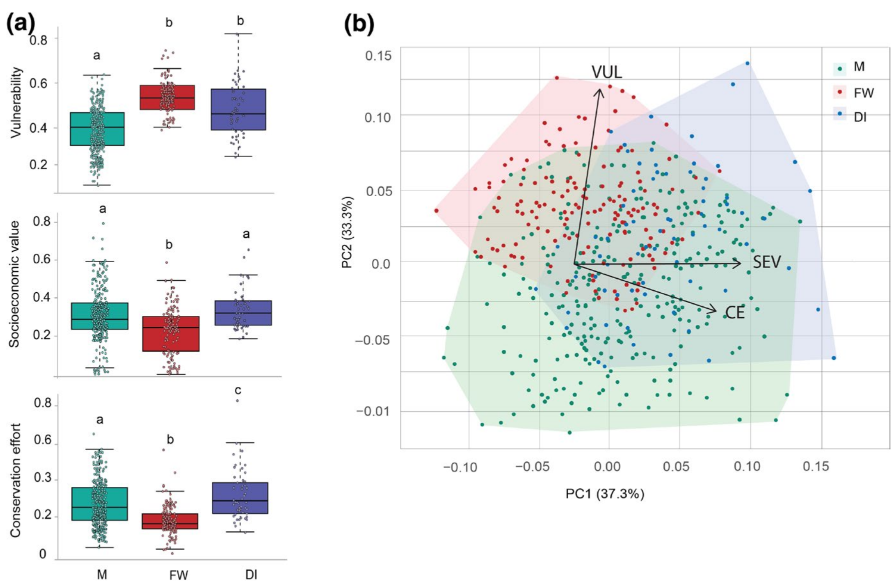

FIGURE 6 Continuous index analyses. (a) Results of ANOVAS exploring differences in climate change vulnerability, socioeconomic value, and conservation effort among marine (M), freshwater (FW), and diadromous (DI) fish. Box plots show the 25th, 50th, and 75th quantiles, and bars represent standard errors. Raw species scores are overlaid with each box. Letters indicate significant differences among groups at $p < 0.01$. (b) PCA biplot showing associations among eigenvectors of vulnerability (VUL), socioeconomic value (SEV), and conservation effort (CE). Each dot represents a species within our dataset. Shaded areas are minimum convex polygons surrounding all data points for marine (M), freshwater (FW), and diadromous (DI) species [Colour figure can be viewed at wileyonlinelibrary.com]

Group	n	Socioeconomic value		Vulnerability		Conservation Effort	
		mean	sem	mean	sem	mean	sem
Marine	245	0.308	0.009	0.395	0.007	0.273	0.008
Freshwater	123	0.228	0.011	0.540	0.006	0.180	0.007
Diadromous	47	0.346	0.018	0.486	0.017	0.320	0.020

TABLE 3 Sample sizes (n), means, and standard errors (sem) for continuous indices calculated from multi-criteria decision analysis. Indices range from 0 (minimum value) to 1 (maximum value)

TABLE 4 PCA results. Eigenvalues, percent variance explained, and correlation of each index on the components extracted in the PCA analysis. Indices are socioeconomic value (SEV), climate change vulnerability (VUL), and conservation effort (CE)

	PC1	PC2
Eigenvalue	1.057	1.020
% Variance	37.2	33.3
SEV	0.691	−0.206
VUL	0.146	0.976
CE	0.707	−0.0001

revealed that marine and diadromous species tend to be associated with socioeconomic value and conservation effort, whereas freshwater and diadromous species extend along the vulnerability axis.

For marine fishes, only eight species that were considered climate change vulnerable were without any form of conservation effort (19% of all vulnerable marine species). Freshwater fishes had 26 vulnerable species with no conservation effort (72% of all vulnerable freshwater species), and six of these species were also of high socioeconomic importance. For diadromous fish, six vulnerable species had no conservation effort (50% of all vulnerable diadromous species), four of which are of high socioeconomic importance. A complete list of species included in this assessment along with their overall scores for vulnerability, socioeconomic value, and conservation effort is presented in Table S2.

