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A collaborative climate vulnerability assessment of California marine fishery species

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Abstract

Climate change and the associated shifts in species distributions and ecosystem functioning pose a significant challenge to the sustainability of marine fisheries and the human communities dependent upon them. In the California Current, as recent, rapid, and widespread changes have been observed across regional marine ecosystems, there is an urgent need to develop and implement adaptive and climate-ready fisheries management strategies. Climate Vulnerability Assessments (CVA) have been proposed as a first-line approach towards allocating limited resources and identifying those species and stocks most in need of further research and/or management intervention. Here we perform a CVA for 34 California state-managed fish and invertebrate species, following a methodology previously developed for and applied to federally managed species. We found Pacific herring, warty sea cucumber, and California spiny lobster to be three of the species expected to be the most sensitive to climate impacts with California halibut, Pacific bonito, and Pacific hagfish expected to be the least sensitive. When considering climate sensitivity in combination with environmental exposure in both Near (2030–2060) and Far (2070–2100) Exposure climate futures, red abalone was classified as a species with Very High climate vulnerability in both periods. Dungeness and Pacific herring shifted from High to Very High climate vulnerability and Pismo clam and pink shrimp shifted from Moderate to Very High climate vulnerability as exposure conditions progressed. In providing a relative and holistic comparison of the degree to which state-managed marine fishery species are likely to be impacted as climate change progresses, our results can help inform strategic planning initiatives and identify

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attribute plots, and aggregated scoresheets (with revisions initiated by CDFW subject matter experts highlighted)) has been uploaded to the following Github repository: https://github.com/thfrawley/California_State_CVA.

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where gaps in scientific knowledge and management capacity may pose the greatest risk to California's marine resource dependent economies and coastal communities.

1. Introduction

Climate change is affecting marine ecosystems worldwide with impacts on embedded species and dependent livelihoods expected to intensify in the coming decades [1,2]. Rising ocean temperatures, acidification, deoxygenation, and changes in ocean circulation and productivity are altering the distribution, phenology, abundance, and ecological interactions of marine species [3–6]. To effectively manage marine species in the face of climate change, it is critical to understand which species and ecosystems are most vulnerable [7,8].

Assessing the climate vulnerability of marine species is an important step in prioritizing limited resources for management, research, and conservation [9] and in adding new context to existing assessments of fisheries management performance [10]. Climate vulnerability assessments (CVA) provide a framework for systematically evaluating the exposure, sensitivity, and adaptive capacity of species to projected changes in climate and ocean conditions [11–13]. These assessments rely on information about species life history, ecology and future climate scenarios, but do not consider current fishing effort and practices or management strategies. As a result, CVAs are not designed to assess current stock status; instead, they indicate future vulnerability to environmental change. Consequently, currently productive and/or sustainable fisheries could rank as having high vulnerability (depending on the nature and extent to which they are likely to be impacted by projected environmental change), while fisheries in decline could rank as having low vulnerability. Several recent studies have conducted CVAs for federally managed fish and invertebrate species in different U.S. regions, including the Northeast Shelf [9], the California Current [14,15], the Bering Sea [16], and the Pacific Islands [17] in addition to a recent assessment of marine mammals in the greater Atlantic Ocean [18]. These assessments leverage expert opinion and available scientific information to rank the relative vulnerability of species and identify key risks.

In the United States, marine fisheries management is divided between federal and state agencies. The National Oceanic and Atmospheric Administration (NOAA) tends to have jurisdiction over fisheries in federal waters, which extend from 3–200 nautical miles offshore, and is therefore responsible for managing commercially important species such as some groundfish, coastal pelagics, and highly migratory species. In California, the Department of Fish and Wildlife (CDFW) manages commercial and recreational fisheries in state waters, including important fishery species like Dungeness crab (*Metacarcinus magister*), spiny lobster (*Panulirus interruptus*), market squid (*Doryteuthis opalescens*), and red sea urchin (*Mesocentrotus franciscanus*). CDFW also manages many nearshore fish and invertebrate species that are not harvested but are key components of coastal ecosystems.

While the vulnerability of federally managed species to climate change has been assessed in several regions including the California Current System Large Marine Ecosystem (CCLME), the vulnerability of state-managed species in California has not been comprehensively evaluated to date. Many species of significant economic and cultural importance to California stakeholders remain unassessed, while those that have (i.e., jacksmelt (*Atherinopsis californiensis)*, market squid, and Pacific herring (*Clupea pallasii*)) were evaluated using broad geographic extents (i.e., the entire California Current system rather than CA state waters) of limited relevance to local resource access. As such, additional information is needed to help CDFW and

Table 1. List of the subset of California state managed fishery species analyzed in this study. Annual commercial landings and value figures represent the statewide annual average between 2000 and 2019 (data obtained from [20]), with annual values adjusted for inflation using 2015 as a base. Weight and value only shown for species reporting associated information in > 75% of years.

Functional Group	Species	Scientific Name	Average Commercial CA Landings (Tons)	Average Commercial CA Landings (Value)
Benthic	Pink shrimp	*Pandalus jordani*	1,948	2,186,022
	Dungeness crab	*Metacarcinus magister*	8,283	45,314,654
	Giant red sea cucumber	*Apostichopus californicus*	73	367,528
	Kellet's whelk	*Kelletia Kelletii*	51	85,938
	Pacific geoduck clam	*Panopea generosa*	-	-
	Pismo clam	*Tivela stultorum*	-	-
	Red abalone	*Haliotis rufescens*	-	-
	Red sea urchin	*Mesocentrotus franciscanus*	5,095	8,972,985
	Ridgeback prawn	*Sicyonia ingentis*	207	877,783
	Rock crabs	*Cancer productus, Metacarcinus anthonyi, and Romaleon antennarium*	505	813,111
	California spiny lobster	*Panulirus interruptus*	385	10,704,472
	Spot prawn	*Pandalus platyceros*	181	4,547,020
	Warty sea cucumber	*Apostichopus parvimensis*	115	624,008
Demersal	Barred sand bass	*Paralabrax nebulifer*	-	-
	Barred surfperch	*Amphistichus argenteus*	17	25,208
	Brown smoothhound shark	*Mustelus henlei*	1	2,310
	California sheephead	*Bodianus pulcher*	42	403,267
	California corbina	*Menticirrhus undulatus*	-	-
	California halibut	*Paralichthys californicus*	310	2,870,296
	Kelp bass	*Paralabrax clathratus*	-	-
	Ocean whitefish	*Caulolatilus princeps*	3	17,393
	Pacific angel shark	*Squatina californica*	9	24,776
	Pacific hagfish	*Eptatretus stoutii*	461	746,838
	Redtail surfperch	*Amphistichus rhodoterus*	7	19,410
	Shiner perch	*Cymatogaster aggregata*	<1	1,343
	Spotted sand bass	*Paralabrax maculatofasciatus*	-	-
	White croaker	*Genyonemus lineatus*	36	65,299
Midwater	Pacific barracuda	*Sphyraena argentea*	28	44,553
	Jacksmelt	*Atherinopsis californiensis*	11	16,463
	California market squid	*Doryteuthis (Loligo) opalescens*	76,442	43,903,815
	Night smelt	*Spirinchus starksi*	139	133,250
	Pacific bonito	*Sarda chiliensis*	445	312,568
	Pacific herring	*Clupea pallasii*	1,398	1,012,619
	White seabass	*Atractoscion nobilis*	172	1,051,768

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other ocean managers anticipate and mitigate climate impacts through the development of adaptive management strategies. Here we conduct a collaborative, trait-based CVA for marine species managed by CDFW. We evaluate the sensitivity and exposure of 34 fish and invertebrate focal species (Table 1) to projected changes in ocean conditions in California waters over two future periods to assess climate vulnerabilities in the Near future (2030–2060) and in the Far future (2070–2100). By identifying relative vulnerabilities across this set of diverse species, we aim to provide a foundation for integrating climate change into CDFW management and research priorities. Our approach builds on recent methods for rapid climate vulnerability assessment [9,19] while tailoring the process to a state-managed context where information concerning stock status and life history parameters may be comparatively scarce [10].

2. Methods

2.1 Study system

The California coastal ocean is shaped by its inclusion in one of the world's major Eastern Boundary Upwelling Systems. Coastal upwelling that has historically peaked in spring-summer produces cold, nutrient-rich, and productive waters near the coast. These waters support a diverse ecosystem characterized by vibrant kelp forests, rocky reef communities and pelagic communities, with high abundance of coastal pelagic (i.e., forage fish and market squid) and highly migratory species [21,22]. At the same time, these upwelled waters are relatively acidic and low in oxygen [23]. On interannual to decadal timescales, basin-scale modes of climate variability such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) impart strong variability across the region. This variability can mask long-term trends over shorter time periods, effectively delaying the "time of emergence" of anthropogenic influence for some variables [24]. For example, a shift from positive to negative PDO between the mid-1980s and ~2010 produced a multi-decadal cooling trend in the California Current System [25], temporarily obscuring the longer-term warming trend. Though ecosystem changes induced by ENSO and PDO offer important insight into mechanisms that may shape species' responses to future climate change [26] they are not perfect proxies for future change. Lessons from species responses to past variability must be translated to the novel set of environmental conditions expected in the future [27].

2.2 Selection & profile preparation of species

In total, this CVA considered a subset of 34 state-managed fishery species, selected in consultation with participating research partners based across the state of California (i.e., the California Department of Fish & Wildlife, NOAA Southwest Fisheries Science Center, the California Ocean Protection Council, and the Nature Conservancy). Species were selected based on a) their interest to California stakeholders; and/or b) whether or not they had been included in previous CVAs. All species occur along the California coast (**Fig 1**), found in portions of coastal waters between the California-Mexico border (32.5˚ N, -117.1˚ E) north to the California-Oregon border (42.0˚ N, -124.2˚ E). The species represent a wide range of life-history traits and habitat associations while being managed using diverse strategies. For example, some species are managed using a formal Fishery Management Plan while other species are managed with less investment (using Enhanced Status Reports (ESR), see below). The species assessed include the 11 most valuable state-managed commercial fisheries: California spiny lobster, red sea urchin, Dungeness crab, California market squid, California halibut (*Paralichthys californicus*), spot prawn (*Pandalus platyceros*), Pacific hagfish (*Eptatretus stoutii*), pink shrimp (*Pandalus jordani*), rock crabs (*Cancer spp*., *Romaleon spp*.), white seabass (*Atractoscion nobilis*), and warty sea cucumber (*Apostichopus parvimensis*). The other 23 species are of key interest to state managers and stakeholders, with many supporting culturally significant and economically productive recreational fisheries across the state. They include 15 bony fishes (California sheephead (*Bodianus pulcher)*, barred sand bass (*Paralabrax nebulifer)*, barred surfperch (*Amphistichus argenteus)*, California corbina (*Menticirrhus undulatus)*, jacksmelt, kelp bass (*P. clathratus)*, night smelt (*Spirinchus starksi)*, ocean whitefish (*Caulolatilus princeps)*, Pacific

