A Framework for the Application of a Fish Stock Climate Vulnerability Assessment (FSCVA) to the Arctic Large Aquatic Basin (LAB)

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Canadian Manuscript Report of Fisheries and Aquatic Sciences 3173

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Canadian Manuscript Report of
Fisheries and Aquatic Sciences 3173

2019

A FRAMEWORK FOR THE APPLICATION OF A FISH STOCK CLIMATE VULNERABILITY ASSESSMENT (FSCVA) TO THE ARCTIC LARGE AQUATIC BASIN (LAB)

by

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Cat. Fs97-4/3173E-PDF ISBN 978-0-660-30046-7 ISSN 1488-5387

Correct citation for this publication:

Fulton S. and Tallman R. 2019. A Framework for the Application of a Fish Stock Climate Vulnerability Assessment (FSCVA) to the Arctic Large Aquatic Basin (LAB). Can. Manuscr. Rep. Fish. Aquat. Sci. 3173: viii + 45 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Fulton S. and Tallman R. 2019. A Framework for the Application of a Fish Stock Climate Vulnerability Assessment (FSCVA) to the Arctic Large Aquatic Basin (LAB). Can. Manuscr. Rep. Fish. Aquat. Sci. 3173: viii + 45 p.

The Arctic is currently warming at almost twice the global rate, likely impacting the productivity, abundance, and distribution of Arctic species. Identifying the relative vulnerability of Arctic fish and invertebrate species to climate change would provide valuable information when developing methods to integrate climate change considerations into Fisheries and Oceans Canada program decision making. Following the Fish Stock Climate Vulnerability Assessment (FSCVA) methodology developed by the National Oceanic and Atmospheric Administration (NOAA), we assessed the biological sensitivity of 20 Arctic fish species, encompassing both the marine and freshwater systems. Sensitivity attributes included aspects such as sensitivity to temperature, growth rates, and mobility. Half of all species assessed were ranked high or very high, with sensitivity to temperature, population growth rate and dispersal of early life stages having the most influence on sensitivity ranks. These sensitivity scores, in conjunction with climate exposure rankings and expert opinion, produce a final multi-species vulnerability ranking. The FSCVA is a useful tool in identifying current knowledge gaps, making recommendations on the direction of future research and to further address DFO's mandate to consider climate change when making decisions affecting fish stocks and ecosystem management.

RÉSUMÉ

Fulton S. and Tallman R. 2019. A Framework for the Application of a Fish Stock Climate Vulnerability Assessment (FSCVA) to the Arctic Large Aquatic Basin (LAB). Can. Manuscr. Rep. Fish. Aquat. Sci. 3173: viii + 45 p.

L'Arctique se réchauffe actuellement presque deux fois plus vite que la planète, ce qui a probablement une incidence sur la productivité, l'abondance et la répartition des espèces arctiques. La détermination de la vulnérabilité relative des poissons et des invertébrés de l'Arctique aux changements climatiques fournira des renseignements précieux pour l'élaboration de méthodes permettant d'intégrer les considérations relatives aux changements climatiques au processus décisionnel des programmes de Pêches et Océans Canada. Suivant la méthode d'évaluation de la vulnérabilité au climat des stocks de poissons mise au point par la National Oceanic and Atmospheric Administration (NOAA), nous avons évalué la sensibilité biologique de 20 espèces de poissons de l'Arctique, couvrant les systèmes marins et d'eau douce. Les attributs de sensibilité comprennent des éléments comme la sensibilité à la température, les taux de croissance et la mobilité. La moitié de toutes les espèces évaluées ont été classées élevées ou très élevées, la sensibilité à la température, le taux de croissance de la population et la dispersion aux premiers stades de vie ayant le plus d'influence sur le classement de sensibilité. Ces scores de sensibilité seront utilisés conjointement avec les classements d'exposition climatique et l'opinion des experts pour produire un classement final de vulnérabilité multi-espèces. La méthode d'évaluation de la vulnérabilité au climat des stocks de poissons sera un outil utile pour cerner les lacunes actuelles sur le plan des connaissances, formuler des recommandations sur l'orientation de la recherche et s'acquitter davantage du mandat du MPO, qui consiste à tenir compte des changements climatiques dans le cadre de la prise de décisions touchant les stocks de poissons et la gestion des écosystèmes