4 | DISCUSSION

4.1 | Summary, caveats, and considerations

This analysis revealed that marine fishes had the highest total number of species that are vulnerable to climate change, but that freshwater fishes had higher proportions of threatened species. A key pattern was that current conservation effort focused primarily on fishes of high socioeconomic value and tended to overlook freshwater fishes that were predicted to be the most vulnerable. However, there are several key considerations and caveats that must be mentioned to guide interpretation of these findings. *First*, given that this study covers a large number of species at a global scale, our scoring method (i.e., binary scores with thresholds) is necessarily coarse compared to techniques that can be applied at finer scales (Foden et al., 2018). Although steps were taken to mitigate sources of uncertainty (i.e., GCM averaging, scenario analyses for binary scores, comparison of binary scores with continuous indices), it is important to recognize that the findings presented are forecasts of plausible future vulnerability patterns rather than precise predictions of outcomes. The binary scoring system generates *relative* vulnerability, conservation effort, and socioeconomic scores that can be used to highlight regions and species of concern, and to compare marine, freshwater, and diadromous fishes. However, the conclusion that some regions or life-history groups are more threatened or more vulnerable or require more conservation attention is not to suggest that the other areas or groups are *not* vulnerable or *do not* require conservation attention. It simply provides a system of comparison among the groups. *Second*, although we had high data availability (69–100%), there are likely to be regional or taxonomic biases in reporting toward well-studied species from developed countries. This is particularly true for traits with larger data gaps such as rarity and population trajectory and could lead to overestimation of high scores for taxa from these regions. *Third*, the different climate change thresholds (i.e., 15, 25, 35%), RCPs (4.5, 8.5), and scoring scenarios (strict vs. lenient) generated varying evaluations of species of concern. Although 75% of scenarios showed similar vulnerability patterns in when comparing marine, freshwater, and diadromous species (Figure S18), several of the scenarios based on RCP4.5 projected marine fishes to have higher proportions of vulnerable fish than freshwater and diadromous. This suggests that by adhering to policies that reduce emissions, we might lessen the relative vulnerability of freshwater fish and should concentrate effort on protection of vulnerable marine regions. Environmental managers and decision-makers are encouraged to consider the variations that arise from these analyses instead of only focusing on the scenario presented in the main text. This can be done by examining the figures in the supplementary results to compare vulnerable regions across scenarios. In addition, the raw species data and spatial vulnerability data for this study are available online (Nyboer, 2021) and can be consulted for such comparisons and for local or regional decision-making (see further details in Section 4.4, below). *Fourth*, data on conservation effort from the IUCN Red List included detailed descriptions of various conservation practices implemented for each species. Although we found 70% agreement between the IUCN data and fish listed in international species protection acts, we did note that some species with fisheries management measures (e.g., Atlantic cod, *Gadus morhua*, and Pacific salmon, *Oncorhynchus spp.*) were not recorded by the IUCN assessment. This indicates that there may be some inconsistency between the conservation efforts listed by IUCN and conservation efforts that have been implemented. These discrepancies were most prevalent for diadromous species (primarily salmonids) and were otherwise equally distributed among marine and freshwater fishes. Although we accounted for this uncertainty by using an area-based approach (i.e., with WDPA data), it is important to recognize that MPAs do not necessarily equate to protection for marine fish given that regulations and enforcement of MPAs are not always effective. We encourage managers and decision-makers to consult local or regional databases to account for any conservation measures that may have been overlooked, and to check local MPA guidelines and enforcement. Despite these considerations, the results of this global assessment offer a big-picture examination of vulnerability patterns of an extremely valuable resource base, highlight the need for conservation effort on freshwater and diadromous fishes, and provide insight into where protection should occur on a global scale to guide future efforts.