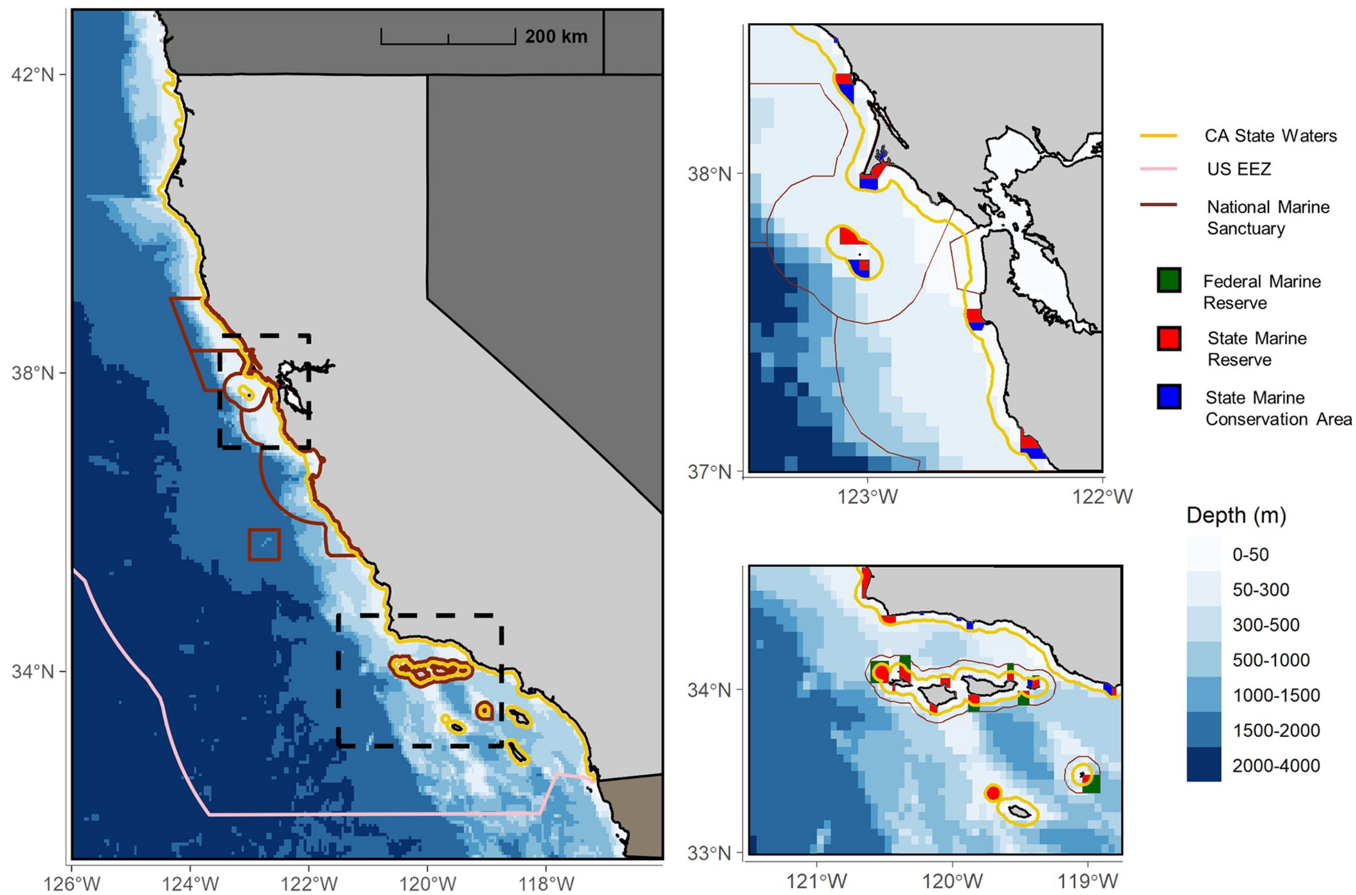

Fig 1. California state-managed waters within the California current large marine ecosystem (as defined by Alexander [28]). The 3 nautical mile (nm) boundary delineating state and federal waters is shown in gold. The boundaries of National Marine Sanctuaries are outlined in maroon while, in the inset (i.e., dotted black line) panels, Marine Protected Areas nested within the 3 nm boundary are shown in green (Federal Marine Reserves), red (State Marine Reserves), and blue (State Marine Conservation Areas). State (i.e., within the 3 nm boundary) and Federal Marine Reserves restrict all commercial and recreational activities while State Marine Conservation Areas have narrower restrictions intended to meet specific conservation goals.

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barracuda (*Sphyraena argentea)*, Pacific bonito (*Sarda chiliensis)*, Pacific herring, redtail surf-perch (*A. rhodoterus)*, shiner perch (*Cymatogaster aggregata)*, spotted sand bass (*P. maculatofasciatus)*, white croaker (*Genyonemus lineatus*); 2 shark species (brown smoothhound shark (*Mustelus henlei)*, Pacific angel shark (*Squatina californica*); and 6 invertebrate species (ridgeback prawn (*Sicyonia ingentis)*, giant red sea cucumber (*Apostichopus californicus)*, Kellet's whelk (*Kelletia kelletii)*, Pacific geoduck clam (*Panopea generosa)*, Pismo clam (*Tivela stultorum)*, red abalone (*Haliotis rufescens)* (**Table 1**). To facilitate synthetic and comparative analysis, all species were grouped into 3 functional groups (based on phylogeny and habitat characterization), defined as species believed to share like characteristics and/or the same ecological niche within a community [9,12].

These species were selected in consultation with CDFW and were limited to species for which an Enhanced Status Report (ESR) had been prepared. ESRs previously prepared by CDFW staff contained all the necessary biological, ecological, and physiological information to support the development of species profiles in this climate vulnerability analysis. Species profiles describe relevant sensitivity attribute categories (see below) and species distributions. ESR species distribution maps (accessible through CDFW Marine Species Portal; see https://marinespecies.wildlife.ca.gov/) were supplemented by map data available through the Ocean

Biodiversity Information System (OBIS) Mapper (see https://mapper.obis.org/). OBIS data are point occurrence data only; however, the US West Coast is well represented in OBIS through the inclusion of data from several ecosystem-wide surveys. Draft species profiles were reviewed by CDFW subject matter experts (i.e., the individuals or projects responsible for managing the species and authoring the ESRs upon which each species profiles was based), and where appropriate, were corrected and/or modified (i.e., providing additional information and citations) prior to being employed in the scoring process described below.

2.3 Biological sensitivity attributes

Sensitivity is a measure of the biological attributes indicative of the ability (or inability) of species to respond to environmental change [9,19]. We used the same twelve biological and life history sensitivity attributes described in the NOAA climate vulnerability assessment methodology [9,19] to assess sensitivity to climate change (**Table 2**). These include Habitat Specificity, Prey Specificity, Adult Mobility, Dispersal of Early Life History Stages, Early Life History Survival and Settlement Requirements, Complexity in Reproductive Strategy, Spawning Cycle, Sensitivity to Temperature, Sensitivity to Ocean Acidification, Population Growth Rate.

Stock Size/Status, and Other Stressors. We considered both the direct and indirect impacts of climate change on these sensitivity attributes. For example, to assess species' Sensitivity to Ocean Acidification we considered the direct impacts of decreasing ocean pH levels on an organism as well as if acidification negatively impacted key prey species (thereby having an

Table 2. List of the twelve sensitivity attributes used in this study (adapted from Morrison et al., 2015 [19]). See Appendix I for the scoring rubric for each sensitivity attribute.

Sensitivity Attribute	Goal	Low Score	High Score
1. Habitat Specificity	To determine if the stock is a habitat generalist or habitat specialist while incorporating information on the type and abundance of key habitats	Habitat generalist	Habitat specialist
2. Prey Specificity	Evaluate the relative prey requirements (generalist or specialist) for a given species.	Prey generalist	Prey specialist
3. Adult Mobility	Evaluate the ability of a given species to move to a new location if their current location changes and is no longer favorable for growth and/or survival.	High mobility	Low mobility
4. Dispersal of Early Life Stages	Evaluate the ability of the stock to colonize new habitats as they become available.	High mobility	Low mobility
5. Early Life History Survival and Settlement Requirements	Evaluate the relative importance of early life history survival requirements for a given species.	Generalist with few requirements (definition from Hare et al., 2016 definition)	Specialist with specific requirements (definition from Hare et al., 2016)
6. Complexity in Reproductive Strategy	Evaluate how dependent reproductive success is on specific or complex environmental conditions.	Low complexity; broadcast spawning	High complexity; aggregate spawning
7. Spawning Cycle	Evaluate the duration of the spawning cycle and the potential for disruption of reproduction due to climate change.	Year-round spawning	One event per year
8. Sensitivity to Temperature	Evaluate the temperature tolerance of a given species; when unknown, breath of distribution may be used as a proxy.	Broad thermal limits	Narrow thermal limits
9. Sensitivity to Ocean Acidification	Evaluate a given species sensitivity to ocean acidification (OA); based on its relationship with "sensitive taxa." (Kroeker et al., 2013)	Insensitive taxa	Sensitive taxa
10. Population Growth Rate	Evaluate the relative productivity of a given species as a measure of its ability to rebound after a negative impact.	High population growth	Low population growth
11. Stock Size/Status	Evaluate the relative level of stress from fishing on a given species.	High abundance	Low abundance
12. Other Stressors	Evaluate the relative level of stress on a given species which could negatively impact its ability to respond to changes.	Low level of other stressors	High level of other stressors

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indirect impact on the assessed species). Note that many attributes were scored on the basis of multiple parameters described in the species profiles. For example, sensitivity attribute 10, Population Growth Rate, was assessed on the basis of each species' intrinsic rate of population increase (r), von Bertalanffy K coefficient, age at maturity, maximum age, and natural mortality rate. For each sensitivity attribute, a detailed scoring rubric was developed to help ensure consistency across species (**S1 Text**).

Note that while some CVAs consider adaptive capacity explicitly as a third component of vulnerability [15,29], in this assessment we have followed precedent established by the federal fisheries CVAs [9,14,16,19] in using sensitivity components which include adaptive capacity (i.e., dispersal, specificity of habitat and prey). This decision is based on the logic that a) many biological attributes contribute to both sensitivity and adaptive capacity, creating methodological difficulties in disentangling one from the other; and b) holistically assessing a diverse group of species with limited personnel within a short period of time necessitates some degree of simplification. Indeed, other vulnerability assessments have justified not including adaptive capacity at all for similar reasons [30,31]. While this combined approach may incompletely highlight the need for more research into adaptive responses or genetic adaptation [20] it does consider biological responses believed to mitigate climate impacts in the overall ranking and is considered sufficient in providing a foundation to guide future research and management response [9,32].

2.4 Climate exposure factors

Climate change exposure is a measure of the expected magnitude of change in the species' marine environment due to changing climate conditions. We use eight exposure factors to estimate the magnitude of change within a species' habitat range (**Table 3**); they are Sea Surface Temperature (SST), Sea Surface Salinity (SSS), Air Temperature at 2 meters (m), Precipitation, Surface pH (as a proxy for ocean acidification), Bottom Oxygen, Phenology of Upwelling, and Sea Level Change. We selected these factors because they were fully or partially used in previous CVAs for marine species in the California Current [14] and in the Northeast

Table 3. List of eight climate change exposure factors. Descriptions and background literature review adapted from [18]. Broadly speaking, low scores were assigned on the basis of low magnitude of change and high scores were assigned on the basis of high magnitude of change. See **S1 Text** for the scoring rubric for each exposure factor (presenting the individual, quantifiable metrics by which different exposure factor scores were assigned).