ABBREVIATIONS

ACCASP – Aquatic climate change adaption services program
CCVA – Climate change vulnerability assessment
COSEWIC – Committee on the status of endangered wildlife in Canada
CSAS – Canadian science advisory secretariat
FSCVA – Fish stock climate vulnerability assessment
GSL – Great Slave Lake
LAB – Large aquatic basin
NOAA – National oceanic and atmospheric administration
SARA – Species at risk act

1.0 INTRODUCTION

The Aquatic Climate Change Adaption Services Program (ACCASP) was developed by DFO to fund climate change research relating to the understanding of climate change effects and the development of adaption tools. Under the umbrella of the ACCASP, the fish stock climate vulnerability assessment (FSCVA) aims to provide information on the vulnerability of Arctic species to different aspects of climate change to be used as a tool by fisheries management. This work will contribute to the adaptation of Arctic programs to climate change, and address the commitment to take into account climate change when making decisions affecting fish stocks and ecosystem management.

The climate is changing across the globe but the impacts are especially prominent in the Arctic (ACIC 2004, IPCC 2014). Arctic temperatures are rising at almost twice the global rate with a 3-4°C increase in the average winter temperature across the past 50 years (ACIA 2004). Temperatures are expected to continue to increase resulting in far reaching effects across the marine and freshwater systems of the Arctic. Glaciers and icecaps are melting contributing to sea level rise and reducing ocean salinity (ACIC 2004, Gardner et al. 2011). There has been a substantial loss of sea ice since the 1950's, with observed decreases greater than those predicted by climate models (Stroeve et al. 2007). The loss of sea ice impacts Arctic species both directly through habitat loss and indirectly though increasing human access to the Arctic (ACIA 2004). In freshwater systems, warming temperatures affect the length of the open water season and mixing regimes in large lakes (ACIC 2004, Williams and Stefan 2006). Changes in precipitation are influencing the timing and amount of flow in river systems (ACIC 2004). Due to the vast area that the Arctic encompasses and variability in habitats, the effects of climate change are not expected to be equivalent across the Arctic.

Collectively, the effects of climate change on Arctic ecosystems will likely impact the distribution, productivity and abundance of Arctic fish species (Reist et al. 2006). Due to the variety of biological and life history characteristics of Arctic fish, the sensitivities of these species to climate change are not expected to be equal. Single species assessments (e.g. cod; Drinkwater 2005, *Salmo* sp.; Jonsson and Jonsson 2009) require large amounts of data and resources and as such are not practical for many species. Vulnerability assessments are used as a tool to categorize a large amount of species in a relatively short amount of time. They can be used not only to identify vulnerable species, but as a management tool to identify factors which contribute most to overall vulnerability, inform about knowledge gaps, and direct future studies (Morrison et al. 2015).

Previous vulnerability assessments have been conducted both globally, (e.g. Foden et al. 2013) and regionally (e.g. Hare et al. 2016) for a wide variety of species. In recent years there have been a number of assessments performed for marine fish species (Chin et al. 2010, Pecl et al. 2011, Stortini et al. 2015, Hare et al. 2016). The details of the methodologies vary between studies but all of the studies are working under the premise that a species vulnerability to climate change is a combination of their sensitivity to changes in their environment and their exposure to these changes. Highly vulnerable species tend to be limited behaviorally or physiologically. For example, cold-adapted species such as Arctic cod (Hop and Graham 1995) will be more sensitive to changes in temperature than species which have adapted tolerances to a wide variety of temperatures.

