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ABSTRACT

Climate change is already affecting fishery resources and the communities that depend on them. Climate change and multidecadal variability have been implicated in the shifting distributions, abundances, and phenology of fish and shellfish species in many marine ecosystems. These impacts are expected to intensify in the future, increasing the need to understand which species may be most vulnerable to climate-related environmental change. We have developed a vulnerability assessment that uses expert elicitation methods to quantify a species' exposure and sensitivity to expected climate change. Vulnerability, as used here, refers to a reduction in a species' productivity and or abundance associated with a changing climate, and includes both climate change and multidecadal climate variability. This methodology uses a vulnerability assessment framework, which is applicable across multiple species and provides a relative rank of vulnerability to climate change and variability.as well as information about why a species may or may not be vulnerable. The results can help fishery managers and researchers identify highly vulnerable species and more effectively target research and assessment resources on species of highest concern.

1.0 INTRODUCTION

Changes in global climate patterns are driving changes in ecosystems around the world, including marine and coastal oceans. These changes result from both from climate change and multidecadal climate variability. Coastal and open oceans are undergoing significant physical and chemical changes, including increases in ocean temperature, increases in acidification, changes in circulation, decreases in dissolved oxygen, and changes to freshwater inputs (Stock *et al.*, 2011; Melillo *et al*., 2014; Doney *et al.*, 2012; Rhein *et al.*, 2013; Howard *et al.*, 2013). Climate variability is also pronounced in ocean systems including the 50-90 year Atlantic Multidecadal Oscillation and the 20-30 year Pacific Decadal Oscillation (Mantua and Hare, 2002, Edwards et al., 2013). Changes in climate can influence the physical and chemical conditions of the marine environment on a variety of spatial and temporal scales, which can affect vital rates of marine organisms (e.g., growth, reproduction, consumption, and respiration), and through time may reduce a species' ability to survive (O'Connor *et al.*, 2007; Badjeck *et al.*, 2010; Ottersen *et al.*, 2010; Stock *et al.*, 2011). Climate-related changes—have been implicated in the shifting abundances and distributions of fish species. These changes are already being observed worldwide (Perry *et al.*, 2005; Brierley and Kingsford, 2009; Cheung *et al.*, 2010; Hoegh-Guldberg and Bruno, 2010), including several important commercial and recreational fish species in the United States (Nye *et al.*, 2009; Mills *et al.*, 2013; Pinksy *et al.*, 2013; Hollowed *et al.*, 2012). Climate change will affect fisheries by both the amount of fish being caught and the species composition of the catch (Sumaila *et al.*, 2011).

The impacts of climate on marine resources will not be uniform across species or regions (Fulton, 2011). Due to the spatial heterogeneity of climate change and ocean conditions, some species will be exposed to greater levels of change than others (Hobday and Pecl, 2014), and biological or behavioral characteristics may make a species in a given region more or less sensitive to change, while other characteristics could make a species more adaptable (Pecl et al. 2014, Sunday *et al.* 2015). Several in-depth investigations regarding climate change impacts on various economically important fish species have been completed (Hollowed *et al.*, 2009; Hare *et al.*, 2010; Hazen *et al.*, 2012; Plaganyi *et al.*, 2013; Wayte, 2013). These in-depth studies are valuable but require considerable investments in time, resources and data collection. It is not feasible to conduct this type of extensive analysis for all managed fisheries; in the U.S. alone there are more than 230 managed fish stocks. Thus, there is a need to develop a faster way to assess the vulnerability of a wide range of fishery resources in a changing climate. While vulnerability assessment tools have been well developed for use in conservation and management of terrestrial resources, there have been a limited number of vulnerability assessments in marine ecosystems (e.g., Chin *et al.*, 2010; Johnson and Welch, 2010; Foden *et al.*, 2013; Mathis *et al.* 2015, Pecl et al. 2014, Stortini *et al.,* 2015). Scientists and managers need to be able to identify species vulnerable to decreases in abundance and productivity to inform decisions about where to invest resources for more detailed and in-depth analyses. Failure to anticipate or prepare for these changes could negatively affect species productivity resulting in negative social and economic impacts (Cooley and Doney 2009; Madin *et al.*, 2012; Mills *et al.*, 2013).

We have developed a transparent assessment methodology to determine the relative vulnerability of fish stocks to a changing climate that may result in changes in abundance or productivity. The assessment includes both anthropogenic climate change as well as natural climate variability. Our assessment methodology leverages existing knowledge—both published sources and expert opinion—and can be used to assess data-rich as well as data-poor species. We designed the assessment methodology to generate transparent, easily understood outputs that will provide insight into which species are likely to be the most vulnerable to decreases in abundance due to climate change and identify the key drivers behind the vulnerability. High vulnerability, in this study, does not imply extinction risk, as a vulnerable species could continue to persist, just at a lower biomass level. Scientists, managers, and fishermen can use this information as they prepare for and adapt to future conditions.

2.0 DEVELOPMENT OF METHODOLOGY

We organized a working group consisting of expert scientists and managers from across the United States to create a vulnerability assessment methodology applicable across tropical, temperate, and high latitude marine systems that can address a wide range of fish and shellfish life history characteristics. We combined characteristics from three existing vulnerability assessments: we modified the logic model from Chin et al. (2010), and we revised the extensive list of biological sensitivities from Johnson and Welch (2010), and Pecl et al. (2014). We concurred with Pecl et al (2014) that life history attributes should be based on current biological characteristics versus predicted changes, as in Johnson and Welch (2010).

Our methodology assumes that current biological parameters and expected exposure to climate change can be used to evaluate the relative vulnerability of a species (Chin *et al.*, 2010; Johnson and Welch, 2010; Foden *et al.*, 2013; Pearson 2014; Pecl et al. 2014). Species' responses to climate can be complex, and our ability to predict which species will be able to adapt via genetic change is low and is thus not explicitly included. The criteria we include in this methodology are specific to life history characteristics of marine fish and shellfish species. With the current set of attributes, this methodology is not applicable to marine mammals, sea-birds, or sea turtles. However, the general framework of the methodology could be adapted for these groups. We note that our analysis of sensitivities at the species (or stock) level will not identify ecosystem changes. For example, changes to ecosystem primary productivity will indirectly impact species throughout the food web, but this kind of indirect effect is not included in the relative ranks provided by this methodology.

The goal of the vulnerability rank is to identify species that may respond to climate change with a decrease in productivity and/or abundance. In addition, understanding and predicting species that are likely to shift their distribution is also important for managers, as these range shifts can have large impacts on fishing communities and natural resource allocations. Pecl *et al*. (2014) use four life history traits to predict species that are at risk for a shift in distribution: larval dispersal, adult or juvenile mobility, physiological tolerance (predicted by species range), and the availability of unoccupied habitat. These categories can be supported and updated by recent data that show a correlation between three life history traits and range expansions in SE Australia: omnivory (i.e. diet generalists), adult mobility and species range (Sunday *et al.* 2015). Therefore, a combination of the scores from a subset of our species attributes can be used to estimate a species' ability or potential to shift distributions: high adult mobility, high dispersal at early life stages, habitat and temperature generalist. Diet generalization could also be included as a predictor. Species that can adapt to climate change and have a high potential for distributional shifts will be more likely to receive a lower vulnerability score.

The time-scale involved with fisheries management (next 1-5 years), interannual climate variability (1-50+ years), and climate change (often projected changes are for the next 50-100 years) cancreate a mismatch in managers and scientists ability to act or detect change in the system. Climate projections are often given with a 40–100 year time horizon; this time scale is needed to detect a climate change signal from climate variability. However, climate has been changing and will continue to change into the foreseeable future. Biological or ecological responses to these changes are hard to predict and have the potential to occur at any point in time. Fishery managers and scientists need to be prepared to anticipate these changes even though they are typically making decisions on a much shorter timeframe (1-3 years).

3.0 VULNERABILITY ASSESSMENT DESIGN

Our vulnerability methodology has four main design features (Figure 1), described below.

3.1 Vulnerability Components

There is considerable diversity in the design of vulnerability assessments (Glick *et al.*, 2011); however, nearly all derive vulnerability by considering at least two components: exposure and sensitivity. We follow the terminology in Chin *et al.* (2010) where the *sensitivity component* is divided into twelve *sensitivity attributes* and the *exposure component* is divided into a number of *exposure factors* (Figure 2). We define climate exposure as the overlap between the species distribution and the magnitude of the expected change in climate. Exposure factors (e.g., temperature, acidification, rate of ice melt, changes in circulation, decreases in dissolved oxygen etc.) considered will differ depending on what climate factors are important to the region of interest (see below). These exposure factors could include changes in means or changes in variability (i.e. extremes) depending on what is appropriate for the region. The magnitude of change can be determined using numerous methods (e.g., climate models, quantitative analyses, and qualitative evaluations).

Our sensitivity attributes are based on the current biological attributes of a species that are indicative of their ability/inability to respond to potential environmental changes.

Some vulnerability assessments also use a third component, *adaptive capacity* (Chin *et al.*, 2010; Johnson and Welch, 2010; Glick *et al.*, 2011), which accounts for biological responses that could reduce or mitigate the sensitivity or exposure, and includes dispersal ability, genetic diversity, and phenotypic plasticity (Beever *et al.* 2015). Our methodology follows a similar approach to the one described in Williams *et al.* (2008) that uses a sensitivity component that includes the adaptive capacity. We chose this approach after a thorough analysis of possible adaptive capacity attributes. Many biological attributes contribute to both sensitivity and adaptive capacity, creating methodological difficulties in disentangling sensitivities from adaptive capacity. We found that we could express the adaptive capacity attributes in terms of sensitivity by inversing the scale (e.g., a species that is a habitat specialist shows high sensitivity and/or low adaptive capacity). Analysis of data from a pilot study highlighted how results were affected depending on how the biological attributes were distributed into the two components. Therefore, combining the biological attributes into a single sensitivity component simplified our analysis and increased our confidence in the results. Other studies have had similar concerns with adaptive capacity and have either included it within sensitivity as we have, or have not included it at all (e.g., Pecl *et al.*, 2014; Gardali *et al.*, 2012). A disadvantage of combining adaptive capacity within sensitivity is that the results may not highlight the need for more research into adaptive responses or genetic adaptation (Beever *et al.* 2015).

With this methodology, the exposure factors included may differ across regions (e.g., importance of ice melt), but the sensitivity attributes included should stay consistent as we developed them to be applicable to most marine fish and shellfish species (e.g., prey specificity is consistently used for all species because all animals eat). There should be 8-14 exposure factors so that scoring of exposure is comparable to the scoring of the 12 sensitivity attributes. We have developed a detailed definition for each sensitivity attribute that includes the rationale for including the attribute, a description of the relationship to climate change, and guidance on how to score it. A summary of the 12 sensitivity attributes are provided here (Table 1), and full attribute definitions are available in Appendix 1.