4.2 | Vulnerability patterns among life-history groups

Our results revealed proportionately higher vulnerability among freshwater and diadromous species compared to marine fish. Freshwater fish have smaller ranges and restricted dispersal capacity, and distribution shifts are not always possible. Climate change can lead to alterations in community composition as some species fare better under novel environmental conditions than others (Lynch et al., 2016). Such shifts can destabilize the ecological balance in systems and threaten the long-term resilience of stocks (Winfield, 2016). If climatic changes are more extreme, a singular catastrophic event can drive land-locked freshwater populations to extinction (Leitão et al., 2016). Freshwater fishes were also shown to have disproportionately high exposure to anthropogenic threats, which can negatively affect their ability to adjust to additional stressors (Xenopoulos et al., 2005). Important stressors for freshwater recreational fishes that interact with climate change include invasive species, water pollution, overexploitation (Lynch et al., 2016), and altered flow regimes (Comte & Grenouillet, 2015), and this complexity makes extinction risk of freshwater fishes difficult to predict or quantify (Olden et al., 2007). The cumulative effects of climate change and other stressors may lead to the decline in or extinction of freshwater species (Heino et al., 2009).

Diadromous fish are highly vulnerable to climate change because they must cope with climate-related stressors in both marine and freshwater locations (McDowall, 1992). This group has highly varied and specialized life-history patterns, often completing difficult migrations and relying upon specific microhabitats and environmental triggers. Coping with climatic stressors during these periods can increase their vulnerability (Lin et al., 2017; Runge et al., 2014). Shifts in the timing of seasonal migrations or spawning events have been documented in several species (Crozier & Hutchings, 2014; Kovach et al., 2015). Unfortunately, altered behaviors to accommodate temperature shifts can be maladaptive (Crozier & Hutchings, 2014); for example, if species' phenological shifts put them out of sync with the rhythms of their primary food sources (Kharouba et al., 2018).

Marine species were proportionally the least vulnerable due to their large range sizes and high dispersal capacity. Poleward range shifts of several marine recreational fishes have been documented with changing environmental conditions (Hollowed et al., 2013; Pecl et al., 2017; Poloczanska et al., 2013). For example, North Sea plaice and whiting have shifted their distributions northward by ~5–15 m per decade since 1980 to escape warming ocean temperatures (Dulvy et al., 2008). However, there will be limits to this expansion and different subpopulations of the same species may not have the same capacity to disperse (Pinsky et al., 2020). In addition, several marine recreational species are tightly linked to climate-sensitive habitats (e.g., coral reefs) for at least a portion of their life cycle. Such species will be at high risk because of temperature-induced physiological effects (Pratchett et al., 2017) and because the habitats are themselves vulnerable to climate change (Hoegh-Guldberg et al., 2017). In many coastal regions, the growing impacts of anthropogenic stressors (e.g., hypoxia, habitat loss, pollution, overharvesting) can result in multiple pressures on fish species, particularly for those that occupy heavily impacted ecosystems (Arthington et al., 2016) and for larger bodied fish (Olden et al., 2007). In addition, marine species face high mortality due to bycatch and high levels of illegal, unreported, and unregulated (IUU) fishing in the commercial sector (FAO, 2016).

4.3 | Regional patterns of vulnerability to climate change

Our analysis revealed higher proportional concentrations of vulnerable species in polar marine and freshwater regions. Polar regions have high proportions of vulnerable fish because of faster rates of warming in these zones (Masson-Delmotte et al., 2006), and because stenothermal polar fishes are more sensitive to temperature change than their temperate counterparts (Peck et al., 2014; Sandersfield et al., 2017). Vulnerable freshwater regions (e.g., northern European rivers, Murray–Darling River, Orange and Zambezi Rivers) are all heavily impacted systems that have been altered by dams, exposed to invasive species, and impacted by urban, agricultural, and forestry effluent (Balcombe et al., 2011; Grafton et al., 2013; Schmutz et al., 2016; Tumbare, 2004).