For the Canadian Arctic we will apply the FSCVA methodology developed by Morrison et al. (2015), adapted for our study area. The vulnerability assessment will encompass marine, anadromous and freshwater fish stocks and will be split into two frameworks. One framework will focus on marine and anadromous fish stocks across the Arctic LAB, while the other will focus on the freshwater species in Great Slave Lake. The results of the two frameworks will be aggregated to produce final multispecies vulnerability rankings for all functional groups. The freshwater portion of the assessment may be extended to include other lakes in the Canadian Arctic. Once a framework is established to perform a vulnerability assessment for Arctic stocks, we can extend the protocol to encompass a greater range of species, stocks and freshwater systems across the Arctic LAB and refine the information as it becomes available.

This report will serve as the first of three reports for the Arctic vulnerability assessment;

(1) Preliminary assessment of the sensitivity of Arctic fish species to climate change
(2) Preliminary assessment of the exposure of Arctic fish species to climate change
(3) Vulnerability of Arctic fish species to climate change

While the overall vulnerability of a species is considered to be a combination of their biological sensitivity (including adaptive capacity) and exposure to environmental changes, this report will focus on the biological sensitivity aspect of the assessment. In addition to the final vulnerability ranking consisting of both sensitivity and exposure, it will also incorporate scoring of each species by several experts. This report will serve as the groundwork for the refinement of sensitivity ranks by experts, which will be incorporated into the final vulnerability report.

2.0 METHODS

There have been several methods developed and implemented to perform climate change vulnerability assessments (CCVA) in recent years (Pecl et al. 2011, Morrison et al. 2015, Stortini et al. 2015).We choose to use the method developed by NOAA (Morrison et al. 2015), and implemented by Hare et al. (2016), as the framework to base this assessment methodology on. In a recent review of CCVA methods (Hunter et al. 2015), the method developed by NOAA (Morrison et al. 2015) had several strengths such as well-developed sensitivity attributes, and a scoring system that accounts for uncertainty and data quality. Due to the data limitations for many Arctic species, accounting for uncertainty and data quality is imperative for the application of a vulnerability assessment of Arctic species. The climate exposure factors will be modified, based on the climate information available for the Arctic LAB, and incorporate aspects of climate change that are likely to be important to marine and freshwater systems in the Arctic (i.e. changes in sea ice).

Hunter et al. (2015) discussed the need for the use of consistent terms. For the context of this project we will use the definitions of sensitivity, exposure, ecological vulnerability as they are written in Hunter et al. (2015);

Exposure: The extent and magnitude (absolute or relative) to which species' or population's surroundings will be subjected to projected changes in climate drivers**.**

Sensitivity: The degree to which a species or population may be impacted, directly or indirectly, by projected changes in climate drivers.

Ecological vulnerability: The degree to which a system or species is susceptible to, or unable to cope with, effects of climate change, including variability and extremes. Vulnerability is not equated to risk of extinction, but rather is identified as a decrease in abundance or productivity.

The fish stock climate vulnerability assessment process developed in Morrison et al. (2015) is composed of four steps; (1) scoping and planning, (2) assessment preparation, (3) scoring, and (4) analyses. This report will only cover the portions of the vulnerability assessment which pertain to biological sensitivity, and will be outlined in detail below.

2.1 SCOPING AND PLANNING

2.1.1 Study Area

The general study area will be the Canadian Arctic large aquatic basin (LAB) as defined by the ACCASP, which encompasses both marine and freshwater environments in the Canadian Arctic (Figure 1). Biological sensitivities will be considered at the species and not stock scale, unless otherwise stated. Fisheries under resource management control are located in the marine environment and large freshwater lakes, encompassing species such as Arctic char which utilize both systems. For this reason the study area includes the marine and freshwater environments utilized by marine and anadromous species.