3.2 Expert Based Scoring

Our methodology relies on technical experts using species profiles, scientific literature, and general knowledge to provide a score for each species for each sensitivity attribute and for each exposure factor. Although these scores are based on well-defined scoring bins, assigning a score is still a subjective process. This methodology uses both individual and group expert elicitation practices to minimize bias and increase precision of the results (Burgman *et al*., 2011). Assembling the right group of experts for the project can influence the results and buy-in from the stakeholders (EPA, 2009). A good expert has technical knowledge of the subject, the ability to extrapolate information to new situations, and the capacity to clearly articulate the reasoning behind their decisions (EPA, 2009). The number of experts will vary depending on the application (time and money, number of available experts, etc.). If a topic is highly controversial, care needs to be taken to ensure all viewpoints are represented and there is transparency in the selection process (EPA, 2009). Scoring of climate exposure and sensitivity attributes can be performed by the same group of experts or by a different group of experts. Specific biases are introduced via the use of expert opinion (EPA, 2009). Our methodology was created to minimize these biases to the extent possible. Clearly defining the attributes and the scoring bins establishes a clear baseline so all experts will interpret the questions similarly, which can reduce unnecessary variability in results (see Appendix 1). Each species should be scored by multiple experts to reduce individual bias and increase confidence in the results. There is no optimum number of experts but the literature suggests a range of four to seven experts is appropriate (Linstone and Turoff, 2002; Angus *et al.*, 2003). We recommend having some overlap in experts across species so that individual expert biases can be identified and scores standardized for comparison.

Experts assign a score based on four scoring bins (low, moderate, high, very high) for each exposure factor or sensitivity attribute assigned to them based on existing information and expert judgment. Pecl et al. (2014) found that a 3 bin scale (low, medium, high) was sufficient for showing resolution between species. We opted to add a bin for “very high” to pull out those most at risk. We recommend that summaries of known life history information be compiled into species profiles (Pecl et al. 2014) which can be referenced by experts when assigning scores (see Vulnerability Process step 2: Assessment Preparation). Experts should also incorporate their expert knowledge on the species. In data-poor situations, the expert may use information on other similar species or general ecological principles to provide a score.

Experts also indicate whether a species is expected to respond positively, negatively, or neutrally to the effects of climate change. This “direction of effect score” will provide initial feedback to managers on the species that might increase abundance and productivity or expand into the region in response to future changes.

3.3 Uncertainty and Data Quality

Life history traits in marine species are diverse, and our understanding of these traits varies across species. For many species, there is little direct knowledge of the life history characteristics that contribute to sensitivity attributes. Even when the life history characteristics of a species are well known, their complexity can lead to difficulty providing a score for a particular attribute. Similarly, future projections of climate change can also have a high uncertainty or vary across the range of a species. Our methodology allows experts to account for their uncertainty when assigning sensitivity, exposure and direction of effect scores. Experts have five “tallies” for each sensitivity attribute and exposure factor, which they distribute among the four scoring bins depending on their confidence in the score (Good *et al.*, 2005; Brainard *et al.*, 2011). Experts who are certain about a score may place all five tallies in one bin (e.g., all five tallies can be placed in the very high bin). Conversely, experts who are unsure about a score may spread all five tallies across the relevant bins (for example, they can put two tallies in the high bin, and three in the very high bin). Distributing five tallies across four bins forces the expert to choose one bin as the most likely. This is a transparent method that clearly shows the expert’s uncertainty about each score. In addition, uncertainty across experts can also be informative. Experts will also score the direction of effect using a similar tally system. Four tallies will be distributed across the three classifications: expected positive, negative or neutral response.

Experts also provide a data quality score for each attribute. This score is based on the guidelines shown in Table 2. Understanding the type and quality of information used to score the attribute allows end users to identify data gaps and areas for future research. We suggest a summary data quality score (e.g. number of attributes with a data quality score > 2.0) that can be used to compare available information among species. Together, the data quality score and the distribution of the tallies that make up the sensitivity attribute and exposure factor score are useful in characterizing the uncertainty in the overall vulnerability.

3.4 Calculating Vulnerability Ranks

We use three steps to combine expert tallies into a final vulnerability rank for each species. These are: 1) calculating a sensitivity attribute and exposure factor mean, 2) determining a sensitivity and exposure component score, and 3) assigning an overall climate vulnerability rank.

First, we calculate the sensitivity attribute and exposure factor means based on the distribution of all expert tallies across the four scoring bins. We assign the low, moderate, high and very high scoring bins the values of 1, 2, 3, and 4; respectively. The attribute/factor mean is calculated as the weighted mean of the number of tallies in each scoring bin and the value of each bin (Equation 1). For example, an attribute/factor with 10 tallies in the moderate scoring bin and 15 tallies in the high scoring bin would have a mean of 2.6.

$$((L * 1) + (M * 2) + (H * 3) + (VH * 4)) / (L + M + H + VH) = \text{Attribute or Factor Mean}$$

where:
L = # of tallies in “low” scoring bin
M = # of tallies in “moderate” scoring bin
H = # of tallies in “high” scoring bin
VH = # of tallies in “very high” scoring bin (1)

Second, a component score is calculated for sensitivity and exposure based on a logic model (i.e. decision rule): results are dependent on the number of attribute/factor means above a certain threshold (Table 3). We use a logic model, rather than averages (e.g., Johnson and Welch 2010, Patrick *et al.* 2010) because our attributes and factors are not intended to be correlated. Averaging tends to minimize the importance of high scoring sensitivity attributes or exposure factors. Our logic model contains strict criteria for receiving a “very high” component score: the species must receive a “very high” attribute mean (>3.5) in three or more of the individual sensitivity attributes or exposure factors. We created this high threshold to pull out those species with multiple risks (i.e., they will experience large changes in multiple environmental parameters, or they have specific life history requirements where environmental change could impact productivity through multiple mechanisms). The cut-offs for receiving “high” and “moderate” component scores follow similar but less strict criteria. A “high” component score requires at least two sensitivity attributes or climate factors receive a "high" attribute or factor mean (> 3.0). Similarly, a "moderate" component score requires at least two sensitivity attributes or climate factors to have an attribute or factor mean > 2.5. Any species that does not meet or exceed the criteria for moderate will receive a "low" score. These thresholds were developed using data from pilot studies.

Third, the overall vulnerability rank is determined by multiplying exposure and sensitivity. Low, moderate, high and very high component scores are assigned 1, 2, 3, and 4 respectively. The product is then classified where 1-3 results in a low vulnerability rank, 4-6 a moderate vulnerability rank, 8-9 a high vulnerability rank, and 12-16 a very high vulnerability rank. Results can be displayed visually using a vulnerability matrix, to show final ranks as well as component scores. For the most part, the overall vulnerability rank ends up being the lesser of the sensitivity or exposure scores (Chin et al., 2010). The theory is that the species needs to be sensitive to a change, as well as be exposed to a change, to be affected. For example, a species with a high sensitivity to temperature located in an area where the water temperature is not predicted to significantly increase will not be affected. Conversely, if temperature is expected to change but the species is not sensitive to temperature it also would not be affected. The vulnerability matrix diverges in one case from this simple logic. When one of the two scores is "very high", the overall vulnerability is increased by one rank. This is a precautionary way to identify the species that have the potential for unexpected responses due to very high levels of exposure or sensitivity.

To test the robustness of the results to different scoring techniques, we used the expert scores collected from the first full implementation of the methodology (see Hare *et al.*, in prep) to compare how the final vulnerability ranks would change if the scoring were based on means (final vulnerability was calculated as the average of mean sensitivity and mean exposure and divided into quartiles for assigning vulnerability rank). Sixty-one percent of the species fell into the same final vulnerability rank when using logic and when using means. Species with a few very high attribute scores had a higher vulnerability rank using our logic model when compared to using averages. This reinforced our decision to use logic because we want to pull out species with two to three high sensitivity attributes from those with moderate scores throughout.

While we believe the scoring rubric we have developed performs well, there are some caveats. First, by using a logic model that pulls out situations where a species is vulnerable from multiple attributes or factors, it can create a disconnect between attribute scores and component scores. For example, a species that experts score as moderate on all sensitivity attributes will receive a sensitivity component score of low. Second, the assessment can be sensitive to slight changes in scores if there are a limited number of high scoring sensitivity attributes or exposure factors. Third, the logic model can create artificial differences between species with very similar attribute/factor means. Theoretically, it is possible that a change in one tally on one attribute could increase or decrease the overall vulnerability rank one level. We recommend using a bootstrap simulation to identify situations where slight changes in expert scores can impact the overall vulnerability rank. By resampling the expert tallies (with replacement), the bootstrap simulation estimates the uncertainty in the final vulnerability rank, given the experts' scores (Hare *et al.*, in prep.).

4.0 VULNERABILITY ASSESSMENT PROCESS

The vulnerability assessment process involves five steps (Figure 3): scoping and planning, assessment preparations, scoring process, assessment results, and communicating results.

4.1 Scoping and Planning:

Three fundamental decisions need to be made when developing a new assessment: define the study area, select species, and determine which climate exposure factors are appropriate to include in the assessment. To ensure the assessment meets stakeholder needs, it is important to involve managers, scientists, decision-makers, and key stakeholders when developing the scope of the assessment.

When defining the study area, choose an area large enough to encompass most of the range of the species being studied. Using only a subsection of the range or life-cycle of the species can cause key vulnerabilities to be missed (Small-Lorenz *et al.*, 2013). A large marine ecosystem (Sherman and Hemple, 2009) is an appropriate scale for many species, but several large marine ecosystems may need to be considered for certain species (e.g., highly migratory species).

A number of factors should be considered when selecting species to include in the assessment, such as presence in the study area and ecological, cultural, or economic importance. The methodology can accommodate species with a wide range of available data. There is an economy of scale in developing the materials for the assessment; therefore, it may be beneficial to be more inclusive rather than overly selective when choosing species to analyze. Keystone species, such as forage fish, should be included as changes in their abundance could have strong impacts on other species.

This methodology can be applied either at the level of species or stock. In some cases, stocks of the same species may have different vulnerabilities due to geographic variability in exposures and/or biological attributes. For this paper, we have consistently described the methodology for species, but implementation at the stock level is encouraged if pertinent stock specific biological information exists. Things to consider when deciding to assess vulnerability at the stock versus species level include: 1) does the species range extend beyond the boundaries of the assessment study area 2) does stock specific information exist, and do life history characteristics or exposure differ substantially between stocks, and 3) at what level (stock or species) would the information be the most useful to management decisions.