Exposure factor	Goal
Mean Sea Surface Temperature	Determine if there are changes in mean ocean surface temperature comparing 1990–2020, 2030–2060, 2070–2100 periods
Mean Sea Surface Salinity	Determine if there are changes in mean ocean surface salinity comparing 1990–2020, 2030–2060, 2070–2100 periods
Ocean Acidification (surface pH)	Determine if there are changes in mean ocean pH comparing 1990–2020, 2030–2060, 2070–2100 periods
Air Temperature (a proxy for nearshore ocean temperature)	Determine if there are changes in mean air temperature (a proxy for nearshore ocean temperature) comparing 1990–2020, 2030–2060, 2070–2100 periods
Mean Precipitation	Determine if there are changes in mean precipitation comparing 1990–2020, 2030–2060, 2070–2100 periods
Phenology of Upwelling (winds)	Determine if there are changes in the timing of upwelling comparing 1990–2020, 2030–2060, 2070–2100 periods
Subsurface Oxygen	Determine if there are changes in mean dissolved oxygen the comparing 1990–2020, 2030–2060, 2070–2100 periods
Sea Level Rise	Evaluate the magnitude of sea level rise relative to the change in habitat of the stock comparing 1990–2020, 2030–2060, 2070–2100 periods

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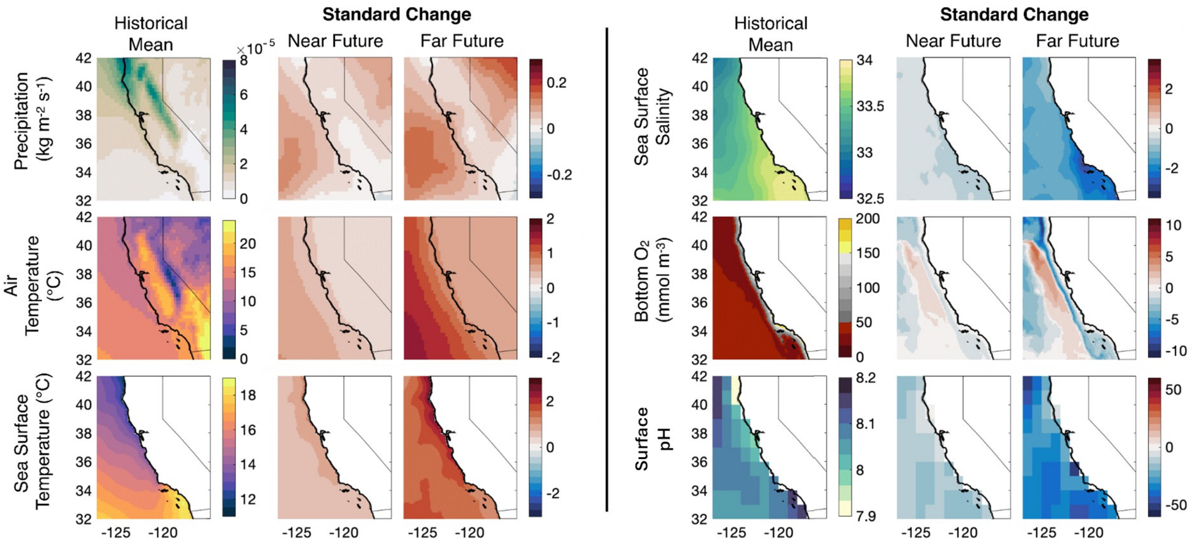

Fig 2. Historical mean (1990–2020, left) and standardized change in the near (2030–2060 relative to historical, center) and far (2070–2100 relative to historical, right) future for the climate change exposure factors: Precipitation, Air Temperature at 2 meters (m), Sea Surface Temperature, Sea Surface Salinity, Bottom Dissolved Oxygen, and Surface pH. Changes in Sea Level Rise and Phenology of Upwelling were assessed through separate mechanisms (see **S1 Text**) Note that while the assessment of exposure factors was limited to projected changes across California state waters within the 3 nm boundary (see **Fig 1**), the data displayed here covers a broader spatial extent to provide geographic context.

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US [9], respectively, and are expected to impact the species being considered. For all exposure factors we assessed change between a historical period (1990–2020) and two future periods: the Near future (2030–2060) and Far future (2070–2100). For each exposure factor, a detailed scoring rubric was developed to help ensure consistency in scoring across species (**S1 Text**). For all exposure factors except Sea Level Rise and Phenology of Upwelling, we obtained quantitative measures of projected change using the historical and future means, and historical standard deviation to calculate standardized change. Standardized change is the difference between mean climate (e.g., SST) in the Near future (2030–2050) and mean climate of the historical period (1990–2020) normalized by the historical interannual standard deviation. Similarly, we also calculated standardized change between the Far future (2070–2100) and historical period (1990–2020). This approach helps to scale the projected change to the observed variance in the system. For example, a 2˚C mean temperature increase is greater in an ecosystem with 0.1˚C inter-annual standard deviation than one with a 1˚C standard deviation. The final maps containing spatially explicit projections used to score Near and Far exposure factor scores are presented in **Fig 2**. For these variables, comparisons between species' distributions across California state waters and exposure maps were made visually and independently by each expert [9,14]. Phenology of Upwelling and changes in Sea Level Rise were assessed using a different method (**S1 Text**), noting that geographically standardized changes in Sea Level Rise were not available at a resolution comparable to that of other exposure factors.

Historical means for atmospheric factors (i.e., Precipitation and Air Temperature at 2m) are from the European Centre for Medium-Range Weather Forecasts version 5 (ERA-5 [33]) at ~25 kilometers (km). Historical mean for pH is from the Global Ocean Data Analysis Project version 2 (GLODAPv2) mapped product (1972–2013 [34]) at ~100km. The historical means of the rest of the oceanic variables (i.e., Sea Surface Temperature and Salinity, and Bottom Oxygen) come from a previously validated CCS ocean regional hindcast [35,36]. The standardized changes of all the variables (except for pH) are from an ensemble of three high-resolution (~10 km) downscaled projections described in [35]. The hindcast simulation corresponds to the historical period of the downscaled projections. Standardized changes for pH are from the Geophysical Fluid Dynamics Laboratory Earth Systems Model version 2M (GFDL-ESM2M), Institut Pierre Simon Laplace Climate Model version 5, Mid-resolution (IPSL-CM5A-MR), and Hadley Centre Global Environment Model version 2, Earth-System configuration (Had2GEM-ES); (near future: 2006–2055 relative to 1990–2020, and far future: 2055–2099 relative to 1990–2020) under the Representative Concentration Pathway (RCP) 8.5 scenario at ~100km (from https://psl.noaa.gov/ipcc/ocn/). These earth system models were chosen because they are the ones used to force the downscaled high-resolution projections, and also because they cover the range of the mean of future changes in the CCS. Phenology (i.e. timing) of Upwelling is assessed from the Coastal Upwelling Transport Index (CUTI), [37–39]. For Sea Level Rise, in 2012 the National Research Council (NRC) predicted future sea level rise in California, Oregon, and Washington for the years 2030, 2050, and 2100 [40]. We used these projections in our rubric in order to examine change in the Near future (2050) and Far future (2100).

2.5 Scoring

The scoring of sensitivity attributes and exposure factors for each of the 34 species was conducted via a decentralized process (**Fig 3**), in which scores were assessed independently by 5 members of the research team (see below), calibrated through a series of virtual workshops, and then validated and/or modified following final review by CDFW subject matter experts. This process was adapted from previous CVAs (and informed by the feedback of participating individuals) in which a large number of individuals scored different subsets of species through time and resource-intensive in-person scoring workshops [9,14] in order to a) make efficient use of a limited project budget and personnel time; b) minimize biases inherent to relative scoring (i.e. see Discussion); and c) formalize a process through which the CDFW subject matter experts responsible for managing the assessed species could provide input and feedback at multiple phases.

First (i.e., Step 1; **Fig 3**), 34 species profiles and a Scoring Rubric for the sensitivity attributes and exposure factors (**S1 Text**) were developed and reviewed by CDFW subject matter experts. Second (i.e., Step 2; **Fig 3**), each species was scored independently and sequentially (i.e., one species at a time) by three or more team members of the five-person scoring team. The scoring team consisted of 5 professional research scientists, listed as co-authors on this manuscript, associated with one or more of the participating partner organizations external to CDFW (see Section 2.2) who were selected based upon their a) familiarity with CVA methodology; b) expertise in US West Coast fisheries science, ecology, and/or oceanography; c) their willingness and availability to participate in the scoring process. For each exposure factor and sensitivity attribute, every scorer was given five tallies to spread across four predefined scoring bins (Low, Moderate, High, Very High), such that greater spread of tallies among scoring bins indicates greater uncertainty (and vice versa) (**S1 Text**). During the first round (i.e., Step 2a; **Fig 3**) of scoring, three species (i.e., California halibut, white seabass, and California sheephead) were scored independently by all members of the scoring team. This first round served as a pilot, where scorers became acquainted with the scoring rubric and process and were able to discuss procedural questions and scoring strategies as a complete group. During the second round (Step 2b; **Fig 3**) of scoring, 12 species were scored by two three-person groups (six species per group), followed by a final round (Step 2c; **Fig 3**) of scoring in which the 19 remaining species were scored (ten species by one group, and nine species by another). Directly following each of

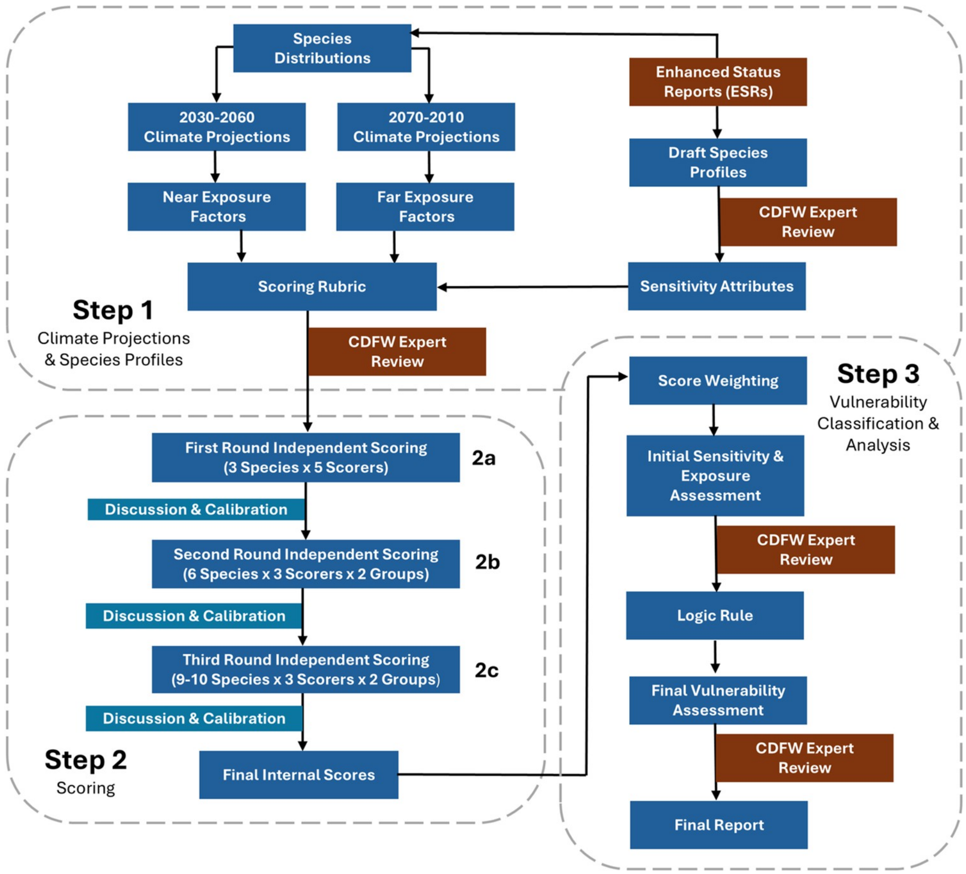

Fig 3. Flowchart of this CVA (modified from [9,14]). Brown boxes indicate tasks undertaken by CDFW subject matter experts while blue boxes indicate tasks undertaken by the research team.

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the three scoring rounds, scorers met in virtual workshops lasting 60–120 minutes (as a complete group following round one and in smaller groups, composed of those with common scoring assignments, following rounds 2 and 3) to discuss their scores and reflect upon the scoring process. The emphasis of these discussions was primarily to highlight instances where a particular scorer was consistently evaluating one sensitivity attribute or exposure factor higher/lower than other scorers, rather than debating specific scores for specific species. By design, group membership varied between rounds 2 and 3 in order to maximize opportunities for cross-scorer calibration. One individual scored all 34 species while the other individuals scored between 12–18 species. Following each virtual calibration workshop, scorers were given the opportunity to independently change their tallies and final scores based on the discussion; however, there was no requirement nor expectation that consensus be reached.

Final climate vulnerability scores (i.e., Step 3; Fig 3) were assigned using: a) the weighted mean of the scoring team's tallies of individual sensitivity attributes and exposure factor scores for each species; b) a logic rule; and c) feedback from CDFW subject matter experts. For each sensitivity attribute and exposure factor, we calculated the weighted mean assessed by each scorer and the weighted mean across scorers. Weighted means were assessed by assigning a numerical value to each component score (Low = 1, Moderate = 2, High = 3, and Very High = 4), multiplying the number of tallies in each bin by the appropriate weighting factor, then dividing by the total number of tallies. All resulting values and the underlying tallies were

Table 4. Logic rule for calculating overall species' climate exposure and biological sensitivity. The scoring rubric is based on a logic model where a certain number of individual scores above a certain threshold are used to determine the overall climate exposure and overall biological sensitivity [19].