Great Slave Lake (GSL) will be the focus for freshwater Arctic species who do not utilize the marine system as part of their life history (Figure 1). Great Slave Lake is a large freshwater lake in Northwest Territories which supports many commercial and subsistence fisheries. GSL is 28 568 km^2 in surface area, making it the second largest lake entirely in Canada (after Great Bear Lake) and the tenth largest in the world (Herdendorf 1982). Because Additionally, with the framework that is being assembled, the FSCVA may be extended to more freshwater systems if the climate information is available.

2.1.2 Species Included

Coad and Reist (2018) list 221 species as having been recorded occurring in the marine Arctic system of Canada, and up to 58 species are recorded as occurring in the freshwater system (Wrona et al. 2005). Many of the species which occur in the freshwater system of the Arctic are diadromous and are listed in Coad and Reist (2018), but there are exclusively freshwater species as well (e.g. Northern pike). Due to limitations in available data and resources, not all species will be assessed in this study. The selection of species to include in the vulnerability assessment includes species which are commercially valuable (e.g. Greenland halibut, Arctic char), of concern (e.g. northern wolfish) or ecologically important (e.g. capelin). Species are initially included for consideration in the vulnerability assessment if they occur within the defined study areas and meet at least one of the following criteria:

1. Commercially or locally harvested within the study area;
2. Bycatch species in the commercial fishery;
3. Species which have been formally assessed through COSEWIC or SARA; or
4. Ecologically important species

The categories are not mutually exclusive and species may fall into several categories. The selection criteria is not meant to categorize species, but as a binary response to decide to include or exclude each species. Species which have been included in this assessment can be found in table 1; while species selected to be included in future assessments can be found in table 2.

2.1.3 Sensitivity Attributes

Sensitivity of a species to climate change refers to both their resilience to change and their adaptive capacity. Although some studies separate sensitivity attributes into the two categories, the FSCVA method developed by NOAA combines both sensitivities with adaptive capacity. Morrison et al. (2015) developed 12 sensitivity attributes that are designed to be applicable to most marine fish and shellfish species. Table 3 outlines the 12 sensitivity attributes from Morrison et al. (2015). Each attribute is well defined in relation to climate change, has general instructions on how to score it and a detailed description of what each scoring bin (low to very high) means (Appendix 1).

The sensitivity attributes were developed for marine species, but the descriptions of scoring bins are applicable to freshwater species as well with relatively few changes. For example, adult mobility is used to determine if a species has the ability to move away from unsuitable habitat but can be interpreted to include aspects of the landscape which can prevent mobility. Sensitivity to ocean acidification is unlikely to be relevant to freshwater systems, but due to the nature of the methodology, this can just be scored as low without any negative impacts to the final sensitivity score. Changes in temperature, productivity and mixing regimes of freshwater systems are likely to change the amount of dissolved oxygen (DO). For example warming water temperatures can result in decreased levels of dissolved oxygen (Stefan et al. 1996). Species which are tolerant to low oxygen environments, either physiologically or behaviorally will be less vulnerable to changes in the dissolved oxygen content of the system. This characteristic of freshwater systems can be included as part of the habitat specificity requirements.

2.2 ASSESSMENT PREPARATION

2.2.1 Species Profiles

Species profiles were assembled in a standardized manner to facilitate scoring. Relative to Atlantic and Pacific commercial stocks, Arctic fish and invertebrate stocks are considered data-poor. The data sources, in descending order of preference to be used to assemble the profiles are

1. Literature about the species from the
2. Literature about the species from locations outside the study area
3. Literature about a similar species from the Canadian Arctic
4. Literature about a similar species from locations outside the study area
5. Personal communication with experts about species
6. Personal communication with experts about similar species

Literature encompasses reference books, such as freshwater fishes of Canada (Scott and

Crossman 1973), CSAS documents, peer-reviewed journal articles, etc. Preference is always given to documents about the specific stock before general documents about the species. Because the majority of the species included in this assessment are only assessed at the species level, much of the information necessary to score sensitivity relies on basic biological information. For example, although specific measurements on habitat use may not be available for individual stocks, general knowledge about occurrences of the species is used as a basis to assign a score. Many of the attributes fall along a continuum, so even if detailed studies are not available any information about the biology of the species from any stock in the area can be used as a basis to guide the score, albeit with less certainty.