Total counts of vulnerable fish were highest in coastal environments in the tropics, primarily because these regions are dominated by climate change-sensitive habitats such as coral reefs, mangroves, and estuaries (Adams & Murchie, 2015; Hoegh-Guldberg et al., 2017; Robins et al., 2016). Coral bleaching and declines in structural complexity can reduce fish abundance and alter reef fish assemblages (Pratchett et al., 2018). Such changes were traditionally thought to have the largest effect on localized, small-bodied fish; however, recent evidence has shown that larger bodied species can be equally threatened (Pratchett et al., 2017). Coral-dependent species are likely to experience range contractions as ocean temperatures rise (Hoey et al., 2016). Similarly, 40% of species in this study rely on estuaries during juvenile or reproductive stages during which vulnerability to climate change is thought to be highest (Pörtner & Farrell, 2008; Rijnsdorp et al., 2009). While the geographic location of coral reefs is predicted to be static (Hoegh-Guldberg et al., 2017), mangrove forests have been shown to opportunistically expand and contract range limits in response to temperature changes (Cavanaugh et al., 2018). Understanding such shifts (or lack thereof) can be used to anticipate how changing climatic conditions will impact fish movement and distribution (Osland et al., 2017). Changes to habitat availability and shifting species distributions are projected to reduce commercial fishery productivity in tropical regions by ~10%–30% by 2050 (Cheung et al., 2016); these patterns will likely be mirrored in the availability of recreational fish.

4.4 | Relating vulnerability and socioeconomic value to conservation effort

4.4.1 | Life-history groups

Conservation effort often coincided with socioeconomic value, leaving some vulnerable species omitted from conservation plans. Such biases are common in conservation. For example, from 1998 to 2012, most spending in the US Endangered Species Act went to only 15 economically important fish species (Evans et al., 2016). Conservation effort also tends to focus on well-studied species (Trimble & VanAarde, 2010), and research efforts are generally higher for marine fish compared to freshwater fish (Allen et al., 2005). Exemplifying these trends, nearly 25% of freshwater species in this study ($n = 30$) were classified as being of "low concern" in the IUCN conservation assessments, despite projections for high exposure to climate change. In contrast, nearly 35% of marine species ($n = 72$) *not* classified as vulnerable had high scores for conservation effort. Thus, species in need of conservation may be overlooked simply because there is too little information to formulate conservation plans.

Both marine and diadromous fishes had high scores in socioeconomic value and conservation effort. Many of the marine and diadromous species in this study are targets of valuable commercial fisheries (i.e., high socioeconomic value), and the conservation measures in place are often commercial harvest restrictions. MPAs are well-established and effective in increasing biodiversity and population sizes (Edgar et al., 2007; Topor et al., 2019) even though differences in management effectiveness and degree of fishing restriction are likely cause variation in their capacity to protect ecosystems (Edgar et al., 2014). Freshwater protected areas (FPAs) are less common (Suski & Cooke, 2007) and have had mixed success (Hermoso et al., 2016). The lack of effectiveness of FPAs has been attributed to insufficient resources directed to freshwater conservation (Thieme et al., 2012), supporting the trends found here. In addition, the results of the PCA showed that conservation effort and socioeconomic value loaded on the same axis, indicating correlation between these two indices. Surprisingly, the family-level analysis revealed that some freshwater (e.g., Cichlidae, Cyprinidae) and diadromous (e.g., Salmonidae) families have limited conservation measures in place (as recorded by IUCN) even though several species within these families are vulnerable to climate change and have high socioeconomic value. However, it should be noted that several species of Salmonid are recorded as having population-level protections in by Canada's SARA that were not noted in the IUCN database.