Overall Sensitivity or Exposure Score	Numeric Score	Logic Rule
Very High	4	3 or more attributes or factors with mean $\geq$ 3.5
High	3	2 or more attributes or factors with mean $\geq$ 3.0
Moderate	2	2 or more attributes or factors with mean $\geq$ 2.5
Low	1	All other scores

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displayed on an interscorer comparison plot prepared for each species (e.g., **S1 Fig**). CDFW subject matter experts (n = 20, with some individuals providing feedback on multiple species) were provided with the Scoring Rubric (**S1 Text**), the interscorer comparison plot, and plots depicting the species rank-order of the cross-scorer weighted means for each sensitivity attribute and exposure factor (see *Data Availability*). As the individuals responsible for managing the assessed species (who had previously synthesized relevant data and literature in the production of associated ESRs and provided feedback on the corresponding species profiles developed for this project), CDFW subject matter experts were considered highly qualified.

To reduce workload, CDFW subject matter experts were asked to focus their feedback on species-specific sensitivity attribute and/or exposure factor scores where: a) the standard deviation associated with the cross-scorer weighted mean was > 0.75, and b) the scores assigned by the scoring team fell into substantially different categories (e.g., where one scorer assessed Adult Mobility as Low and another scorer assessed Adult Mobility as High). In such instances, CDFW subject matter experts were provided the opportunity to adjust the scoring category assigned based upon the previous cross-scorer weighted mean (e.g., when considering kelp bass and Sea Level Rise as in **S1 Fig**, proposing a shift from Moderate Far Exposure to High Far Exposure). In instances where CDFW subject matter experts proposed scoring adjustments to a sensitivity attribute or exposure factor scores in the absence of substantial interscorer variability, the scoring team decided whether or not to make these adjustments based on their collective evaluation of the weight of available evidence (i.e., scientific references and management reports). Though the scoring team endeavored to undertake a consistent and uniform process when evaluating and incorporating CDFW expert opinions, a degree of discretion was exercised in initiating follow-up dialogues and determining final scores in order to accommodate the variable content, quantity, and format of subject matter expert feedback.

Once all proposed score revisions had been reviewed and (where appropriate) incorporated into a final scoresheet for each species (**S1 Data**), overall sensitivity and exposure scores were assigned using a logic rule (**Table 4**), and the overall climate vulnerability score was calculated by multiplying the overall exposure and sensitivity scores (products resulting in a value between 1–3 were classified as Low, products between 4–6 were classified as Moderate, products between 8–9 were High, and products between 12–16 were Very High). These methods follow [19]. To conclude, CDFW subject matter experts were then given a final opportunity to review the analysis and help provide interpretation following the preparation of a draft manuscript, which presented all project results.

2.6 Sensitivity and certainty analysis

We conducted a sensitivity analysis to determine which exposure factors and sensitivity attributes were most influential in the overall vulnerability score and rank. To do this, the overall vulnerability score for each species was calculated by iteratively leaving out the scores for each sensitivity attribute or exposure factor and then reassessing the resulting vulnerability classifications. In addition, bootstrap analysis was used to calculate the certainty of the climate vulnerability classifications associated with the scores initially assessed by the scoring team [9,12,14]. The scores of all scorers for a given exposure factor or sensitivity attribute (n = 15; 3 experts and 5 tallies) were drawn randomly with replacement. Following methodology employed by federal CVAs [9,14] and adapting associated code [19] within R programming software [41], this process was repeated 10,000 times for each of the 12 sensitivity attributes and the 8 exposure factors, and the overall vulnerability classification was calculated for each iteration. The outcomes of each iteration were recorded and the proportion of these 10,000 repetitions that scored in each overall vulnerability bin was enumerated.

2.7 Potential for distribution change & overall directional effects of climate change

Studies using ichthyoplankton survey data to investigate long-term shifts in the distribution of fish have shown that several sensitivity attributes can skillfully predict the likelihood that species will change distribution in response to environmental change [42]. This information is likely to be essential for the timely and effective development of adaptive management strategies. Following the methodology employed by previous CVAs [9,14], species with high potential for distribution change were defined as having highly mobile adults, broadly dispersing early life stages, low habitat specificity, and high temperature sensitivity. We calculated the distributional shift score by applying the same logic model described previously to the Sensitivity to Temperature score and the reverse (i.e., new score = (number of scale points +1)—original score) of the weighted mean scores for Adult Mobility, Dispersal of Early Life Stages, and Habitat Specificity, with 4 being the number of scale points used in the analysis (i.e., Low, Moderate, High, and Very High). Note that this method represents a slight modification from that utilized in previous CVAs, where the tallies assigned to scoring bins were swapped (i.e., Very High tallies become Low tallies and *vice versa*, High tallies become Moderate tallies and *vice versa*) and before recalculating the weighted mean [9,14] in order to account for the fact that CDFW subject matter expert feedback resulted in adjustments to the weighted mean scores rather than the underlying tallies.

In addition (and concurrently) to reviewing exposure and sensitivity scores, CDFW subject matter experts were asked to score the expected overall impact of climate change on each species as positive (value of 1), negative (value of -1), or neutral (value of 0) to describe the directional effect of climate change [19], distributing four tallies across the three categories and calculating the mean. In instances subject matter experts choose not to provide this evaluation (n = 5), tallies were assigned based on the scoring team's expert judgement. In this analysis, species scoring a mean of $<$ -0.25 were classified as being strongly negatively affected; species scoring between -0.25 and 0 were classified as being weakly negatively affected, species scoring 0 were classified as being neutrally affected, species scoring between 0 and 0.25 were classified as being weakly positively affected, and species scoring $>$ 0.25 were classified as being strongly positively affected.

2.8 Calculation of relative climate risk of commercially targeted species

In addition to using the logic rule to classify the climate vulnerability of different species, we calculated risk, defined as a product of the average sensitivity attribute scores and exposure factor scores [43,44]. As a general rule, averaging tends to minimize the importance of high scoring sensitivity attributes or exposure factors [19], yet it may better enable holistic comparisons between species while highlighting the cumulative impacts of a broad suite of co-occurring stressors (rather than having classifications driven by a limited number of high values). To facilitate relative, visual comparison between species, average sensitivity and exposure factor scores for all 27 commercially landed species included in this analysis (i.e., those species listed in **Table 1** with commercial landings reported 75% of the years between 2000–2019) were scaled between 0 and 1, with qualitative risk categories (i.e., low, medium, & high) assigned using the Euclidean distance of each species from the origin in a space defined by exposure and sensitivity indices (i.e., risk increases with distance from the origin in exposure-sensitivity space with both variables having an equal contribution to risk) [44,45].

2.9 Ethics statement

This study was reviewed by the UC Santa Cruz Office of Research Compliance Administration (Study # HS-FY2025-71) which determined that activities described do not meet the regulatory definition of human subjects research according to federal regulations (i.e., Department of Health and Human Services CFR 45 part 46.102(e)) and state and local laws.

3. Results

3.1 Inter-scorer variability

Across the 34 species whose sensitivity attributes and exposure factors were assessed by the scoring team, sensitivity attribute and exposure factor scores were moderately variable, though this variability decreased substantially following score calibration meetings (**Fig 4**). When considering sensitivity attributes, agreement in post-calibration scores for demersal species was

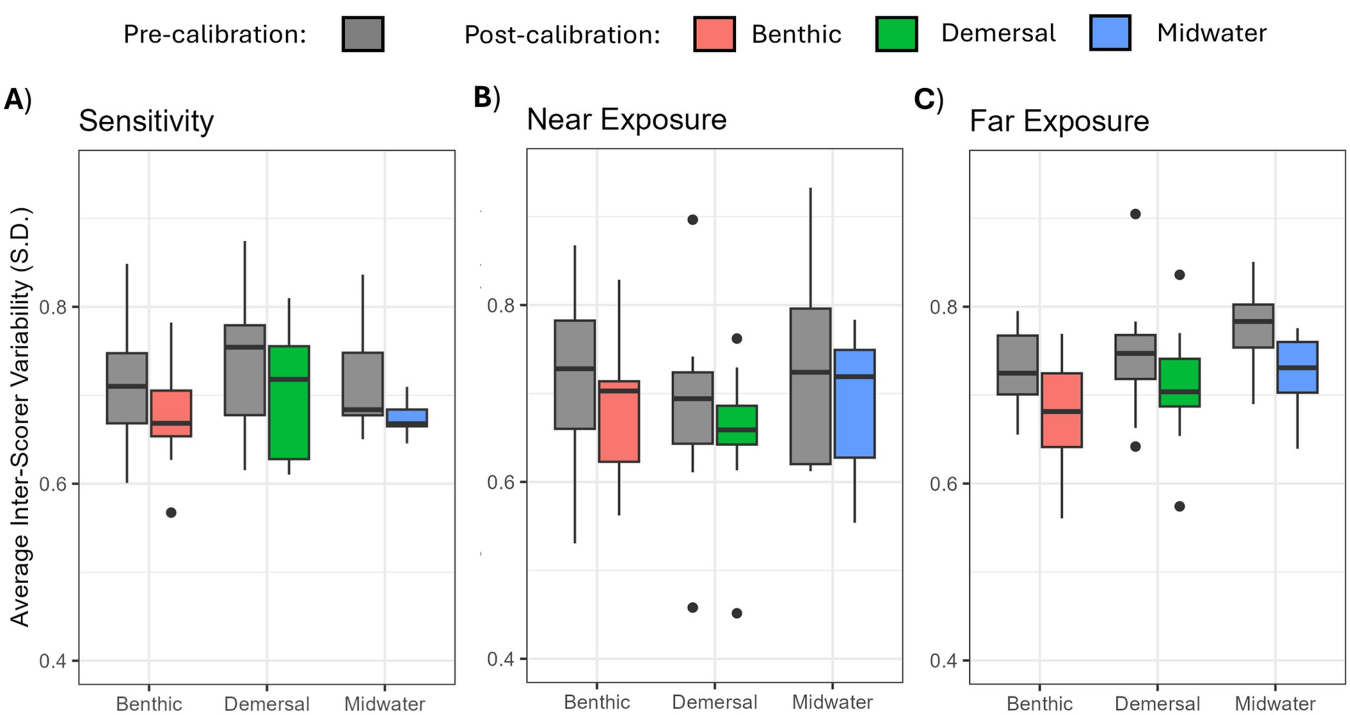

Fig 4. Comparison of average inter-scorer variability (i.e., the average of standard deviations of scores) Pre- (grey) and Post- (colored) score calibration (prior to revision proposed by CDFW subject matter experts), as assessed across all sensitivity attributes (**A**), Near Exposure (2030–2060) factors (**B**), Far Exposure (2070–2100) factors for each species between different functional groups, i.e., benthic invertebrates (red; n = 13), benthic & demersal fishes (green; n = 14), and midwater fishes and invertebrates (blue; n = 7) species. Box and whisker plots show the median (black line) and interquartile range of average inter-scorer variability (25th through 7th percentile; colored areas) as well as maximum and minimum values (whiskers) and outliers (points representing values over 1.5x the interquartile range over the 75th percentile or any values under 1.5 times the interquartile range under the 25th percentile).