2.3 SCORING

2.3.1 Biological sensitivity and data quality

Each sensitivity attribute was scored using four bins; low, moderate, high or very high using the criteria for each attribute found in appendix 1. Five tallies were assigned across the four bins. Distribution of the tallies across the bins is used to assess certainty. For example, all five tallies assigned to the same bin would imply high certainty, while tallies spread across three or four bins would imply low certainty. In addition to scoring each sensitivity attribute or climate exposure factor, the data quality is scored from 0 to 5 (Table 4). The data quality ranks were modified from hare et al from a scale of 0 to 3, to a 0 to 5 scale to reflect a greater refinement in both the uncertainty and availability of data about Arctic species.

2.4 ANALYSES

2.4.1 Overall biological sensitivity rank

The average score for each sensitivity attribute is calculated as a weighted mean using the number of tallies in each scoring bin.

Average score = ((L*1)+(M*2)+(H*3)+(V*4))/(L+M+H+V)

Where L, M, H and V are the number of tallies in the low, moderate, high and very high scoring bins respectively. Once an average score is calculated for each attribute , overall sensitivity rank is calculated using a logic rule (Table 11). A rank of very high was assigned to species with more than three attribute means >3.5, a rank of high was assigned to species with two or more means >3.0, a rank of moderate was assigned if 2 or more means are >2.5, and finally a rank of low was assigned to any remaining species.

2.4.2 Potential for distribution change

When developing the methodology, Morrison et al. (2015) used the attributes described by Pecl et al. (2014) to determine a species potential to shift its distribution. Pecl et al. (2014) described species which have dispersive larvae, highly mobile adults, a wide range of physiological tolerances, and occupy a range of habitats will have the highest potential to shift their distribution.

Scores for adult mobility, dispersal of early life stages and habitat specify were reversed, and along with sensitivity to temperature they made up the subset of variables used to score distributional changes. The same logic rule used for the sensitivity rank was applied to the four sensitivity attributes used to calculate the overall potential for distribution change rank.

2.4.3 Certainty in scores

Uncertainty in the results was taken into account during scoring with the use of multiple tallies. High certainty would result in all tallies concentrated in a single scoring bin, with high uncertainty manifesting in tallies which are spread out across 3 or 4 scoring bins. The rank calculations for sensitivity and potential for distribution shift were bootstrapped 1000 times to obtain a certainty for each species. For each of the 10000 iterations, tallies were randomly sampled with replacement from the original data to produce a new set of tallies. The overall sensitivity and distributional shift rank was then recalculated and the percentage of the 10000 iterations which produced the same result as the original rank was recorded.

2.4.4. Importance of sensitivity attributes

Sensitivity ranks were recalculated by iteratively leaving out each of the twelve attributes to determine the overall impact each attribute had to the final rank. These results were then pooled across all species to determine which sensitivity attributes had the greatest influence on the overall sensitivity rank of a species.

2.4.5 Functional groups

Each species was assigned to one of six functional groups; diadromous, elasmobranchs, groundfish, pelagics, invertebrates or freshwater. Sensitivity ranks and potential for distribution change were aggregated to determine if there are any broad patterns across group.

3.0 RESULTS

3.1 OVERALL BIOLOGICAL SENSITIVITY RANK

For the 20 species considered in the assessment, biological sensitivity scores ranged from low to very high. The majority of species fell within the moderate (45%) or high (40%) sensitivity rank, with only 1 species ranked as low (5%) and 2 ranked as very high (10%; Figure 2). Based on the results of the bootstrap analysis, 40% of the scores were considered to have very high certainty (>95%), with the remaining 60% of scores split evenly between moderate (95%>66%) and low certainty (<66%; Figure 2).