4.4.2 | Geographic regions

Of greatest conservation concern are regions that have high concentrations of vulnerable and socioeconomically valuable species that do not currently have PAs or other conservation measures in place. There is a need for increased protection of valuable recreational marine fisheries in the Gulf of Mexico, the Caribbean Sea, and the Banda Sea. The lack of protection in these regions as well as in several East Asian and African river basins is troubling given the highly valuable and climate change vulnerable species concentrated in these regions. Governance of recreational fisheries is poor in many parts of the world (Potts et al., 2020), and many of the countries overseeing these marine and freshwater systems are unable to devote sufficient financial resources to conservation (Lindsey et al., 2017). However, this problem persists elsewhere. For example, despite the high economic value of Canadian inland recreational fisheries (DFO, 2019) with established legislation for identifying species at risk (e.g., SARA), several "at-risk" species do not have conservation measures in place due in part to inadequate allocation of resources (Raymond et al., 2018). Effective management of recreational fisheries at a global scale is needed to reduce vulnerability.

4.5 | Management and conservation recommendations

Managing complex social–ecological systems such as recreational fisheries under climate change requires an adaptive approach to protect against predicted climatic changes and to account for unexpected shifts in the social or ecological landscape being managed (Arlinghaus et al., 2017; Laurenco et al., 2015; Paukert et al., 2016). Broad-scale CCVAs that combine climate change forecasts with predictions of fishes' responses can help to pinpoint where and why species are vulnerable, providing valuable information for guiding conservation interventions (Foden et al., 2013). Efforts should be focused on regions where there are the most or the highest proportion of vulnerable species, taking into consideration the locations of species or families with no protections in place.

Recreational fisheries require monitoring to determine stock status and to track the success of current conservation efforts (Paukert et al., 2016). Except the strictest no-take zones, the management of several PA types like National Parks may allow different levels of recreational fishing (Alic et al., 2021). Nevertheless, allowing recreational fishing activities without monitoring stock dynamics over time could neglect the effects of fishing and other stressors such as climate change. This study helps managers and stakeholders identify vulnerable species and areas that may require monitoring studies across waters within and beyond existing PAs. This is particularly important for the nascent recreational fisheries in developing countries where projected impacts are highly uncertain (Jimenez-Cisneros et al., 2014). Recreational fishing is emerging as an important industry in the inland waters across Africa (Weyl et al., 2007), Brazil (Freire et al., 2012), India (Gupta et al., 2015), and Southeast Asia (Coates et al., 2002), and this analysis showed that target species in these regions may be at risk from climate change. As the recreational fishing industry develops, it will be essential to ensure that monitoring and other adaptive management protocols are in place. Next steps for local-scale analyses would involve paring down the data to just those species that are relevant to a given region, updating trait information (e.g., population trajectory) as it applies to the local population, and selecting species to prioritize for protection or management from that pared-down list. Likewise, the spatial data from this study (Nyboer, 2021) can be used to compare vulnerability patterns among emission scenarios for a given region of interest. Specific conservation or protection plans can consider the climate change impacts likely to emerge for the most vulnerable species.

Understanding how recreational fish and fisheries are likely to be impacted by climate change can mean reinventing current management approaches for both freshwater and marine habitats (reviewed in Paukert et al., 2016) and there are growing examples of cases where management actions do account for climate change (Jeanson et al., 2021). Instead of practices that focus on one population in a specific location, the goal should be to maintain a diversity of species and a heterogeneous age structure that can improve resilience under various climate scenarios (Cowx et al., 2010; Hansen et al., 2015). Making decisions about protecting recreational fisheries under climate change requires a strong emphasis on the social aspect of recreational fisheries (Arlinghaus et al., 2017; Camp et al., 2020; Hunt et al., 2016). Climate change can alter fishers' behavior and exploitation patterns, which can in turn affect fish populations and fisheries management decisions (Lewin et al., 2006). Applied research should focus on understanding the highly varied motivations of recreational fishers, and how fishers adapt to climate-related changes to recreational fisheries (Mackay et al., 2018; Townhill et al., 2019).

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data have been made publicly available on the OSF platform and have been cited in the text.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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