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comparatively low (as assessed by the high median value of average inter-scorer variability), though there was substantial variation among species (Fig 4A). There was high variability in the scores associated with ocean whitefish, redtail surfperch and low variability in the scores associated with Pacific hagfish and barred sand bass (S2 Fig). In contrast there was much higher agreement when scoring benthic species (Fig 4A) as driven by a broad correspondence in the elevated sensitivity scores reported for species like spiny lobster and Pacific geoduck clam (S2 Fig). Across all species, Population Growth Rate (mean inter-scorer variability = 0.753) and Sensitivity to Temperature (mean inter-scorer variability = 0.750) were the sensitivity attributes associated with lowest agreement among scorers post-calibration, while Adult Mobility (mean inter-scorer variability = 0.568) and Sensitivity to Ocean Acidification (mean inter-scorer variability = 0.584) were associated with highest agreement among scorers. When considering Near (Fig 4B) and Far (Fig 4C) futures, agreement in scores for midwater species was consistently the lowest, as driven by consistently low agreement in scores for jacksmelt, night smelt, and Pacific barracuda (S2 Fig). Across all species, when considering Near and Far Exposure post-calibration scores collectively, there was the lowest agreement when scoring Mean Salinity (mean inter-scorer variability = 0.736) and Mean SST (mean inter-scorer variability = 0.713) exposure factors, and the highest agreement when scoring Mean pH (mean inter-scorer variability = 0.603) and Mean Precipitation (0.674) exposure factors.

3.2 Vulnerability

Of the 34 species assessed, ~3% of species were classified as having Very High vulnerability to climate change under Near Exposure conditions (i.e., 2030–2060), ~9% were Highly vulnerable, ~35% were Moderately vulnerable, and ~53% had Low vulnerability (Fig 5A). Under Far Exposure (i.e., 2070–2100) conditions, ~15% had Very High vulnerability, ~38% were Highly vulnerable, ~35% were Moderately vulnerable, and ~12% had Low vulnerability (Fig 5B). Red abalone, a gastropod listed by the International Union for Conservation of Nature as critically endangered, was classified as having Very High vulnerability under both Near and Far Exposure conditions. Three additional benthic species (the crustaceans Dungeness crab and pink shrimp and a bivalve, the Pismo clam) as well as the Pacific herring (a pelagic, mid-water species) were also classified as having Very High vulnerability under Far Exposure conditions. Overall, benthic species were comparatively more vulnerable under Near (~7% Very High and ~15% High) and Far (~31% Very High and ~39% High) Exposure conditions than demersal species (0% High or Very High during Near Exposure conditions; 0% Very High and ~43% High during Far Exposure conditions) or midwater species (0% Very High and ~14% High during Near Exposure conditions; ~14% Very High and ~29.2% High during Far Exposure conditions) (Fig 6).

As compared to the initial vulnerability classification prior to CDFW subject matter expert score review (S3 Fig), the final Near Exposure classification resulted in three increases (i.e., night smelt and California spot prawn shifted from Low to Moderate; Pacific herring shifted from Moderate to High) and two decreases (i.e., market squid moved from High to Moderate; ridgeback prawn shifted from Moderate to Low). Following subject matter expert review, the final Far Exposure classification contained four increases (Pacific herring shifted from High to Very High; spot prawn shifted from Moderate to High; California corbina shifted from Low to Moderate; and night smelt shifted from Moderate to High) and two decreases (market squid moved from Very High to High; and California sheephead moved from High to Moderate).

3.3 Exposure & sensitivity

Under both Near and Far Exposure conditions, average pH and SST scores were comparatively higher than other exposure factors (Fig 7A) and had a substantial impact on the overall

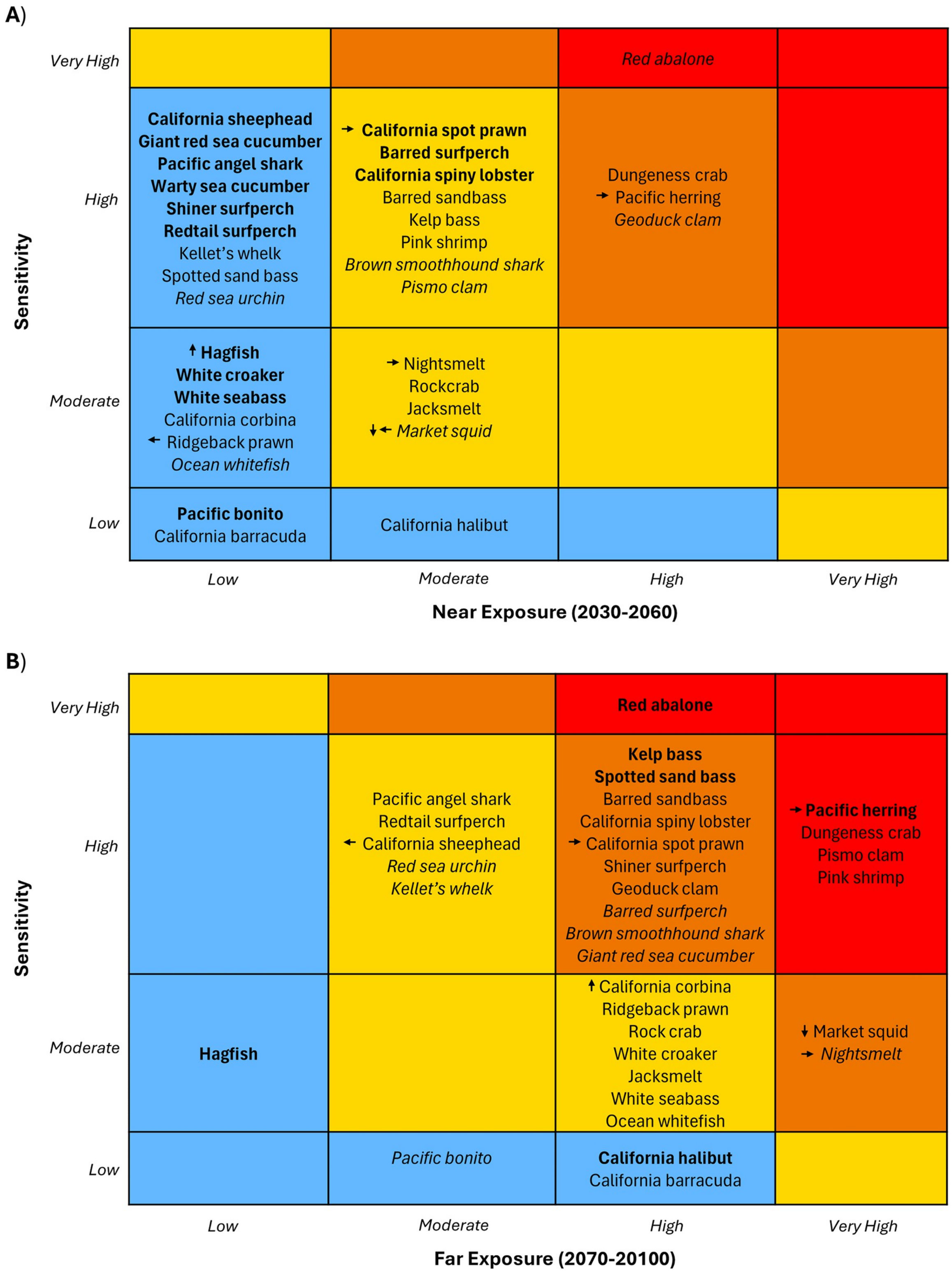

Fig 5. Final vulnerability classification for 34 California State-managed species under Near Exposure (2030–2060; A) and Far Exposure (2070–2100; B) environmental conditions following CDFW subject matter expert review. Vulnerability categories are colored from Low (blue), Moderate (yellow), High (orange), and Very High (red). Fonts reveal the certainty scores associated with the initial classification assessed by the scoring team, comparing very high certainty (i.e., > 95%; bold, black font) and very low certainty (< 75%; italic, black font), while vertical (sensitivity) and horizontal (exposure) arrows indicate shifts in classification (as compared to the initial, internal scoring classification; see S3 Fig) informed by CDFW subject matter expert review.

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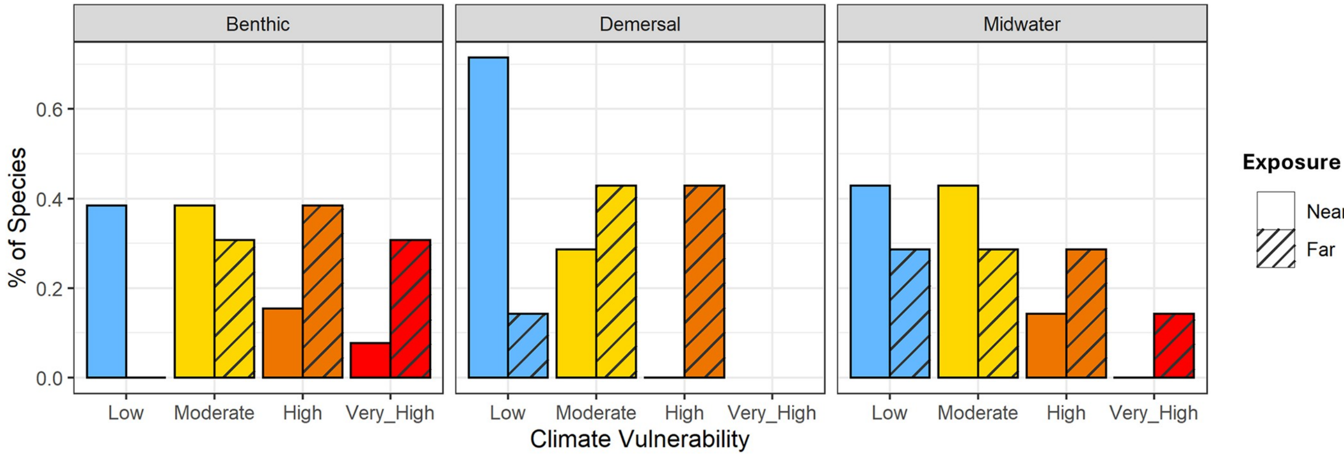

Fig 6. Percent of species by climate vulnerability category as shown for Near and Far Exposure climate futures.

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vulnerability rankings (Fig 7B). Likewise Bottom Oxygen and Phenology of Upwelling can be considered as two other exposure factors of high relative importance, though their impact on overall vulnerability rankings was most acute during Far Exposure conditions (Fig 7B). All four of these exposure factor scores were comparatively higher for benthic species as compared to demersal and midwater species, except for SST during Far Exposure conditions where the highest impacts were observed for midwater species (S4 Fig). In contrast, changes in Precipitation and Salinity were some of the lowest (Fig 7A) and least impactful (Fig 7B) exposure factor scores, though it is worth noting that scores for these exposure factors (alongside scores for Sea Level Rise), were often higher for demersal species than for benthic or midwater species (S4 Fig), presumably due to their high reliance on estuaries for one or more life history stages.

The highest sensitivity scores were associated with Spawning Cycle, Ocean Acidification, and Early Survival and Settlement attributes (Fig 8A), though only Spawning Cycle (alongside Early Dispersal) had a substantial impact on overall vulnerability rankings (Fig 8B). Adult Mobility, Survival and Settlement, Other Stressors, Ocean Acidification, and Sensitivity to Temperature sensitivity attributes scores were consistently the highest for benthic species, while Early Dispersal, Prey Specificity, and Stock Status scores were consistently higher for demersal species (S4 Fig). Reproductive Complexity, Prey Specificity, and Stock Status were evaluated as sensitivity attributes with comparatively low scores (Fig 8A) and no impact on the overall vulnerability rankings (Fig 8B).