3.2 POTENTIAL FOR DISTRIBUTION CHANGE

Potential for distribution change scores were more evenly split across the four categories (low, 25%; moderate, 15%; high, 40%; very high, 20%) than the sensitivity scores (Figure 3). Almost half (45%) of scores were considered to have very high certainty (>95%)

according to the bootstrapping results. However all of the species with very high certainty also had scores indicating a high to very high potential for a distributional shift. Species with low to moderate certainty in distributional shift scores were spread out between the low, moderate, and high scoring ranks (Figure 3).

3.3 IMPORTANCE OF SENSITIVITY ATTRIBUTES

Seven of the twelve sensitivity attributes were found to change the overall sensitivity score for at least one species when they were removed from the analysis (Figure 4). Of these seven attributes, population growth rate, sensitivity to temperature and dispersal of early life stages had the greatest influence on overall sensitivity scores. Scores were altered for six, five, and five species respectively when each attribute was removed from the analysis. Scores across species for the twelve sensitivity attributes ranged from 1 to the maximum of 4. Prey specificity and sensitivity to ocean acidification were on average the lowest scoring, with dispersal of early life stages and population growth rate scoring the highest.

Using the logic rule from table 5, the average attribute score for a species must be greater than 2.5 to contribute to a rank greater than low. Complexity in reproductive strategy, sensitivity to ocean acidification and other stressors did not score above 2.5 for any species (Figure 4 and Figure 5). All attributes had at least seven species (35%) that did not score above 2.5 (Figure 5).

3.4 FUNCTION GROUPS

Freshwater and diadromous species tended to have high scores for biological sensitivity and lower scores for their potential for distribution shift (Figure 6). Elasmobranchs, groundfish and invertebrates had the highest scores for potential for distribution change and moderate to high scores for their biological sensitivity. Pelagic species were spread out between the low, moderate, and high ranks for both sensitivity and directional change.

3.5 DATA QUALITY

Data quality scores ranged from 0 (no data) to adequate data (5; Figure 5). Half of all species assessed had an average data quality score <4 indicating limited data. Roughhead grenadier had the lowest average data quality score with 3.1, while dolly varden had the top score of 5. When results are aggregated across species, stock size/status and other stressors have the lowest quality data, while habitat specificity had the highest (Figure 5, Figure 7). While the majority of sensitivity attributes have an average data quality score >4, eight of the twelve attributes had at least one occurrence of data quality <2.

4.0 DISCUSSION

Of the 20 species included in this preliminary assessment, half of them were ranked as having high or very high sensitivity to climate change. The slow population growth rates and preference for colder temperatures contribute to many of the species high sensitivity rankings. A high sensitivity to change may not manifest in a high vulnerability if the species is not exposed to large climactic changes, but in the Arctic this is unlikely as it is currently warming at twice the global rate (ACIC 2004). Although negative for many species, exposure and the response to changing temperatures is not ubiquitous for all species. For species such as lake trout, warming water temperatures can restrict their movement and force them to spend a greater amount of time in cooler deeper water away from their prey (Guzzo et al. 2017). In contrast, warming Arctic temperatures can allow sub-Arctic species, such as capelin, to expand their range (Rose 2005).