When deciding which exposure factors should be included in the assessment, the project developers should consider: the magnitude of expected changes in the region, the importance of the climate factor to the biology of the species, and the confidence in future projections. For example, the extent of sea ice may be used in Arctic areas, while the number of coral bleaching events may be important in tropical areas (Donner, 2009). Project leaders will also have to decide if annual means, seasonal means, and/or variance is the most appropriate measure for each climate factor.

4.2 Assessment Preparation

The vulnerability assessment described in this paper is a “rapid” assessment compared to the in-depth single species investigations that have been described elsewhere (Hollowed *et al.*, 2009; Hare *et al.*, 2010; Hazen *et al.*, 2012; Plaganyi *et al.*, 2013; Wayte 2013). However, this method still requires resources, including staff time to prepare for and conduct the assessment.

A summary of the pertinent life history characteristics is needed to score each species and should be compiled in a document prior to the assessment. These “species profiles” do not need to be exhaustive, but should provide information on the characteristics needed to score each attribute. If information is not available for a species, data on a related species or data from outside the study area may be used with a lesser degree of certainty. Developing species profiles is a time consuming step (approximately 4 hours per species; J. Hare, pers. comm.) in the assessment process; however, pilot testing showed that species profiles are critical to the scoring process. These species profiles can use the scientific literature as well as the numerous summary documents generated as part of the scientific advice and fisheries management process (e.g., stock assessments, essential fish habitat documents, environmental impact statements).

Similar to a species profile, information about predicted climate change must be compiled prior to implementing this vulnerability methodology. Exposure factors can be based either on qualitative descriptions or quantitative outputs from climate models. In part to support the methodology reported here, NOAA’s Earth System Research Laboratory (ESRL) developed an online tool to provide the climate projections needed to score exposure factors (http://www.esrl.noaa.gov/psd/ipcc/). This tool can provide climate projection outputs from a number of climate models for a range of time frames (including seasonal variations) and for a range of factors. It is envisioned that this website could provide most of the climate exposure information needed in an implementation of this methodology. However, if downscaled models exist, they should be used as marine organisms have a stronger response to local vs global change (Pinsky et al. 2013). When possible, ensemble averages should be used, as they are often more accurate at matching past conditions than any one model (Stock *et al.*, 2011). Choose models that perform best in hindcasting recent conditions in the study area of the assessment. It is also important to consider the timeframe of the climate projections. If the timeframe is too long, (e.g., 100 years), the results are less relevant for current management decisions. If the timeframe is too short, (e.g., 10 years), the results will be dominated by interannual variability and not long-term change. We suggest using model averaged outputs for the past 50 years for determining current conditions and the next 50 years for the future condition.

We recommend that when data are available, the scoring bins for the exposure factors use a measure of the magnitude of change as a function of past variability. This is because change relative to natural fluctuations can be more important than absolute change (Richardson *et al.*, 2010, Tewksbury et al. 2008). For example, in terrestrial ectotherms, tropical species have adapted to low variability in temperature and many live near their thermal maximum, while temperate species with a wider thermal tolerance have a larger ability to adapt (Tewkesbury et al. 2008). We recommend the bin for a very high exposure factor represent projected means that are at or exceed historic extremes (see example in Hare *et al.*, in prep). We note that there may be some cases where changes in extremes may be a more suitable measure of change; for example, changes in temperature variability could be used to predict changes in extreme events (Hare *et al.*, in prep).

Some projected climate changes expected to affect fish species (e.g. changes in circulation) are not captured by climate models in a quantifiable way due to model resolution issues. For these exposure factors, qualitative descriptions of the expected changes can be used (Hare *et al.*, in prep), but they should provide as much spatial information as possible (e.g. any expected latitudinal or inshore/offshore gradients).

Knowledge of a species' distribution is needed to determine the area over which to evaluate the exposure factors. Distributional maps of species are available from a variety of sources including existing literature, survey databases or public online databases such as FishBase (www.fishbase.org) or the Ocean Biogeographic Information System (www.iobis.org). If possible, maps that overlay the current species distribution on top of the expected climate change would allow quick quantification of exposure scores. If the magnitude of exposure varies across the range of the species, the experts scoring exposure can spread their five tallies appropriately.

4.3 Scoring Process

We recommend the expert scoring process be split into two rounds: a preliminary round of individual scoring and a final round that includes a group discussion and the option to change their score. The preliminary stage ensures each expert has an equal opportunity to provide an initial score that is not influenced by other opinions (Ariely, 2009). During the final round the experts compare and discuss their scores in a workshop setting.

Experts have the chance to explain the rationale behind their scores and can change their scores based on new information provided during the workshop (for a similar approach, see Patrick and Damon-Randall, 2008; McDaniels *et al.*, 2010). This process is not intended to garner consensus among the group; rather, it helps identify and fix errors, reduce individual bias, encourage buy-in from the experts, and increases the precision of the final scores. Experts may or may not choose to change their scores based on what they heard, and final results do not identify which tallies came from which expert, allowing some anonymity.

4.4 Assessment Results

The assessment's outputs include an overall relative vulnerability rank for each species, information on the key sensitivity attributes and exposure factors that contributed to that rank, details on major data gaps, and a rank for the potential for shifts in distribution. The bootstrap analysis (see vulnerability assessment design component on calculating vulnerability ranks) describes the uncertainty associated with each ranking and shows where small changes in expert scores could result in a change in the overall vulnerability rank. Additional analyses such as jackknife analyses (systematically removing scores from one attribute, factor, or expert one at a time and re-running the analysis) can show the influence of each of these components on the final result. These subsequent analyses are very important, as they provide information regarding uncertainty in the final vulnerability rank, guidance as to data gaps and future research needs, and information about the importance of individual biological attributes and exposure factors.

4.5 Communication and Application of the Vulnerability Assessment Results

It is important to communicate results from the assessment in a way that maximizes the usefulness to the end users and limits misinterpretation (Table 4). The vulnerability matrix (Figure 4) is an effective tool for displaying the relative vulnerability of the species. Species with high sensitivity and high exposure are clearly identified in the matrix and should be the initial focus for both scientists and managers. Species that have high sensitivity scores and low exposure scores can have high latent vulnerability (*sensu* Foden *et al.* 2013). These species may not be vulnerable at this time but there is the potential for the species to be impacted if actual climate change differs substantially from predicted climate change. Species with high exposure and low sensitivity are potential persisters (*sensu* Foden *et al.* 2013). These species tend to have life history traits with high plasticity that allow them to adapt to environmental changes and possibly exploit newly created or vacated niches. Although, species with low sensitivity and low exposure may not be of the highest concern, there could still be key climate impacts on these species. In addition, there could be additional stressors (e.g., overharvest, pollution, and habitat loss) affecting the productivity and abundance of these species.

Although the vulnerability matrix provides a good overview of the results, species specific vulnerability narratives are a critical communication tool. The vulnerability narratives should not only identify the sensitivity attributes and exposure factors driving the score but should also explore the interplay between these factors and where important data gaps exist. Certain combinations of attributes, when found together, may either mitigate or exacerbate each other. For example, species experiencing high exposure changes in ocean acidification may not be impacted if their sensitivity to ocean acidification is low.

These vulnerability narratives add important context to the species' vulnerability rank and help managers and scientists identify specific areas for further analysis and potential management actions. Scientists can use the results to identify stocks that can benefit from additional research such as examining potential adaptive responses, developing mechanistic models, or incorporating environmental variability into stock assessments. Scientists can also use the results in combination with other information, such as social and economic importance, to identify research priorities (from data gaps) and species that could benefit from increased monitoring (and at what life stage). By identifying the key drivers for these species, scientists can investigate the development of mechanistic vulnerability models.

In the face of a changing climate, fisheries management can focus on two overarching strategies: increasing the resilience of the stock or system to predicted changes, or increasing the adaptability of the fishery or system. Managers can look at existing fishery management plans to determine if modifications are needed in light of climate change. There is debate over the definition of resilience as it relates to climate change. For the purposes of this paper, resilience is defined as the capacity of an ecosystem to absorb recurrent disturbances or shocks and reorganize or adapt to change while retaining essentially the same function and structure (Walker et al. 2004; McClanahan *et al.* 2012); and thus includes both resistance to change and recovery back to the original form. The species specific vulnerability narratives can provide context for the results and help managers identify species-specific attributes that make a particular species more or less resilient to climate change. For example, long-lived species tend to have one of two main life-history strategies: consistent low reproductive output (e.g., elasmobranchs) or high recruitment variability (e.g., *Sebastes* species) where the species withstands periods of poor environmental conditions by surviving until favorable conditions produce a strong year class—often called the storage effect (Chesson, 1984). The latter life history strategy could become less favorable with climate change, as the conditions required for successful recruitment may become less frequent or disappear altogether. Both these life-history strategies may benefit from management options that protect age class structure (Stevens *et al.*, 2000; Field and Francis, 2002) such as marine protected areas, reverse slot limits, or area closures based on distribution of older adults.

The second overarching fisheries management strategy is to increase the adaptability of the fishery or fishing community. Adaptation includes pro-active changes to the social or ecological systems that will improve their ability to adjust as environmental changes affect the system. "Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities" (Moser and Eckstrom 2010). Management regimes that increase flexibility may increase adaptability of the fishermen or community when changes occur. Flexibility in fisheries management can be separated into three hierarchical levels: management within fisheries, management between fisheries, and management across jurisdictions. Flexibility to adapt across all these levels will be needed as species abundances and distributions change through time. For example, species with specific environmental requirements for the egg, larval, and settlement stages could be more susceptible to match-mismatch dynamics (including prey, predators, favorable transport, etc.), where necessary resources are not available at the correct time (Kristiansen *et al.*, 2011; Peck *et al.*, 2012). Increased monitoring may allow scientists to identify when a recruitment failure occurs. The management framework for these species should be tailored to quickly respond to the recruitment failure as decreasing the lag time between changes in recruitment and management response decreases the probability for population collapse (Brown *et al.*, 2012). Alternatively, to increase the adaptability of the fishing community, the information on species-specific vulnerabilities from this assessment can be combined with information about a community's dependence on fishing (e.g. Jacob and Jepson 2009) to determine which communities may be more vulnerable. Vulnerable communities may require alternative management measures that allow fishermen to switch target species as the abundances change, or to increase the availability of alternative livelihoods that are not dependent on fishing.