3.4 Overall impact & potential for distribution change

Of the 34 species included in this CVA, 17 were assessed as having moderate potential for a distribution shift and 10 were assessed as having high potential (Fig 9A). The benthic and demersal functional groups had the largest percentage (Fig 9A) of species assessed as having high potential for a distribution shift (~38.4% benthic; 28.5% demersal). Benthic species with high potential for distribution shift had either elevated early dispersal ability and sensitivity to temperature (i.e., Dungeness crab, spiny lobster); elevated early dispersal ability and generalist habitat requirements (giant red sea cucumber, rock crab); or elevated early dispersal ability and sensitivity to temperature and generalist habitat requirements (ocean pink shrimp). For these benthic species, elevated early dispersal ability was a common attribute reflecting that early life history stages of this functional group may have an increased ability to colonize new habitats (S5 Fig). Demersal species with high potential for distribution shift had either high

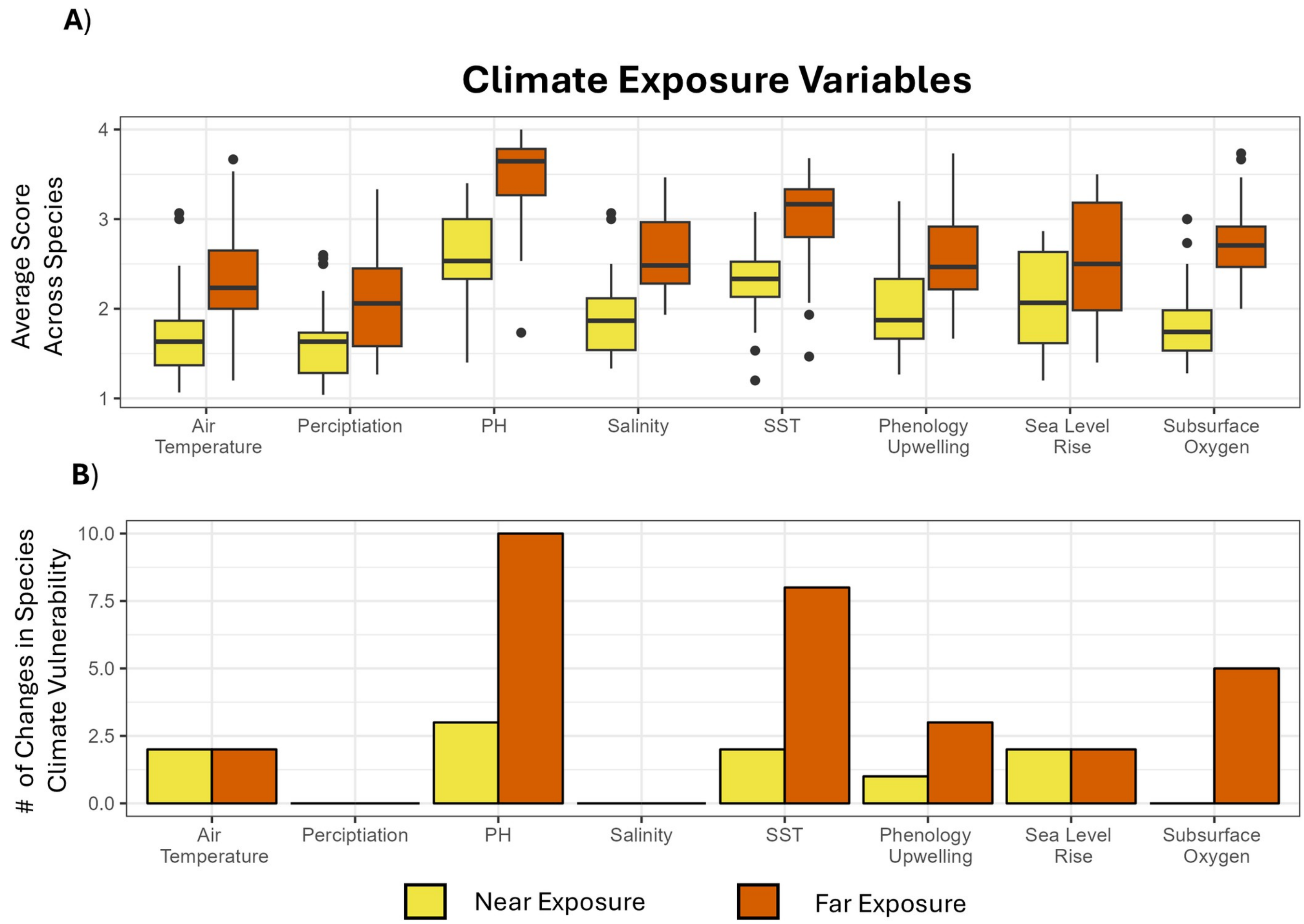

Fig 7. Range of average climate exposure factor scores for all species (**A**) and results of sensitivity analysis quantifying the effect of individual exposure factors on overall climate vulnerability (**B**). Box and whisker plots (**A**) show the median (black line) and interquartile range of average scores (25th through 7th percentile; colored areas) as well as maximum and minimum values (whiskers) and outliers (points representing values over 1.5x the interquartile range over the 75th percentile or any values under 1.5 times the interquartile range under the 25th percentile). Sensitivity analysis methods (**B**) follow those in [19] with results (i.e., number of changes in species climate vulnerability if that factor is removed from the analysis, reported on the y-axis) reported for both Near and Far Exposure scenarios. Factors with large y-axis values in panel **B** had a comparatively large impact on the final vulnerability classifications.

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adult mobility and generalist habitat requirements (i.e., Pacific angel shark, and redtail surfperch); high adult mobility and elevated dispersal ability (California halibut); or high adult mobility, generalist habitat requirements, and elevated dispersal ability (white croaker). For these demersal species, high adult mobility was a common attribute, indicative of an increased capacity to move to a new location (**S5 Fig**). The midwater species (with the exception of market squid) assessed in this analysis only had moderate change for potential distribution despite often having high adult mobility. This was due to unknown and/or comparatively restricted early dispersal ability, lower sensitivity to temperature (see Discussion section 4.5), and more specialized habitat requirements (as frequently associated with vulnerable nearshore nursery habitat).

Climate change was assessed as having a strong negative impact on the largest percentage of benthic species (i.e., ~69.2%, **Fig 9B**), while the majority of assessments for midwater species (~71.42%) were neutral (though strong negative impacts were predicted for night smelt and Pacific herring, two species reliant on spawning habitat expected to be acutely impacted by Sea

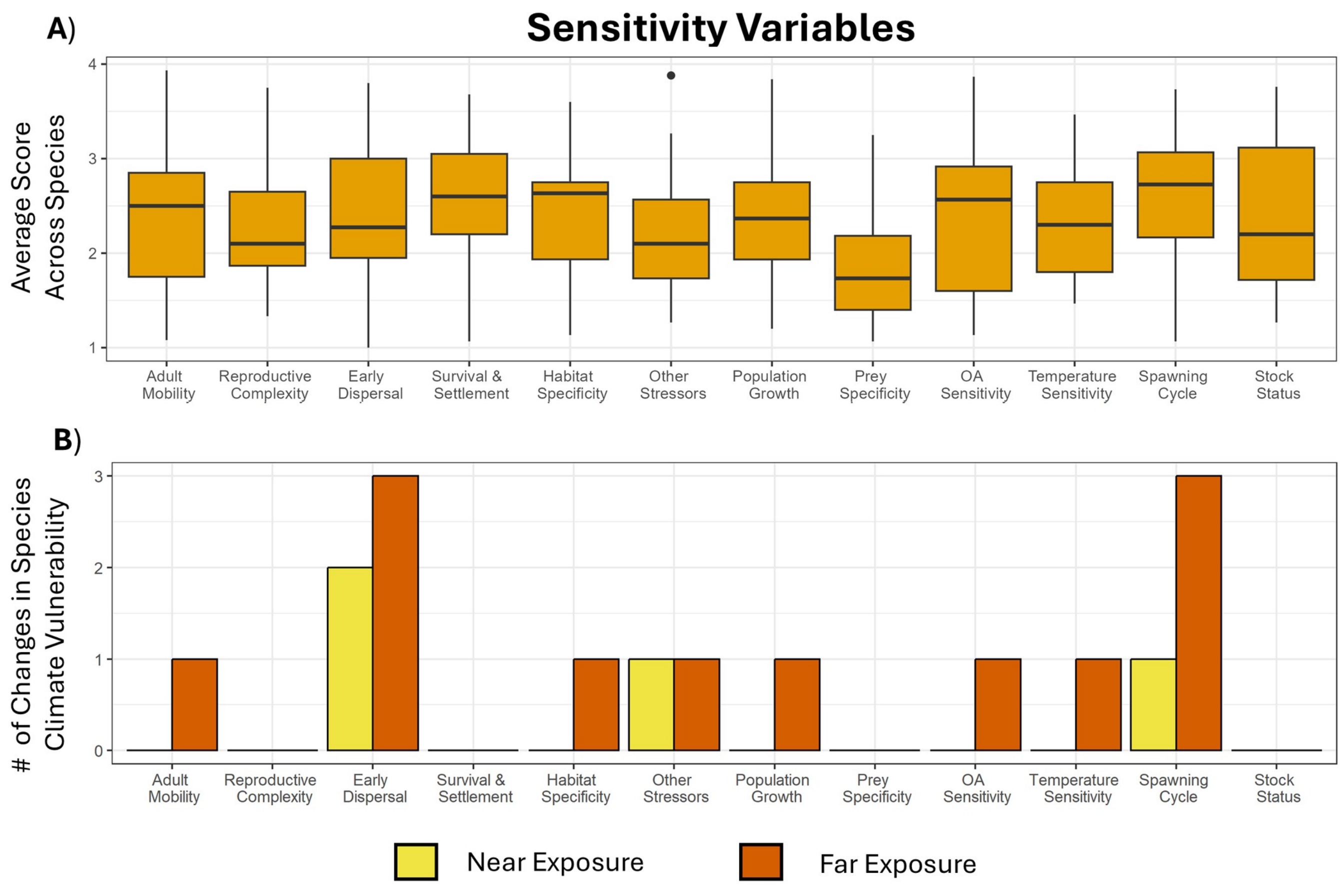

Fig 8. Average sensitivity attribute scores across all species **(A)** and results of a sensitivity analysis (i.e., removing the attribute) for quantifying the effect of individual sensitivity attributes on overall climate vulnerability scores **(B)**. Methods follow those in [19]. Box and whisker plots in (**A**) show the median (black line) and interquartile range of average sensitivity attribute scores across all 34 species (25th through 7th percentile; colored areas) as well as maximum and minimum values (whiskers) and outliers (points representing values over 1.5x the interquartile range over the 75th percentile or any values under 1.5 times the interquartile range under the 25th percentile).

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Level Rise). The only species for whom the impact of climate change on California state-managed waters was expected to be positive was the demersal species ocean whitefish (**S6 Fig**).

3.5 Commercial fisheries climate sensitivity and exposure

Analysis of average sensitivity attribute and Near and Far Exposure factor scores, which can be considered collectively to indicate climate risk, suggests that some of California's most historically valuable commercial fisheries are among those assessed as the most sensitive and exposed to a potential suite of co-occurring stressors (**Fig 10**). Dungeness crab, the species supporting one of California's most valuable fisheries between 2000–2019 ($45.3 Million average annual ex-vessel revenue), was ranked as Highly Vulnerable under Near Exposure conditions and Very Highly vulnerable under Far Exposure conditions (see section 3.2), with one of the highest average exposure scores in both scenarios. Market squid, the 2nd most valuable fishery ($43.9 Million average annual ex-vessel revenue), and California spiny lobster, the 3rd most valuable fishery ($10.7 Million average annual ex-vessel revenue), were both assessed as having moderate vulnerability under Near Exposure conditions and High Vulnerability under Far Exposure conditions in section 3.2, with elevated risk levels driven by market squid's comparatively elevated average Far Exposure score and California spiny lobster's high average