Inconnu (*Stenodus leucicthyes*) and Dolly Varden (*Salvelinus malma*) were both ranked as 'very high' for sensitivity to climate change. The slow population growth rates, narrow spawning windows, benthic eggs and overall low stock status were score highly for both species. Unlike many other Arctic species, Dolly Varden have been well studied and as of 2010 are designated as special concern by COSEWIC (COSEWIC 2010). Dolly Varden are highly specific in their habitat requirements, and when combined with their anadromous life history and current low stock size, results in a species that may be highly impacted by a changing climate. Similar to Dolly Varden, freshwater populations of Inconnu are likely highly sensitive to climate change, in part due to their low stock size (DFO 2013). Unlike many cold Arctic marine species, which have a greater availability of suitable habitat and a more flexible life history strategy, freshwater and anadromous species are limited in their timeframe for spawning and suitable habitat for overwintering of their eggs. Many Arctic salmonids are also slow growing and late maturing (Coad and Reist 2018). When considered collectively, these characteristics of Arctic salmonids all contribute to a group that is sensitive to changes in their environment. When additional stressors are considered, such as low stock size due to fishing or anthropogenic influences such as hydro dams or mining, vulnerabilities of these stocks is only increased.

As a species, Arctic char are highly variable and elastic in their behaviour, morphology, and life history (Balon 1980). Although they rank high in their biological sensitivity, this plasticity makes them excellent colonizers, and may help buffer some of the negative effects of climate change. Unlike the closely related Dolly Varden, Arctic char across their range are highly variable in their habitat usage, spawning timing, and even prey consumption (Klemetson 2010). Although individual stocks may be impacted by a changing climate, such as seen in a Nain Arctic char stock (Powers et al. 2000), their diversity may be beneficial to their persistence for when the species is considered as a whole (Moore et al. 2014). Due to the negative effects associated with low stock size, management of commercial char stocks may be vital in helping to buffer negative effects associated with climate.

Similar to the results from Hare et al. (2016) our results show a large proportion of our species with a high potential for distribution change. High potential for distribution change was calculated using a subset of the sensitivity attributes, and as such species with a high sensitivity rank tend to have a lower potential for distribution change. In general, marine species tended to have a high potential for distribution change, while anadromous or freshwater species did not. Because many anadromous species home to natal rivers, straying is required for dispersal (e.g. Moore et al. 2013). Because homing results in an additional behavioural barrier to dispersal, these species were likely ranked low relative to species like the Greenland shark. Additionally, the certainty was calculated at >90% for all species ranked as low or moderate and will benefit from the incorporation of expert opinion.

Because only 20 species were included in this preliminary assessment of sensitivity to climate change, trends in functional groups are of limited use. Once a greater number of species has been assessed, more trends may arise. Unsurprisingly, freshwater and anadromous species tend to have the highest sensitivity to change. As discussed above with Inconnu and Dolly Varden, benthic eggs and limited spawning time frames tend to contribute to an overall higher sensitivity rank. The majority of the anadromous or freshwater species include in this preliminary assessment were also salmonids (7 of 9 species) and as such share similar life history characteristics. Both elasmobranchs included in our assessment were scored high for population growth rate and sensitivity to temperature but low in all other attributes, resulting in species that is ranked only moderate overall. Although both species prefer colder temperatures, their more generalist tendencies associated with habitat and diet along with their high mobility (Yano et al. 2007,Peklova et al. 2014) mean they will likely be able to mitigate climate effects through their behaviour.

Data quality was ranked from 0, indicating no data, to 5 indicating adequate data. A data quality score of 5 does not indicate that the data is overly detailed; only that is was adequate to assign a score. Despite many of the attributes and species having data ranked as 5, almost all categories could benefit from more data. Much of the data was ranked as a 5, as the quality was adequate, but uncertainty in the measurement was reflected in the assignment of the five tallies during scoring. In future reports, it is recommend to add a data quality score of 6 to reflect the few instances where the data quality is more than adequate. The large number of 4s also reflects the lack of biological measurements from within the Canadian Arctic. For some of the attributes, such as temperature, measurements from outside the Arctic may be more useful as they reflect the thermal tolerance of the species. Across all sensitivity attributes, current stock status and other stressors had the lowest data quality. There are many likely stressors in the Arctic ecosystem that may be affecting fish species, but any direct measurements on stocks are lacking. Shipping and mercury contamination are likely stressors, but species specific information is needed (Corbett et al. 2010, Braune et al. 2015, Andersen et al. 2017).