5.0 CONCLUSIONS

Global climate change is affecting the physical, chemical, and biological characteristics of the world's oceans. These impacts are expected to increase in the future with continued changes in the planet's climate system. To effectively prepare for and respond to these impacts, the fisheries management community needs information on the potential impacts of climate change on important fisheries resources. Fishermen also need to know the impacts of climate change on fish species when making decisions (e.g., whether to buy or sell a permit or transferable quota). The methodology described here applies across multiple species and provides a relative rank of vulnerability to climate change as well as information about why a species may or may not be vulnerable to it. However, this methodology is not the only step necessary to prepare for climate change impacts on living marine resources. Rather, it is designed to be an early-step in the conversation about how to manage fisheries resources with changing climate and ocean conditions, and help guide the science needed to design and implement effective management actions. A better understanding of the vulnerability of fish and shellfish species will help fisheries scientists and managers identify and implement actions that increase the resiliency of managed fisheries.

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Table 1. A summary of the 12 sensitivity attributes, including the goal of the attribute and brief descriptions of what would be considered a low and a high score. Detailed attribute definitions can be found in Appendix 1.

Attribute	Goal	Low Score	High Score
Stock Size/Status	To determine if the stock's resilience is compromised due to low abundance	High abundance	Low abundance
Other Stressors	To account for other factors that could limit population responses to climate change	Low levels of other stressors	High levels of other stressors
Population Growth Rate	Estimate the productivity of a stock	High productivity	Low productivity
Complexity in Reproductive Strategy	Identify reproductive strategy that may be disrupted by climate change	Low complexity	High complexity
Spawning Cycle	Identify spawning strategies that are more sensitive to changes	Year round spawners	Short duration aggregate spawners
Early Life History Survival and Settlement Requirements	Determine the relative importance of early life history requirements for a stock	Larval requirements are relatively resistant to environmental change	Larval requirements are specific and likely to be impacted by environmental change
Sensitivity to Ocean Acidification	Determine the stock's relationship to "sensitive taxa"	Is not a sensitive taxa or rely on a sensitive taxa for food or shelter	Stock is a sensitive taxa
Habitat Specificity	Determine the relative dependence a stock has on habitat and the abundance of the habitat	Habitat generalist with abundant habitat available	Habitat specialist on a limited habitat type
Prey Specificity	Determine is the stock is a prey generalist or a prey specialist	Prey generalist	Prey Specialist
Sensitivity to Temperature	Known temperature of occurrence or distribution as a proxy for sensitivity to temperature	Species found in wide temperature range or has a distribution across wide latitudinal range and depths	Species found in limited temperature range or has a limited distribution across latitude and depths
Adult Mobility	Determine the ability of the stock to move if their current location becomes unsuitable	Highly mobile adults	Sessile adults
Dispersal of Early Life Stages	Estimate the ability of the stock to colonize new habitats	High dispersal	Low dispersal

Table 2. Data quality scoring guidelines.

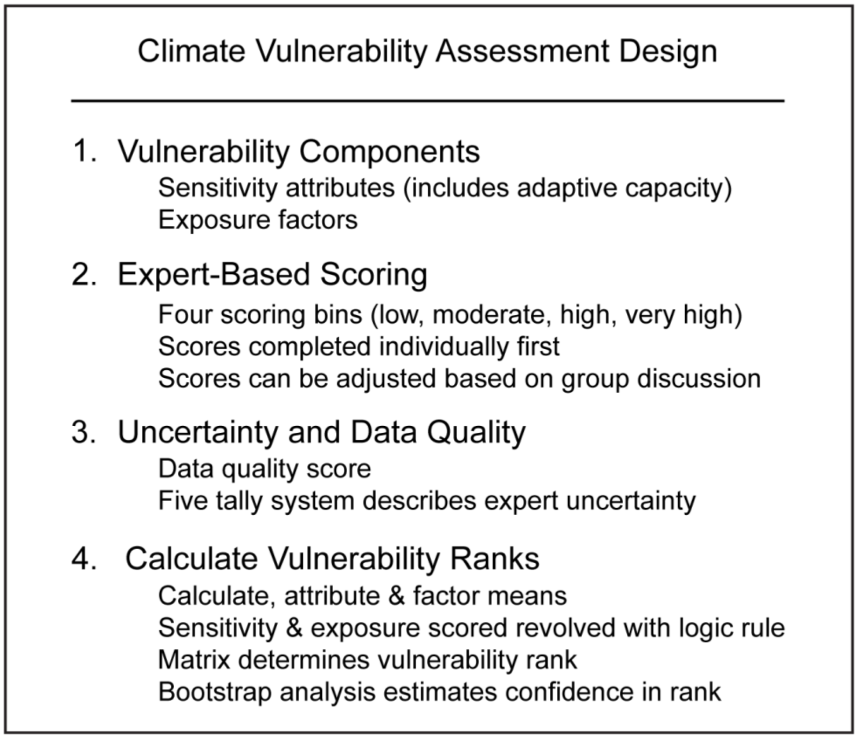
Data Quality Score	Description
3	**Adequate Data.** The score is based on data which have been observed, modeled or empirically measured for the species in question and comes from a reputable source.
2	**Limited Data.** The score is based on data which has a higher degree of uncertainty. The data used to score the attribute may be based on related or similar species, come from outside the study area, or the reliability of the source may be limited.
1	**Expert Judgment.** The attribute score reflects the expert judgment of the reviewer and is based on their general knowledge of the species, or other related species, and their relative role in the ecosystem.
0	**No Data.** No information to base an attribute score on. Very little is known about the species or related species and there is no basis for forming an expert opinion.

Table 3. Logic rules for determining each species' sensitivity and exposure component scores.

Component Score	Scoring Criteria
Very High	3 or more mean attribute or factor scores ≥ 3.5
High	2 or more mean attribute or factor scores ≥ 3.0
Moderate	2 or more mean attribute or factor scores ≥ 2.5
Low	Less than 2 or more mean attribute or factor scores ≥ 2.5

Table 4. Potential uses and misuses of assessment results.

Appropriate uses	Inform stakeholders as to the relative vulnerability of species. Identify important climate exposure factors and sensitivity attributes. Inform data gaps and contribute to setting research priorities. Identify species where mechanistic models are needed. Suggest species that could benefit from management strategy evaluations.
Potential misuses	Vulnerability rank does not indicate magnitude of effects, and therefore, results do not suggest appropriate catch levels or harvest control rules. Vulnerability rank does not replace need for mechanistic models. Results are region specific and may not extrapolate to regions outside of the designated study area



Climate Vulnerability Assessment Design

1. Vulnerability Components
    - Sensitivity attributes (includes adaptive capacity)
    - Exposure factors
2. Expert-Based Scoring
    - Four scoring bins (low, moderate, high, very high)
    - Scores completed individually first
    - Scores can be adjusted based on group discussion
3. Uncertainty and Data Quality
    - Data quality score
    - Five tally system describes expert uncertainty
4. Calculate Vulnerability Ranks
    - Calculate, attribute & factor means
    - Sensitivity & exposure scored revolved with logic rule
    - Matrix determines vulnerability rank
    - Bootstrap analysis estimates confidence in rank

Figure 1. Four design components for the climate vulnerability assessment.

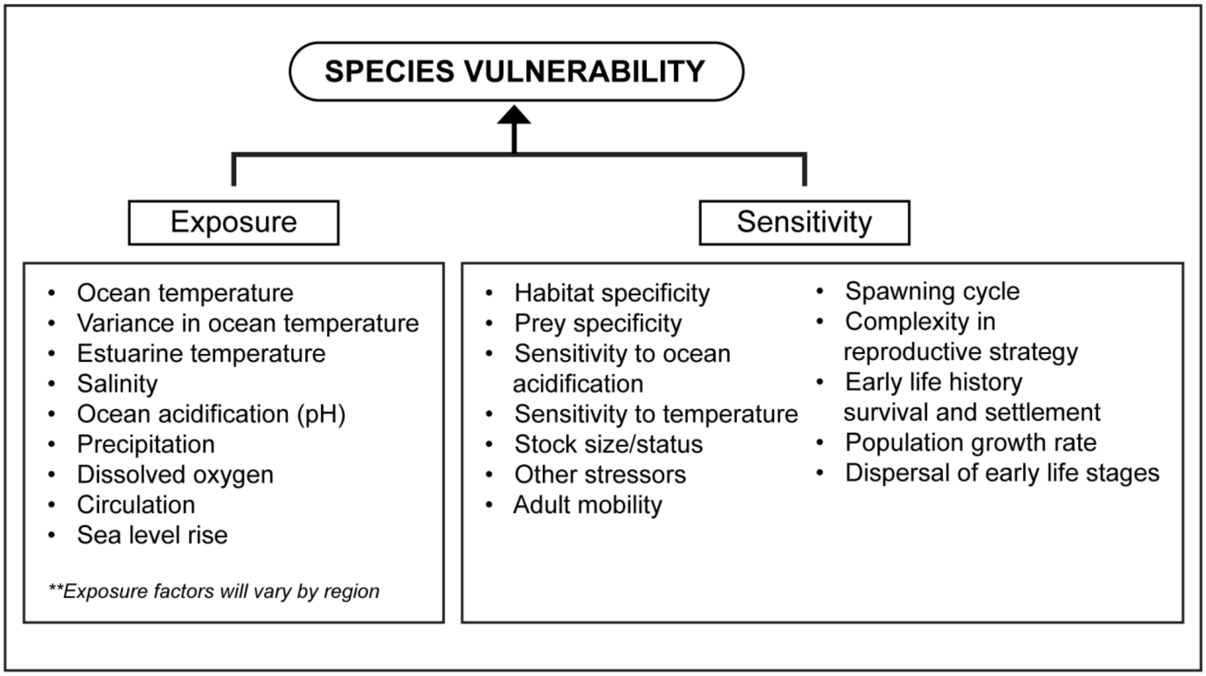
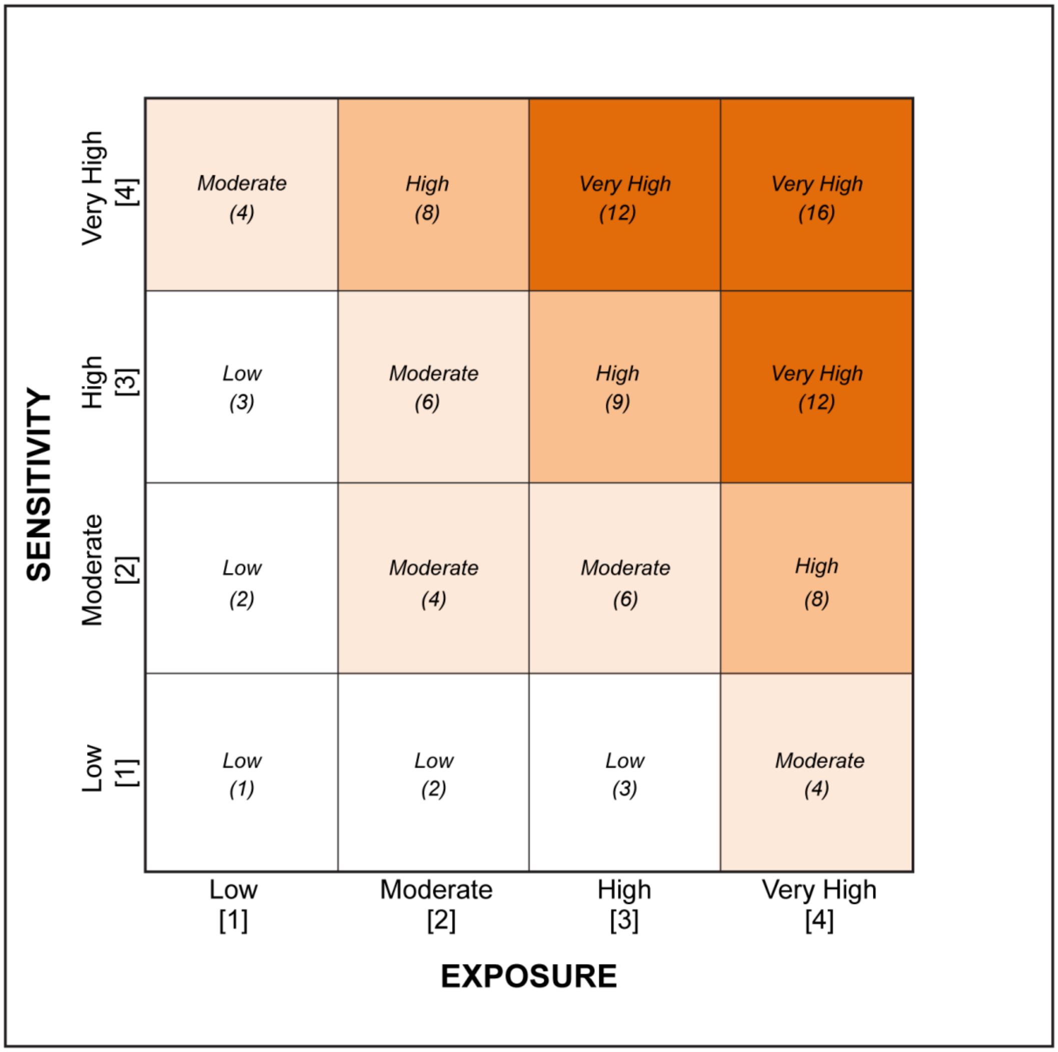