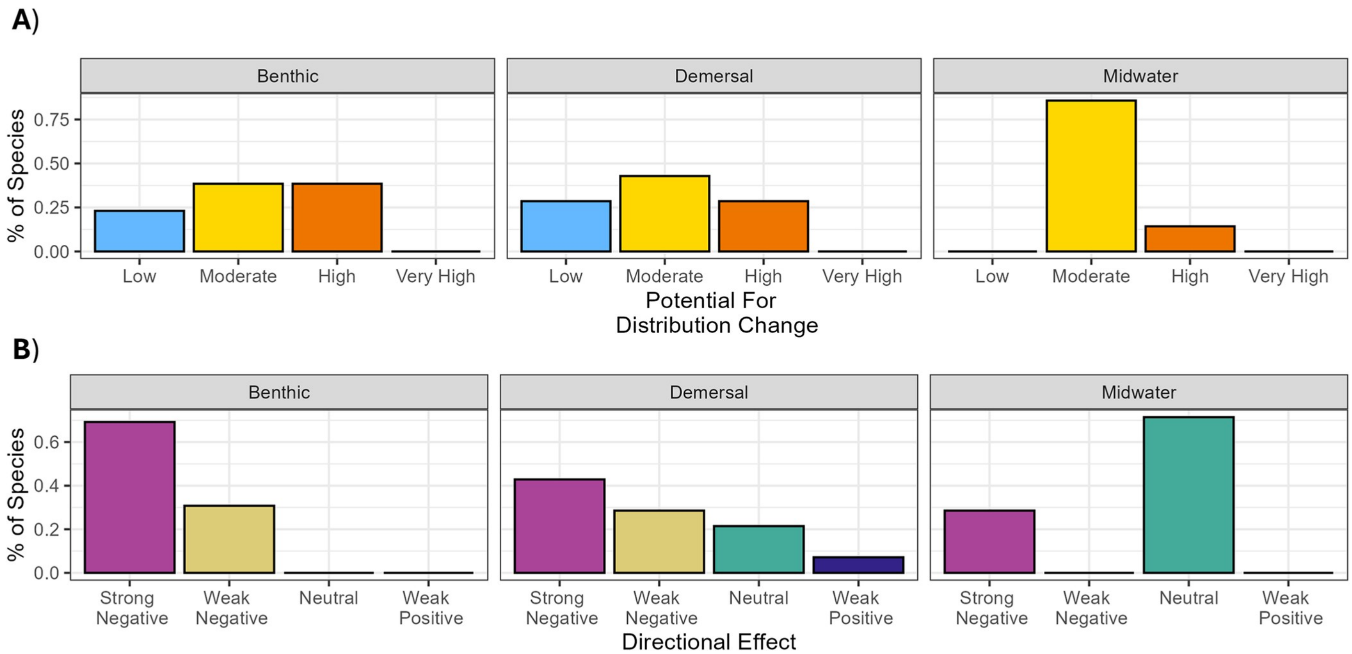

Fig 9. Percent of species by **(A)** likelihood of change in geographic distribution; and **(B)** likelihood that climate change effects will be negative, neutral, or positive in each functional group. Alternate versions of the panels presented in this figure, where the individual species assigned to each category are explicitly labeled, are presented in S5 and S6 **Figs**.

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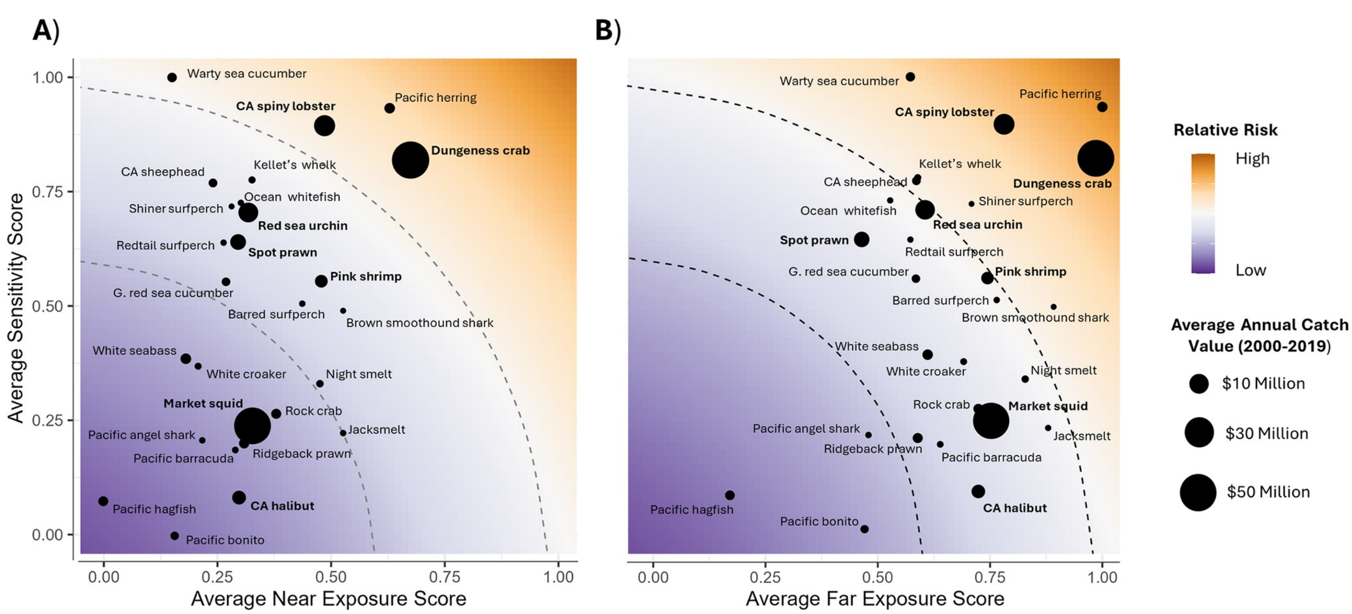

Fig 10. Average sensitivity attribute (y-axis) and exposure score (x-axis), considered collectively as risk, for California state managed species targeted by commercial fisheries under Near (**A**) and Far (**B**) exposure scenarios. Note that risk as assessed in these plots follows methods from Samhouri et al. (2019) and Koehn et al. (2022) and differs from the vulnerability calculations in Fig 5. Points are sized according to average annual revenue generated by CA commercial fisheries (2000–2019) with labels of fisheries associated with > $2 million average annual revenue (see Table 1) bolded. To facilitate relative comparison, average sensitivity attribute and exposure factor scores of species included in this analysis have been scaled between 0 and 1. Dashed lines represent combinations of sensitivity and exposure scores which produce equivalent risk and can be used to qualitatively distinguish between low (purple), medium (white), and high (orange) relative risk.

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sensitivity and Far Exposure scores (Fig 10). Under Far Exposure conditions pink shrimp (classified in section 3.2 as having Very High vulnerability), Pacific herring (classified in section 3.2 as having Very High vulnerability) and red sea urchin (classified as in section 3.2 as having Moderate vulnerability) likewise stand out as species supporting historically substantial commercial fisheries that are anticipated to face the greatest climate risk (Fig 10).

4. Discussion

The results of this climate vulnerability assessment indicate that of the 34 species assessed, ~12% (n = 4) are expected to be Highly or Very Highly vulnerable in the Near Exposure scenario (2030–2060), with that number increasing more than threefold to ~53% (n = 15) in the Far Exposure scenario (2070–2100). A number of these species are of critical importance to California's commercial and recreational fishers. These results are not surprising, as many climate driven changes have already been observed in the system [46,47]. In the past decade, multiple California nearshore fisheries (e.g., Dungeness crab, red sea urchin, and Chinook salmon) have been formally declared as federal fishery disasters, driven in part by marine heatwave conditions [47,48] that are expected to intensify as climate change progresses [49]. Overall, this assessment emphasizes the need for additional research and the development of adaptive management strategies for some of California's key state-managed fisheries.

4.1 Ecological and oceanographic climate futures across the California coast

Species and population responses to climate change are diverse and dynamic [4,46]. Physiological and biological intolerances of new ocean conditions are driving population-level redistributions of species, as well as local invasions and extinctions [50]. As a result, the restructuring of ecosystems is likely to impact ecosystem services and threaten the sustainable management and harvest of key fisheries resources. California's marine ecosystems have already undergone significant changes associated with global warming with additional changes expected by the end of the century. Indeed, California's waters are projected to become warmer, more acidic, and more stratified as a result of global climate change [35] with significant predicted redistribution of demersal [51] and pelagic species [52,53].

The California Current is a highly productive ecosystem characterized by seasonal upwelling of cool, nutrient-rich waters [54,55]. Despite the importance of such Eastern Boundary Upwelling Systems globally, there are significant uncertainties regarding their projected dynamics under climate change [56]. Off California, models don't agree on the direction of changes in upwelling strength, though they do show a tendency toward less-nutrient rich upwelled water and an associated reduction in phytoplankton biomass [38]. However, climate projections indicate a general trend that upwelling will intensify in poleward regions of upwelling systems, and that these near-coastal cool-waters will help to mitigate ocean warming under climate change and potentially provide thermal refuges for species [56]. This trend is particularly noteworthy for coastally restricted benthic and demersal species, where their distribution within upwelling areas may function as climate refugia [57]. However, significant uncertainties remain concerning their response and adaptive capacity as reflected in the final classifications presented in our CVA results. Though climate refugia may help to buffer the exposure to and impacts of ocean warming, it is important to note they may also put species at greater exposure to low dissolved oxygen and ocean acidification. Additional research is required to identify locations of climate refugia across the California coast, evaluate their capacity to advance the conservation of vulnerable species and habitats as climate change progresses, and explore how to maximize their potential for overlap with area-based management strategies (such as

MPAs). Indeed, despite the significant resources allocated to the establishment and monitoring of MPAs over the past several decades, the ability of these fixed geographic areas to meet (or optimize) resource management objectives in a changing climate as currently designed and positioned remains a key point of uncertainty [58].

When periods of strong climate variability and climate change align, extreme events such as marine heatwaves may occur, but these are often more difficult to predict in time and space [59]. While our analysis of climate vulnerability attempted to capture signals associated with historical ENSO cycles (see Sensitivity to Temperature in **S1 Text**) as well as extreme events like hypoxia and/or harmful algal blooms (see Other Stressors in **S1 Text**), future research would be well served in considering how to more explicitly represent and consider such factors and the interactions between them.

4.2. Reflections on CVA methodology

Though the decentralized procedures through which this Climate Vulnerability Analysis was conducted were initially adopted out of necessity (see Methods), we would assert that they provided an opportunity to address several limitations of previous scoring processes. A key feature of most conventional Climate Vulnerability Assessments are in-person stakeholder workshops in which experts are asked to review their scores, compare them to other experts, discuss the results, and adjust their scores based on those discussions [19]. While using both individual and group expert elicitation practices are thought to help minimize bias, concerns exist regarding the impact of a) inconsistent baselines through which individuals unconsciously assign relative scores that are shaped by the subset of species which they are assigned to assess (i.e., those considering a subset of pelagic species may have a different perception of what constitutes low species mobility as compared to those considering a subset of benthic species, irrespective of scoring rubric instructions); and b) individuals with dominant personalities and/or conflicts of interest asserting their opinions at the expense of other knowledgeable experts with different communication styles and/or backgrounds [60]. Having a small, independent team score a large number of species with diverse biological characteristics and life history traits (while meeting regularly to discuss process) prior to soliciting feedback from external, subject matter experts may help future CVAs avoid such pitfalls while limiting financial and logistic hurdles associated with large in-person scoring workshops. Indeed, in our estimation such benefits outweigh any potential drawbacks associated with broad (rather species-specific) technical expertise informing the initial round of scoring.

CVAs rely on the best available data on species' sensitivity attributes and their current spatial distributions. However, the resolution of the available information for some species can be poor, making it challenging to assign accurate scores. Moreover, many of the species in this CVA have spatial distributions that extend beyond the boundaries of California state, creating additional difficulties of assessing the sensitivity and exposure when the scope of scoring is limited to state waters, even though some populations may extend well beyond. To address these concerns, data quality scores (see **S1 Data**) were assigned to individual attributes in the species profiles, indicating whether the biological and ecological information is based on adequate data (3), limited data (2), expert judgment (1), or no data (0). With many of the species assessed in this analysis considered "data-poor", it is important to note that 5 of the 12 assessed sensitivity attributes (i.e., Other Stressors, Stock Size/Status, Early Life History Survival & Settlement, Dispersal of Early Life Stages, and Population Growth Rate) had average data quality scores < 2 (the threshold for what is considered limited data). While this approach helps to evaluate the nature and extent of knowledge gaps between species, it is important to note that vulnerability scores could potentially change as new information is collected about species' sensitivity and/or exposure.

Similarly, the impacts of climate change on California's state-managed species will depend not only on how biological and ecological parameters are impacted by projected environmental change, but also by the socioeconomic characteristics of the fisheries that target them [61] and the strategies through which they are managed [62]. Though comprehensive consideration of socioeconomic data is beyond the scope of the present analysis and the collective expertise of individuals engaged in the project, other assessments have begun to evaluate vulnerability as a coupled social-ecological process [44,45,63,64]. Such work explicitly considers the interactions and feedback between human and natural subsystems, while considering social adaptive capacity (i.e., the potential of communities to cope with future changes) as an additional, essential conceptual layer. Likewise, additional attention could be directed towards refining the process of knowledge co-production thought to facilitate awareness and the success of adaptation actions [13]. Though this assessment sought input from scientists, managers, and policy makers, the inclusion of knowledge and perspectives offered by fishery participants and tribal communities would be a valuable next step.