Figure 2. A species' vulnerability is based on a combination of its sensitivity and exposure. Exposure is determined by the overlap of the species' current distribution and the magnitude of the expected climate change (exposure factors used for the first full implementation (Hare *et al.*, in prep) are listed). Twelve sensitivity attributes characterize life history characteristics believed to be indicative of how much a species may be affected by a changing climate.

Climate Vulnerability Assessment Process

1. Scoping and Planning
    - Define scope (area, stocks, exposure factors)
    - Indentify and task leaders, staff, and experts
    - Indentify task leaders, staff, and experts
2. Assessment Preparation
    - Species profiles
    - Climate projections
    - Species distributions
3. Scoring
    - Train experts (webinar)
    - Preliminary round scoring (individual)
    - Final round scoring (workshop)
4. Results
    - Tables and figures
    - Sensitivity analysis
    - Final reports
    - Species vulnerability narratives
5. Communication
    - Engage with stakeholders
    - Communicate results:
        - Vulnerability ranks
        - Climate drivers
        - Data gaps
    - Promote use/application

Figure 3. The five process steps for the climate vulnerability assessment.



SENSITIVITY \ EXPOSURE	Low [1]	Moderate [2]	High [3]	Very High [4]
Very High [4]	*Moderate (4)*	*High (8)*	*Very High (12)*	*Very High (16)*
High [3]	*Low (3)*	*Moderate (6)*	*High (9)*	*Very High (12)*
Moderate [2]	*Low (2)*	*Moderate (4)*	*Moderate (6)*	*High (8)*
Low [1]	*Low (1)*	*Low (2)*	*Low (3)*	*Moderate (4)*

Figure 4. Matrix for determining a species, vulnerability rank based on component scores for exposure and sensitivity. Component scores are given a value of 1-4 (in brackets). Vulnerability rank is determined by multiplying the two component scores (in parenthesis).

APPENDIX A – Sensitivity Attribute Definitions and Bins

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Habitat Specificity

Goal: To determine, on a relative scale, if the stock is a habitat generalist or a habitat specialist while incorporating information on the type and abundance of key habitats.

Relationship to climate change: Generalists stocks should be more resilient to changing resource availability (habitat and food) than specialists (Wilson et al. 2008, Clavel et al. 2011, Graham et al. 2011, Pecl, 2014). This is because specialists are dependent on not only their own response to climate change, but also the impact on their habitat (EPA 2009). Note: the type and distribution of these habitats should be considered for this attribute.

Background: Changes in climate are expected to alter marine and coastal habitats that fish stocks depend upon. Species that are habitat generalists (can utilize several different habitat types) are expected to be more likely to succeed in a changing environment (Wilson et al. 2008, Clavel et al. 2011). The more a species specializes on a specific habitat, the more likely the species will be impacted by an environmental change. However, not all habitats are expected to be impacted equally. Species that depend on habitats that are abundant and wide ranging are less likely to be impacted by changes than species that depend on habitats that are limited in scope. We expect habitats that are created by disturbances (e.g., coral rubble or edge habitats) to increase with climate change. In addition, biological habitats (i.e., live coral reefs, deep water corals, mangroves, salt marshes, sea grass beds) are more likely to be impacted by the changes than physical habitats (sand, mud, rocky bottom). When considered together, these three criteria (habitat specialist or generalist; whether or not the stock depends on biological habitats; and habitat availability) are indicative of how a stock will be impacted by climate-induced changes on habitat.

How to use expert opinion: This attribute will be scored using a combination of the three criteria described above: habitat specialist or generalist; whether or not the stock depends on biological habitats (i.e., live coral reefs, deep water corals, mangroves, salt marshes, sea grass beds); and habitat availability (limited vs. abundant). It is understood that these criteria are not dichotomous but are a continuum. Stocks that are dependent on “disturbed” habitats should do fine or increase with climate change, so put these species in the “low” bin. If you think that a stock fits in multiple scoring bins, weight your 5 tallies between the appropriate bins. Using your expert opinion, account for any lifespan or ontogenetic shifts in diet; however, limit your response to the juvenile and adult life stages as larvae are considered under the attribute “early life history survival and settlement requirements.”

Habitat Specificity Bins:

1. **Low: The stock is a habitat generalist and/or utilizes very common abiotic habitats.** Occurrences of the stock have been documented in diverse habitats. Also, included in this bin are stocks that are restricted to one abiotic habitat which is widespread and common (e.g., vast stretches of sandy bottom, or pelagic waters over a large range).
2. **Moderate: The stock strongly prefers a particular habitat.** The stock prefers a particular habitat, but can survive in other habitats (with possible impacts to their fitness).
3. **High: The stock is a specialist on an abundant biological habitat.** The stock is a specialist that is restricted to a specific, but common biological habitat.
4. **Very High: The stock is a specialist on a restricted biological habitat.** The stock is a specialist that is restricted to a specific and uncommon biological habitat.

Prey Specificity

Goal: To determine, on a relative scale, if the stock is a prey generalist or a prey specialist.

Relationship to climate change: Generalists stocks should be more resilient to changing resource availability (habitat and food) than specialists (Wilson et al. 2008, Clavel et al. 2011, Graham et al. 2011, Pecl et al. 2014). Understanding how reliant a stock is on specific prey species could predict its ability to persist as the climate changes. Specialists (who have specific prey requirements) are likely to be more vulnerable to climate change because their persistence is dependent on not only their own response to climate change, but also the response of their prey. During mass extinction events of the past, diet specialists were more prone to extinction than diet generalists (Clavel et al. 2011).

Background: Climate change impacts extend beyond the stock in question to include species within its food web (e.g., prey, predators and competitors).

How to use expert opinion: The scoring bins below estimate the stocks' relative distribution along a continuum that runs between prey specialists and prey generalists. Using your expert opinion, account for any lifespan or ontogenetic shifts in diet; however, limit your response to the juvenile and adult life stages as larvae are considered under the attribute "early life history survival and settlement requirements." For this attribute, prey type refers to groups of similar species; copepods, krill, forage fish, etc., for example, are each categorized as a prey type.

Prey Specificity Bins:

1. **Low: The stock eats a large variety of prey.** The stock can eat a variety of prey types depending on what is available. Include detritivores, herbivores, and omnivores in this bin.
2. **Moderate: The stock eats a limited number of prey types.** The stock can feed on a wide variety of prey species, but are restricted to a limited number (~3) of prey types (copepods, krill, forage fish, etc.).
3. **High: The stock is partial to a single prey type.** The stock's diet is composed of one main prey type. The stock is able to switch to a different prey type if the preferred food is unavailable, but this may negatively impact fitness.
4. **Very High: The stock is a specialist.** The stock is dependent on one prey type and is unable to switch to alternatives if the preferred prey is unavailable.

Adult Mobility

Goal: To estimate the ability of the stock to move to a new location if their current location changes and is no longer favorable for growth and/or survival.

Relationship to climate change: Site-dependent species that are unable to move to better habitat when a location becomes unfavorable are less able to adapt to environmental change than highly mobile species (Foden et al. 2013).

Background: As climate change occurs, habitats that were once suitable may change and no longer be able to sustain a given stock of fish. Similarly, what was once unsuitable habitat may become suitable. A stock can survive changes in habitat as long as they have the ability to disperse from unsuitable habitat and find new, suitable habitat; and dispersal ability can be used as a proxy for the capacity to change distribution (Pecl et al. 2014). This can occur through larval dispersal and settlement (covered under the "Dispersal of Early Life Stages" attribute) or through adult mobility. Species can be limited in their mobility by physical or behavioral (e.g., won't swim across open ocean) barriers.

How to use expert opinion: This attribute represents a continuum from sessile to highly migratory organisms. Use your expert opinion to place the stock in question in the appropriate bin according to its physical and behavioral ability to move. Homing behavior for spawning should not be considered here as it is accounted for in the "Complexity in Reproductive Strategy" attribute. For this attribute, we define site-dependent stocks as those whose adults are site-attached (i.e., spend their entire adult phase in one limited location).

Adult Mobility Bins:

1. **Low: Non-site dependent**. The stock is highly mobile and non-site dependent.
2. **Moderate: Site dependent but highly mobile.** The stock has site-dependent adults capable of moving from one site to another if necessary.
3. **High: Site dependent with limited mobility.** The stock has site-dependent adults that are restricted in their movement by environmental or behavioral barriers.
4. **Very High: Non-mobile.** The stock has sessile adults.

Dispersal of Early Life Stages

Goal: To estimate the ability of the stock to colonize new habitats when/if their current habitat becomes less suitable.

Relationship to climate change: In general, the greater the dispersal of larvae, the better its ability to respond to climate change. Wide distribution of eggs and larvae can lead to greater ability to colonize new habitats in areas that are suitable for survival. Conversely, if a stock has limited larval distribution and the habitat in the localized area becomes unsuitable, then the stock is more likely to be negatively affected.

Background: For marine species, extended larval dispersal is an important strategy for colonizing new areas. Duration of the larval stage may impact dispersal distance and stock persistence. Jablonski and Lutz (1983) found that marine invertebrates with relatively long planktonic larval stages were more persistent in the fossil record than those species with non-planktonic larvae and had lower extinction rates. Early life stage dispersal is affected by a number of factors including spawning, advection, diffusion, larval behavior, planktonic duration, planktonic survival, and settlement habitat (Pineda *et al*. 2007; Hare and Richardson 2014). In general, studies have found that spawning time and place and planktonic duration are key factors, but the other factors can be important in specific situations.

How to use expert opinion: The main point of this attribute is to estimate dispersal ability. If no information is known about actual dispersal distances, capacity for larval dispersal can be estimated by a stock's larval duration (hatching to settlement in benthic species and hatching to yolk-sac re-absorption in pelagic species) (Pecl et al. 2014). However, if information about actual dispersal distances are known, use that information. If a stock has a relatively short larval duration, but is known to disperse large distances, or if the larvae are able to influence dispersal through selective tidal stream transport, adjust your tallies accordingly. Keep in mind that long-distance dispersal of only a small fraction of the larvae could still be adequate for colonization of new areas in a changing climate. We note that since elasmobranchs have evolved life history strategies that produce a smaller number of well-developed offspring, the impact of this attribute will be reduced: 1) for elasmobranchs with live birth, dispersal will occur while in utero and should be scored as low to moderate, 2) for elasmobranchs with egg cases, egg dispersal will be more limited, but juveniles will have the ability to disperse if needed so these stocks should be scored as moderate to high.

Dispersal of Early Life Stages Bins

Larval durations utilized in Bins are adapted from Pecl *et al*. (2014); distances are provided on a log-scale to show general/large changes in magnitude.

1. **Low: Highly dispersed eggs and larvae.** Duration of planktonic eggs and larvae greater than 8 weeks and/or larvae are dispersed >100 km from spawning locations.
2. **Moderate: Moderately dispersed eggs and larvae.** Duration of planktonic eggs and larvae less than 8 but greater than 2 weeks and/or larvae are dispersed 10-100 km from spawning locations.
3. **High: Low larval dispersal.** Duration of planktonic eggs and larvae less than 2 weeks and/or larvae typically found over the same location as parents.
4. **Very High: Minimal larval dispersal.** Benthic eggs and larvae or little to no planktonic early life stages.

Early Life History Survival and Settlement Requirements

Goal: To determine the relative importance of early life history requirements for a stock.

Relationship to climate change: In general, the early life stages (eggs and larvae) of marine fish are characterized by high mortality rates, via predation, starvation, advection, or unsuitable conditions. Small changes in the environment can lead to large changes in early life survival, which can affect recruitment and year-class strength. Large scale climate change could have a greater impact on species that have more specific early life history and settlement requirements.

Background: Close to 100 years ago, fisheries scientists recognized the importance of recruitment variability in fish populations (Hjort 1914). Despite considerable research devoted to fisheries recruitment, there is still considerable uncertainty about how environmental variability impacts recruitment (Punt et al. 2013). Scientists now understand that multiple processes are important during the egg and larval stages (Houde 2008). Conditions that can lead to decreased or negligible recruitment include:

- Larvae that are dependent on specific biological conditions in the water column during their larval stage. For example, if the larvae are dependent on the presence of food at a specific point in development, different emergence of the larvae and the food (due to dependence on different cues) could result in a mismatch in availability. Alternatively, if the larvae have evolved to survive in low predator (and low food) conditions, a change in predation pressure could impact survival (Bakun 2010).
- Larvae or eggs that are dependent on specific physical conditions to survive (e.g., specific temperature requirements for eggs, temporary gyres that provide food and retention for larvae, calm conditions that allow for concentration of larval prey, specific transport pathways to nursery habitats, etc.) (Houde 2008).
- Larvae that are dependent on a cue for settlement or metamorphosis that could be impacted by a changing climate (Pecl et al. 2014).

For the purpose of this assessment, early life history requirements include the environmental conditions necessary for larval survival, and encompass the eggs, pelagic larvae stages, and settlement. The more specific the early life history requirements, the more precise the environmental conditions may need to be, and thus the more vulnerable the stock may be in a changing environment. Note: some fish species, namely elasmobranchs, have evolved life history traits which minimize or eliminate early life stages either by birthing well-developed young or by laying egg cases that allows embryos to fully develop before hatching. Therefore, elasmobranchs should be ranked as “Low.”

How to use expert opinion: Marine species are largely dependent on both physical and biological conditions during their larval stage. However, the reliance on specific conditions varies between stocks. For the bins below, recruitment can be characterized as low variability when there is relatively constant recruitment events every 1-2 years, and high variability when the stock experiences highly episodic recruitment events (Pecl et al. 2014). If no citable reference is available on a stock’s early life history survival and settlement, the score may be based on expert opinion.

Early Life History Survival and Settlement Bins:

1. **Low: Larval requirements are minimal.** Stock has general requirements for the larval stage that are relatively resilient to environmental change. Elasmobranchs should be ranked as “Low.”
2. **Moderate: Larval requirements are minimal or unknown.** Stock requirements are not well understood and recruitment is relatively constant, suggesting limited environmental influence.
3. **High: Larvae have some specific requirements.** Stock requirements are not well understood, but recruitment is highly variable and appears to have a strong dependence on environmental conditions.
4. **Very High: Larvae have multiple specific requirements.** Stock has specific known biological and physical requirements for larval survival.

Complexity in Reproductive Strategy

Goal: To determine how complex the stock's reproductive strategy is and how dependent reproductive success is on specific environmental conditions.

Relationship to climate change: Species that have complex reproductive strategies (that require a series of events or special conditions) are more likely have these conditions disrupted by changes in the environment.

Background: There is great diversity in reproductive strategies in marine fishes. The more complex the reproductive strategy, the more precise the conditions may need to be, and thus the more vulnerable the stock may be to environmental change. For our purposes, complexity in reproductive strategy is defined as reproductive behaviors, characteristics or cues that create specific requirements that must be met in order for reproduction to be successful. Species with reproductive events that are dependent on temperature (vs. day-length) cues will be more sensitive to climate change (Pecl *et al*. 2014).

How to use expert opinion: A list of common reproductive characteristics that may affect the reproductive capacity of a stock in a changing climate is provided below. To score, determine if any of these examples apply to the stock. Note: this is not intended to be an exhaustive list. If other characteristics exist that may affect a stock's reproduction capacity in a changing climate, incorporate that information and adjust your score appropriately.

Example reproductive characteristics that create "complexity":

- The stock has known temperature effects on reproduction. Examples include temperature-dependent sex changes, and temperature cues that impact spawning, gonad development, etc.
- The stock uses large spawning aggregations. Large spawning aggregations can contribute to a high sensitivity because a large number of individuals must get to the spawning area simultaneously (i.e., migration or cues to migrate may be impeded by a change in the environment), the spawning area has to retain the environmental conditions that made it successful in the past, and the reproductive success for that year is dependent on the conditions present at one time period.
- The stock experiences decreased recruitment per spawner, or a weakening in the strength of density dependence, at low stock sizes, potentially because of depensation/Allee effects. If unknown, does the stock share life history characteristics that would predict depensation effects (e.g., significant changes in the relative abundance of the stock's predators/prey at low stock densities, decreased fertilization success at low stock sizes)?
- The reproductive success of the stock requires the use of vulnerable habitats (freshwater, estuaries, mangroves, salt marshes, corals) for spawning or rearing of young. Vulnerable habitats are likely to experience larger climate change impacts (such as changes in salinity, dissolved oxygen, pollution, sedimentation, or water depth), and stocks that require these habitats for successful reproduction will likely be impacted.

Complexity in Reproductive Strategy Scoring Bins:
If a particular characteristic is suspected to have a large impact on the stock, adjust the score appropriately.

1. **Low: Simple reproductive strategy.** The stock contains no more than one characteristic that suggest complexity in reproductive strategy.
2. **Moderate: Slight complexity.** The stock has two characteristics that suggest complexity in reproductive strategy.
3. **High: Complex reproductive strategy.** The stock has three characteristics that suggest complexity in reproductive strategy.
4. **Very High: Very complex reproductive strategy.** The stock has four or more characteristics that suggest complexity in reproductive strategy.

Spawning Cycle

Goal: To determine if the duration of the spawning cycle for the stock could limit the ability of the stock to successfully reproduce if necessary conditions are disrupted by climate change.

Relationship to climate change: It is assumed that stocks that spawn throughout the year will be more likely to be successful in a changing environment: "Protracted spawning is believed to enhance offspring survival by allowing the stock to "hedge its bet" against adverse environmental conditions" (Marteinsdottir and Thorarinsson 1998). Conversely, stocks that spawn all at once in major events are more likely to experience recruitment failure with potential changes in environmental conditions.

Background: Spawning characteristics describe the spawning activity of a stock (in aggregate, not individually) over a particular time frame. If a stock spawns several times per year across a variety of seasons, then they will likely be less susceptible to climate change because their reproductive events are not dependent on just one set of very specific conditions (e.g., phenological events). Increased spawning events, also help to protect against vulnerabilities associated with single spawning aggregations (see the "Complexity in Reproductive Strategy" attribute). Similarly, stocks that reproduce seasonally are also less likely to adapt to climate change as they are dependent on environmental conditions historically present during a given season that may not persist through time. For example, spring-like conditions and related activities have occurred progressively earlier since the 1960s (Walther *et al*. 2002) and changes in spawning season and location have already been observed and predicted to continue (Shoji *et al*. 2011; Rijnsdorp *et al*. 2009). Note: We are describing the spawning activity of the entire stock, not the individual. In other words, we are interested in the time from when spawning commences until when it ends, not how long a single individual spawns.