4.3 Contextualizing vulnerability scores for California state-managed species

Considering the biological and ecological characteristics driving assessed vulnerability and how they may vary within and between functional groups may help better contextualize the results of this study for state managers and facilitate the development of targeted adaptive management strategies. In general, benthic species exhibited the greatest overall vulnerability (**Fig 6**), as driven by elevated sensitivity scores associated with specific larval requirements, limited adult mobility, and high degrees of sensitivity to temperature and ocean acidification (**S4 Fig**). However, deep-dwelling benthic species with generalist habitat requirements (i.e., red sea urchin and giant red sea cucumber) were somewhat less vulnerable than those species associated with shallower waters and/or vulnerable nearshore habitat (i.e., red abalone and pismo clam) (**Fig 5, S1 Text**). These findings agree with other studies which suggest that shallow water, calcifying invertebrate species may be among those marine species most impacted by climate change [65,66]. In contrast demersal species, with more limited sensitivity to temperature and often less stringent larval requirements (**S4 Fig**), had the lowest overall vulnerability (**Fig 6**). Yet those demersal species with viviparous reproductive strategies (i.e. barred and shiner surfperch, brown smoothhound shark) associated with limited early dispersal or spawning aggregations that have been targeted by historic fishing pressure (i.e., barred sand bass, kelp bass) (**Fig 5**, **S1 Text**) may be more susceptible to future projected changes [67,68]. Finally, vulnerability classifications for highly mobile midwater species were mixed (**Fig 6**) with wide-ranging, coastal pelagic schooling fish (i.e., Pacific bonito, Pacific barracuda) among least vulnerable species, and those reliant upon sensitive, nearshore spawning habitat (i.e., Pacific herring, and night smelt) among the most (**Fig 5, S1 Text**). Overall, the regional pelagic ecosystems in which midwater species are embedded may be comparatively resilient given the temporal asynchrony and high population growth rates of many key species and functional groups [69].

4.4. Comparisons with other climate vulnerability assessments

McClure et al. [14] conducted a CVA focusing primarily on federally managed West Coast species. While our study focused instead on state-managed species, there were three species (Pacific herring, jacksmelt, and market squid) that overlapped between the two studies when considering the common time period represented by our Near Exposure scenario. Vulnerability estimates aligned for market squid between the two studies, but [14] estimated jacksmelt and Pacific herring vulnerability as Low and Moderate (respectively), while our study categorized them as Moderate and High (respectively) in the near-term scenario. Variability in such classifications can likely be attributed to differences in the scope of assessment species and geography. As mentioned above, all CVAs are inherently relative with rankings informed by the breadth of information that scorers are assigned to consider. Likewise, while our study focused on potential impacts within California state managed waters, the McClure et al., assessment spanned the complete extent of the California Current.

Both studies (as well as Hare et al. [9]; upon which the underlying methodology is based) agreed that Early Life History and reproduction-related sensitivity attributes were important for influencing vulnerability, although [14] had a stronger emphasis on Population Growth Rate. Exposure estimates generally showed strong agreement between the two studies for the three overlapping species, so variations in vulnerability estimates were driven more by differences in sensitivity scores (with the vast majority of [14] species classified within the same sensitivity bin). Both studies agreed that Ocean Acidification and Sea Surface Temperature were the two dominant exposure factors influencing climate vulnerability overall. This result is consistent with recent CVAs focusing on west coast salmonids [15] and East Coast US fisheries [9]. Hare et al. [9] similarly found that benthic invertebrates were among the most vulnerable species to climate change on the US east coast, as did another recent CVA from the Humboldt Current system in Peru [12]. These results specific to benthic invertebrates are not only consistent across recent CVAs, but they are also consistent with commercial fishers' perceptions of the most vulnerable species on the US West Coast [70]. Finally, it is worth noting the Chinook (King) Salmon (*Oncorhynchus tshawytscha*), a federally managed species of considerable historic importance to CA commercial fishers [71] that was not considered in our assessment, was classified as Very Highly Vulnerable in each of the two CVAs in which it has been assessed [14,15] and has been the subject of several federally declared fishery disasters linked to climate change in California [48].

4.5 California commercial fishers face an uncertain future

The high reliance of CA commercial fishers on species assessed as having High or Very High vulnerability to climate impacts is cause for concern. US West Coast fisheries can be characterized by high levels of diversity, productivity, and variability, with many California fishers historically targeting diverse species assemblages while moving between fisheries within and between years [72,73]. Yet following efforts in the 1970s and 1980s to limit access and the number of licenses, many fishers are dependent on fewer fisheries now than ever before [74]. While traditionally important salmon, groundfish, and herring populations declined in the early 2000s [71,75] and the fishery for albacore tuna shifted north [76]; the booming Dungeness crab resource [77] has become a dominant focus [78]. Yet, our analysis suggests this fishery may be acutely vulnerable as climate change progresses due to the impacts of multiple stressors like deoxygenation [79] and ocean acidification [80] in addition to harmful algal blooms and whale entanglement issues that have functioned to constrain fishing opportunities in recent years [81–83]. Likewise, the market squid fishery has represented the principal harvest of CA coastal pelagic fisheries (CPS) following the Pacific sardine fishery closure [84], but aspects of the species' life history and reproductive dynamics may result in high environmental sensitivity as climate change progresses [85–88] as debate continues concerning the adaptive capacity of the population within California waters [89–91].

4.6 Challenges and opportunities for California's recreational fishing sector

Recreational fisheries contribute substantially to California coastal economies and are an important part of the state's cultural heritage [92,93]. But recreational fisheries are comparatively challenging to monitor and manage due to data limitations inherent to a large number of geographically dispersed participants. The diverse portfolio of targeted species, many of which are included in this study, exhibit a broad range of responses to oceanographic variability at varying time lags [26,94]. In southern California, for example, populations of Barred Sand Bass and Kelp Bass (which our analysis classifies as Highly Vulnerable during Far Exposure conditions) targeted by Commercial Passenger Fishing Vessel (CPFV) fleets have been in decline for several decades [95,96]. While Kelp Bass has shown signs of recovery [97], both bass species may face a difficult road ahead if environmental variability increases and recruitment becomes even more sporadic [96,98]. In northern California, the red abalone fishery (classified here as Highly Vulnerable, and which at one time generated an estimated $24-$44 million of recreational value each year [93]) has been closed since 2018, following population declines associated with a marine heatwave event and the loss of kelp forest habitat [99–101].

Yet recreational fishers engaged in multispecies fisheries (without single species licensing requirements) may be best positioned to opportunistically target emerging species [102] and/or rapidly shift targets in response to in-season management intervention [103]. Potential benefits to some recreational fisheries may occur in southern California, similar to those experienced during the 2014–2015 marine heatwave when the catch of warm-water, southern species (i.e., wahoo and blue marlin) in local waters became increasingly common [104,105]. The CPFV fleet in southern California also benefited significantly (and continues to benefit) from the anomalously large Pacific bluefin tuna that shifted their distribution into local waters [106]. Beyond recreational fisheries in southern California, anglers north of Point Conception stand to benefit from the potential range expansion of species whose historical centers of abundance lie within the southern California bight. For example, white seabass, which are typically caught in Baja California and southern California, shifted northward during the 2014–2015 marine heatwave, with catch increasing in the northern ports of San Francisco and Bodega Bay in both years [107]. Indeed, our analysis of potential distribution changes, as based on the methods presented in previous Climate Vulnerability Assessments [9,14,16], may underemphasize the likelihood of such emergent opportunities, in a) focusing on species whose historic ranges were substantially within CA state waters; b) considering neutral and positive impacts to changes in local species abundance driven by warm water anomalies equally (see Sensitivity to Temperature in **S1 Text**). Likewise, considering Sensitivity to Temperature, Dispersal of Early Life Stages, and Habitat Specificity as having an equivalent influence on a potential for distribution change as Adult Mobility may lead to lower distribution change estimates for midwater species and higher distribution shift estimates for benthic species than might intuitively be expected.

4.7 Conclusion & management implications

Climate variability and change will require management to be proactive and adaptive to maintain resilient ecological and socioeconomic fishery systems. Species tend to respond differently to cool or warm periods and more flexible management may be required to address climate-driven fluctuations in distribution and population dynamics. An adaptable and responsive management system could help stem if not mitigate negative ecological responses while capitalizing on new fishery opportunities. To incorporate climate readiness into fisheries management, it is important to increase our understanding of possible impacts of climate variability, not only through impacts of long-term warming trends, but also impacts of short-term extreme environmental events that are already affecting fisheries and fishing communities. While a number of federal CVAs are in process or have already been conducted [9,14,17,19], there is an urgent need for more state-level analyses in order to increase the breadth of species assessed and to better match the geographic scale across which many resources are accessed and managed. The results of this CVA can help inform first level triage across the California coast, by providing initial scoping concerning how state managed species, and the fishing communities that depend on them, may fare under climate change scenarios. These results provide valuable information to direct management efforts, including prioritizing fisheries for management attention, identifying appropriate management strategies, and advancing a holistic approach to fisheries management based on assessing and managing risk to resources and livelihoods. As part of the Marine Life Management Act implementation, results from this assessment will help guide where additional investment in adaptive management is most needed and will be incorporated into the development of Enhanced Status Reports in the CDFW Marine Species Portal and Fishery Management Plans.

Supporting information

S1 Fig. An example of an inter-scorer comparison plot, as prepared for Kelp Bass, which served as the basis of the CDFW subject matter expert score review. The y-axis of each panel shows the individual tallies and the weighted mean associated with individual scoring team members (i.e., the top three factors), and the cross-scorer weighted mean (i.e., the bottom factor, labeled "all") used to determine overall sensitivity and exposure scores. Mean (i.e., "All) scores displayed by an open circle rather than a filled circle are indicative of high inter-scorer (i.e., IS) variability (i.e., a lack of agreement between scorers), based on having a standard deviation (across all scorer's tallies) of ≥ 0.75. Black dots indicate placement of raw tallies in bins, color dot-and-whisker bars indicate the weighted mean and standard deviation of tallies. Color indicates the bin of the weighted mean.
(PNG)

S2 Fig. Boxplots depicting the median and interquartile range values of standard deviation values (calculated from all tallies provided by all scorers) for each sensitivity attribute and near and far exposure factor. Species listed on the top of the y-axis of each panel are indicative of high inter-scorer variability while species listed on the bottom of the y-axis of each panel are indicative of low inter-score variability.
(PNG)

S3 Fig. Initial vulnerability classification for California state-managed species under Near Exposure (2030–2060) and Far Exposure (2070–2100) environmental conditions prior to CDFW subject matter expert review. Vulnerability categories are colored from blue (Low) to red (Very High). Certainty score, calculated via bootstrap analysis, is denoted by text font and text color: very high certainty (> 95%, black, bold font); high certainty (85–95%, black, italic font), moderate certainty (75–85%, white, italic font), low certainty (< 75%, white, bold font).
(PNG)

S4 Fig. Average sensitivity attribute (A), Near exposure factor (B), and Far exposure factor (C) scores across all species, as grouped by functional group.
(PNG)

S5 Fig. Potential for a change in species distribution. Potential changes are shown by functional group category with % of species displayed on the y-axis and the individual species

comprising each classification labeled in bold.
(PNG)

S6 Fig. Directional effect of climate change. Directional effects are shown by functional group category with % of species displayed on the y-axis and the individual species comprising each classification labeled in bold.
(PNG)

S1 Text. Final scoring rubric.
(PDF)

S1 Data. Final aggregated scoresheet. Cross-scorer weighted means and CDFW subject matter expert adjustments of each Near and Far exposure factor and sensitivity attribute.
(CSV)

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