How to use expert opinion: It is impossible to distill every potential spawning cycle into 4 scoring bins. The below bins are rough breaks in a continuum of possibilities. If a species does not fit the below bins, use your expert judgment to best score the species based on the above discussion. For stocks (such as elasmobranchs) that are born as fully developed juveniles capable of long distance movements, there is less concern over a short hatching/mating period, and these stocks should be ranked low to moderate.

Spawning Characteristics Bins:

1. **Low: Consistent throughout the year.** Stocks that spawn continuously throughout the year without a defined "spawning season" are less likely to suffer spawning failure. Example: a stock that spawns daily or monthly.
2. **Moderate: Several spawning events throughout the year.** Stocks that spawn several times per year and spawn across more than one season have a moderate likelihood of spawning success to be impacted by climate change. Example: a stock that spawns in both the spring and summer.
3. **High: Several spawning events per year within a confined time frame.** Stocks that may spawn several times per year but all spawning events in that year take place in one season have a higher likelihood of being affected by climate change. Example: the spawning season occurs once a year and lasts over a period of less than 3 months.
4. **Very High: One spawning event per year.** Stocks that require very specific environmental/social cues to initiate spawning and that only spawn once per year have the highest likelihood of being affected by climate change. Example: the spawning season occurs once a year over a brief period of time.

Sensitivity to Temperature

Goal: To use information regarding temperature of occurrence or the distribution of the species as a proxy for its sensitivity to temperature.

Relationship to climate change: Species that experience a wide range of temperature regimes are more likely to persist in a warming ocean.

Background: A species temperature requirements can be a good predictor of how it will respond to climate change. For species that lack specifics on temperature requirements, the latitudinal coverage of the species can be a proxy for temperature tolerance (Pecl *et al*. 2014). Since species can cover a wide tropical latitude but still have a limited temperature tolerance, distribution of a species within or across provinces can be used instead. Spalding *et al*. (2007) (Figure A1) divides coastal waters of the world into 62 provinces and 232 ecoregions. Even though Spalding's provinces are not specifically based on temperature (they also consider upwelling, currents, salinity, nutrients, etc.), they can be used to delineate areas with similar thermal conditions.

In addition, a species' distribution in the water column and seasonal movements can indicate its sensitivity to temperature. Species that make large diurnal migrations across the thermocline have lower sensitivities to changing temperatures than species that have limited depth distributions. Additionally, species that make large seasonal migrations and track seasonally changing water temperatures may have more sensitivity to temperature than indicated by range alone.

How to use expert opinion: Use known temperature requirements to score this attribute when available. When temperature information is not known, use the species distribution, along with Figure A1 to determine if a species is found across >1 province. Also use knowledge of seasonal and diurnal movements to adjust the tallies. Keep in mind that you can adjust your tallies depending on the distribution of the species relative to the area of interest (i.e., if the area of interest is at the edge of the distribution of the species, consider if the species is expected to move out of or expand into the area of interest). Spalding *et al*. (2007) only characterize coastal environments; therefore, use your expert opinion for open ocean species. If information about temperature requirements or depth distributions is available, use this to modify your response. For example, if a species is found across 2 provinces, but it has a limited depth distribution, the expert could distribute the 5 tallies between bins 2 and 3. If a species' sensitivity changes with ontogeny, consider the most limited stage when determining the most appropriate bin(s). Given that a stock range will always be less than a species range, if scoring temperature dependence for a stock, consider not only the stock range, but also the species range as the species range may predict the stock's ability to adapt. Consideration of the species distribution relative to the study area is also important. Stocks at the cold edge of the species range would be expected to fare well, while stocks at the warm edge of its species range may not (Planque and Fredou 1999, Drinkwater 2005).

Temperature Sensitivity Bins:

1. **Low: Large temperature range.** Species occurs in a wide range of temperatures (>15^{o}C), or is found across 3 or more provinces.
2. **Moderate: Moderate temperature range.** Species occurs in a moderately wide range of temperatures (10-15^{o}C), or is found across 2 provinces.
3. **High: Somewhat limited temperature range.** Species occurs in a moderately narrow range of temperatures (5-10^{o}C), or is found within one province but has a variable depth distribution.
4. **Very High: Very limited temperature range.** Species occurs in a narrow range of temperatures (<5^{o}C), or is found within one province and has a limited depth distribution (i.e., depth range is <100 m).

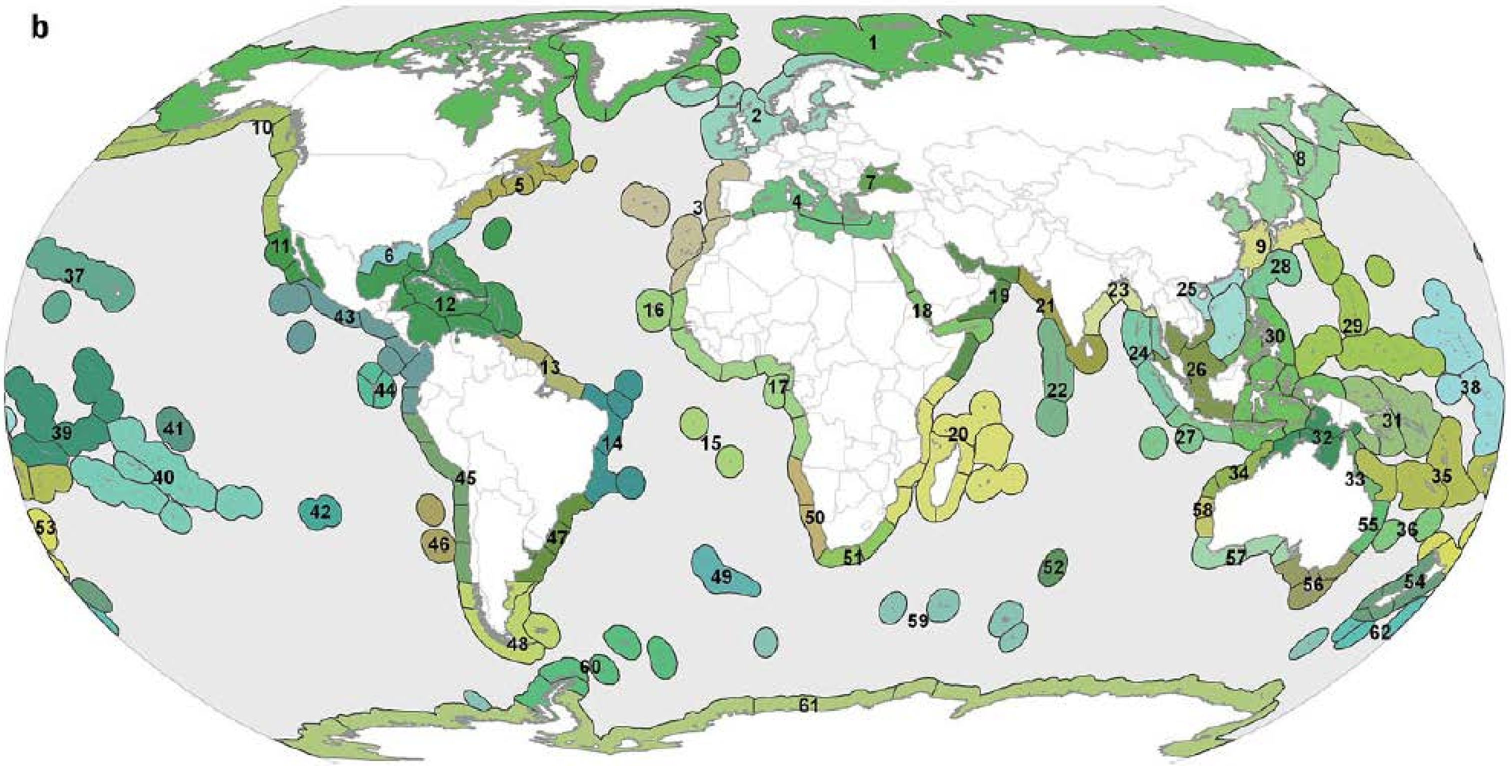

Figure A1. Originally published in Spalding *et al*. 2007. Provinces are provided in color with ecoregions outlined.

Sensitivity to Ocean Acidification

Goal: To estimate a stock's sensitivity to ocean acidification (OA) based on its relationship with "sensitive taxa."

Relationship to climate change: Impacts of OA on marine organisms can be highly variable, with considerable variability between taxa and species. Therefore, we are estimating impact of OA by examining the dependence of the stock on sensitive taxa. For example, current research shows a consistent negative impact of OA on mollusks, corals, calcified algae and echinoderms (Kroeker et al. 2013), so species in these classes or dependent on species in these classes should be considered more sensitive to changes in ocean pH. We expect the volume of research into ocean acidification to increase in the near future, so this attribute will be updated as new information becomes available.

Background: Ocean acidification is often called "the other carbon dioxide problem," and is the term given to the chemical changes in the ocean as a result of carbon dioxide emissions (Wicks and Roberts 2012). While initial research suggested that the majority of species that have calcium carbonate or chitin shells or those that lay down calcium carbonate skeletons (corals) will be negatively impacted by ocean acidification (Arnold *et al*. 2009; Hoegh-Guldberg *et al*. 2007; Honisch *et al*. 2012; Kawaguchi *et al*. 2011; Orr *et al*. 2005), recent studies have highlighted a high variability in response between different shelled organisms and suggest that not all shelled species will be impacted to the same degree and not all impacts will be negative. (i.e., Ries *et al*. 2009; Kroeker *et al*. 2013). For example, Kroeker *et al*. (2013) in a meta-analysis of 228 studies found significant and consistent negative impacts of OA on the larval stages of mollusks and corals. However, recent research suggests soft corals may not be as sensitive as stony corals (Gabay et al. 2014) In contrast, high variability in the responses of crustaceans suggests impacts may be species specific within this group, with brachyuran crustaceans showing a higher resistance (Kroeker *et al*. 2013).

The direct effect of ocean acidification on finfish is not well understood. Recent research suggests impacts on finfish stocks will be most prevalent at the egg and early larval stages (Baumann *et al*. 2011; Franke and Clemmenssen 2011; Frommel *et al*. 2011), but juvenile and adult olfaction and behavior may also be affected (Munday *et al*. 2009; 2014). Despite these studies, not enough is known to be able to predict which finfish stocks will be more sensitive. This attribute will be updated when more information is available on which finfish stocks are more likely to be directly impacted by ocean acidification.

How to use expert opinion: Use current information on a species' reliance on sensitive taxa (e.g. corals, mollusks, echinoderms, or calcified algae; see Kroeker et al. 2013) to bin species. When scoring, base your score on the most sensitive life stage, if appropriate. In cases where research has shown that the effects of OA may be positive or mitigated by biological processes (e.g., reduced OA by plant absorption of CO_2), use your expert judgment to inform the score. We have binned sensitive taxa which are directly impacted by changes in OA as "very high" and those dependent on sensitive taxa as "high" due to the indirect impact. However, use your expert opinion to place your tallies between these groups depending on your perception of the species' adaptability.

Sensitivity to Ocean Acidification Bins:

Sensitive taxa are taxa that consistently show negative effects from OA, such as hard corals, mollusks, calcified algae, and echinoderms (Kroeker *et al*. 2013).

1. **Low: Stock either does not use sensitive taxa, or is expected to respond positively to ocean acidification.** The stock does not utilize sensitive taxa for food or habitat. Species expected to respond positively to ocean acidification should be scored as low.
2. **Moderate**: **Stock is somewhat reliant on sensitive taxa.** The stock utilizes sensitive taxa as either food or habitat, but can switch to non-sensitive taxa when necessary. This can include omnivores and species that prefer coral habitats but can utilize any rigid structure.
3. **High: Stock is reliant on sensitive taxa.** The stock is dependent on sensitive taxa for either food or habitat (i.e., cannot switch to a non-sensitive alternative).
4. **Very High: Stock is a sensitive taxa.** The stock is a sensitive taxa (such as hard corals, mollusks, calcified algae, and echinoderms) that have been shown to have a consistent negative impact of OA on survival.

Population Growth Rate

Goal: To estimate the relative productivity of the stock.

Relationship to climate change: More productive stocks are, in general, more resilient to long term changes in the environment, such as climate change (Lande 1993; Pecl et al. 2014).

Background:

Productivity is a measure of the capacity of the stock to reproduce and recover if the population is reduced. In general, it is thought that highly productive stocks are more resilient to change because they are quicker to respond to impacts, such as fishing, or catastrophic events (Lande 1993; Pecl et al. 2014). In fisheries, productivity can be measured as the maximum intrinsic rate of increase (r_{max}). We are interested in the maximum intrinsic rate of increase as it describes how fast a population is able to recover from a disturbance. Given density dependence, the classic model of population growth can be given by: $\partial N/\partial t = r_{max} N(1 - \frac{N}{K})$, where K is carrying capacity and for which population growth rate is maximized at 0.5K.

If a direct measurement of the maximum intrinsic rate of increase (r_{max}) is unavailable, other biological reference points that are correlated with population growth rate can be used: von Bertalanffy growth rate (k), age at maturity, maximum age, natural mortality and maximum length (Patrick *et al*. 2010; Hutchings et al. 2012). Scoring bins for these proxies were developed from an analysis of 141 marine fish species that were considered to be representative of U.S. fisheries (Patrick *et al*. 2010).

How to use expert opinion: Multiple proxies may be used to inform the final score, but the accuracy and precision of the different proxies should be considered. For example, a stock with a “good” estimate of age at maturity is in the range for a “High” score, and a “fair” estimate of maximum age is in the range for the “High” scoring bin. In that case, the scorer should use their expert opinion to weight their response according to their confidence in the estimates. If no estimates are available, estimate a relative score for the stock across a continuum of r-selected (low) vs. k-selected (high) species.

Population Growth Rate Bins:

Parameter	**Low**	**Moderate**	**High**	**Very High**
Maximum growth rate (r_{max})	> 0.50	0.16 - 0.50	0.05 - 0.15	< 0.05
von Bertalanffy K	> 0.25	0.16 - 0.25	0.11 - 0.15	<= 0.10
Age at maturity	< 2 yrs	2 - 3 yrs	4 - 5 yrs	> 5 yrs
Maximum age	< 10 yrs	11 - 15 yrs	15 - 25 yrs	> 25 yrs
Natural mortality (M)	> 0.50	0.31 - 0.50	0.21 - 0.30	< 0.2
Maximum length	< 55 cm	55 – 85 cm	85 – 150 cm	> 150cm

Stock Size/Status

Goal: To estimate stock status to clarify how much stress from fishing the stock is experiencing and to determine if the stock's resilience or adaptive capacity are compromised due to low abundance.

Relationship to climate change: It is assumed that a stock that has a large biomass is more resilient to changes in climate. Conversely, stocks with very low biomass are likely to be in a compromised ecological position and therefore may have a diminished capability to respond to climate change (Rose 2004). The genetic diversity, as well as the abundance, of a stock can impact its susceptibility. The assumption is that species with a limited genetic diversity could be more negatively impacted by climate change as their offspring would be less variable and thus less likely to have the combination of genes needed to adapt to changes in the environment. Note: stocks that are at historical high biomass levels may be an indication of a net positive effect to an environmental change.

Background: Fish stocks that are already being affected by other stressors are likely to have faster and more acute reactions to climate change. Fishing is the largest stressor currently impacting fish stocks (Jackson *et al*. 2001), and the magnitude of the stress can be estimated through the status of the stock. Stock size/status can be measured as a ratio of the current stock size (B) over the biomass at maximum sustainable yield (B_{MSY}) and is a commonly used biological reference point for U.S. federally managed stocks. For other areas, B_{max} may be available and can also be used. Use the following link for information on current estimates of B/B_{MSY} in U.S. species: http://www.nmfs.noaa.gov/sfa/statusoffisheries/SOSmain.htm.

Low genetic variation can decrease a species' ability to adapt to climate change. Large variation in reproductive success between individuals, large fluctuations in population size, and frequent local extinctions can all decrease genetic diversity (Grosberg and Cunningham 2001). Presence of these characteristics could suggest a decreased ability to adapt to changes in the environment.

Beyond stock status and genetic diversity, there are additional concerns for stocks that are particularly rare. The IUCN classifies stocks with a population <10,000 mature individuals as vulnerable (IUCN 2015). Therefore, for the purposes of this attribute, stocks with population sizes less than 10,000 individuals are considered to have significantly reduced ability to adapt to climate change and should be scored as "Very High."

How to use expert opinion: If a direct measure of biomass is not available, biomass proxies (such as survey indices or spawning stock biomass) may be used. For data-poor stocks with an unknown status, or stocks that are analyzed as part of a species group, use your expert opinion to estimate the stock size and rate the data quality accordingly. We note that B_{MSY} can change (NEFSC 2012), which will affect B/B_{MSY} ratio and thus vulnerability scores. In situations where B_{MSY} has been recently updated, use your expert opinion to adjust your scores appropriately. Also, if a stock has known low genetic diversity, adjust your ranks accordingly.

Stock Size/Status Bins:

1. **Low:** $B/B_{MSY} \geq 1.2$ (or proxy)
2. **Moderate:** $B/B_{MSY} \geq 0.8$ but < 1.2 (or proxy)
3. **High:** $B/B_{MSY} \geq 0.5$ but < 0.8 (or proxy)
4. **Very High:** $B/B_{MSY} < 0.5$ (or any stock below <10,000 mature individuals)

Other Stressors

Goal: To account for conditions that could increase the stress on a stock and thus decrease its ability to respond to changes.

Relationship to climate change: In most cases but not all, climate change is predicted to exacerbate the effects of other stressors. Fish stocks that are already being affected by other stressors are likely to have faster and more acute reactions to climate change.

Background: Scientists theorize that species experiencing additional stressors are more likely to have faster and more acute reactions to climate change (Stein et al. 2013, Sumaila et al. 2011). A stress is an activity that induces an adverse effect and therefore degrades the condition and viability of a natural system (Groves *et al*. 2000; EPA 2008). This attribute attempts to take into account interactions between climate change and other stressors already impacting fish stocks. Some examples of other stressors include: habitat degradation, invasive species, disease, pollution, and hypoxia. Although climate change is not currently the biggest threat to many natural systems, its effects are projected to be an increasingly important source of stress in the future (Mooney *et al*. 2009). Consideration of observed and projected impacts of climate change in the context of other environmental stressors is essential for effective planning and management (Tingley et al. 2014).

How to use expert opinion: For the purpose of this assessment, we are looking for detrimental impacts from other stressors. We have provided examples of other stressors that may be impacting stocks, but the list is not exhaustive. If the stock being scored is suffering from a known or suspected stressor that is not listed below, adjust the score appropriately. The magnitude of the stressors should also be considered. If a single stressor is suspected of a large impact on the stock, adjust the score appropriately. It is expected that in some cases, impacts of climate change could create positive impacts (e.g., reduction in predators). If you suspect positive impacts, adjust tallies toward the lower bins as appropriate. We are not including fishing pressure as a stressor here as it is covered under the "stock size/status" attribute.

Example of stressors the stock may be experiencing:

- The habitat on which the stock depends is degraded. Examples include anthropogenic effects or changes to freshwater input, stratification, storm intensity, and hypoxia.
- The stock is currently exposed to detrimental levels of pollution (chemical and/or nutrient).
- The stock has experienced a known increase in parasites, disease, or harmful algal bloom exposure.
- The stock has experienced a detrimental impact due to a change in the food web. Examples include increases in the abundance of predators or competitors, or the introduction of an invasive species that negatively impacts the stock. Do not include changes to prey here as they are covered under the "prey specificity" attribute.

Other Stressors Bins:
If a single stressor is suspected of a large impact on the stock, adjust the score appropriately.

1. **Low: Stock is experiencing no known stress other than fishing.** Stock is experiencing no more than one known stressor.
2. **Moderate: Stock is experiencing limited stress other than fishing.** Stock is experiencing no more than two known stressors.
3. **High: Stock is experiencing moderate stress other than fishing.** Stock is experiencing no more than three known stressors.
4. **Very High: Stock is experiencing high stress other than fishing.** Stock is experiencing four or more known stressors.

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transferable quota). The methodology described here applies across multiple species and provides a relative rank of vulnerability to climate change as well as information about why a species may or may not be vulnerable to it. However, this methodology is not the only step necessary to prepare for climate change impacts on living marine resources. Rather, it is designed to be an early-step in the conversation about how to manage fisheries resources with changing climate and ocean conditions, and help guide the science needed to design and implement effective management actions. A better understanding of the vulnerability of fish and shellfish species will help fisheries scientists and managers identify and implement actions that increase the resiliency of managed fisheries.

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