Although the results from this assessment are broad scale and require refinement, they provide a first look at generally vulnerabilities and trends across Arctic species. Like many vulnerability assessments, the FSCVA methodology developed in Morrison et al. (2015) aggregates adaptive capacity of a species with sensitivity (Thompson et al. 2015). Accounting for adaptive capacity directly, such as through genetics, may be beneficial but the results are also highly sensitive to the data inputs (Wade et al. 2017). When fine scale information on demographics is available, quantifying adaptive capacity allows for a more robust vulnerability assessment, but for data poor systems this information is generally unavailable. Selecting a methodology which allows for uncertainty in scoring and the ability to assign scores based on qualitative information (i.e. Pecl et al. 2009, Morrison et al. 2015) is beneficial in data poor situations. Once a species is assigned a vulnerability ranking, the information obtained on data gaps and important attributes can be used to guide the development of mechanistic models to answer more direct questions.

5.0 FUTURE WORK

The next stage of this assessment is to score climate exposure by comparing the most current climate projection maps to species distribution maps. Similar to this preliminary assessment on sensitivity, this first look at climate exposure will be summarized in a second report. The final report on species overall vulnerability to climate change will use both of these preliminary assessments in conjunction with expert opinion. The FSCVA methodology is based upon the Delphi method, which involves using expert opinion in a predetermined fashion to increase the reliability of the results (Linstone and Turoff 2002, Morrison et al. 2015). Experts will score species individually, then come together to discuss the results. During the group discussion experts can choose to change how they scored each species based on the discussions and views exposed by the group. This Delphi approach will serve to refine the preliminary results presented here (and in the future report on exposure). In addition to refining current scores with expert opinion, additional species (as listed in table 2) will be added to the assessment as time allows. As part of the final vulnerability report, species profiles will be produced to outline the sensitivity and exposure factors which are most influential, and to provide information of species specific knowledge gaps.

6.0 CONCLUSION

Fish and invertebrate species in the Canadian Arctic are found across a wide variety of habitats and implement various life history strategies, likely culminating in a range of impacts from climate change. Assessing the relative vulnerability of different fish stocks or species is an important step in providing managers with information needed to prepare for impacts of climate change. The FSCVA assessment methodology developed by Morrison et al. (2015) and applied by Hare et al. (2016) provides us with a way to relatively quickly assess the vulnerability to climate change for a large number of species. The FSCVA methodology can be applied at both the stock and species level allowing us to compare stocks whose exposure to climate change may be variable across their range as well as account for variation in sensitivity attributes. Differences between stocks such as stock size, growth rates and exposure to stressors may impact a stocks' sensitivity to climate change and require different mitigations to buffer against the effects of a changing climate.

Accounting for fish and invertebrate occupying Morrison et al. (2015) identified the following five potential uses for the information that is provided by the FSCVA:

1. Inform stakeholders as to the relative vulnerability of species
2. Identify important climate exposure factors and sensitivity attributes
3. Inform data gaps and contribute to setting research priorities
4. Identify species where mechanistic models are needed
5. Suggest species that could benefit from management strategy evaluations
6.

Along with identifying potential uses of the assessment, Morrison et al. (2015) are clear in stating that the vulnerability methodology is not designed to replace mechanistic models or suggest harvest control rules. Overall, this preliminary assessment of sensitivity indicates that slow population growth rates and limited temperature tolerances are attributes shared by many Arctic species which contribute to a high sensitivity to change. Additionally, one of the biggest data gaps across a wide variety of species is our lack of knowledge of current stock size and current stressors. Refining these preliminary results with expert opinion and incorporating an estimate of exposure will improve our ability to incorporate climate considerations into future management recommendations.

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Table 1. Species which have currently had their biological sensitivity assessed, using primary literature, as part of the fish stock climate vulnerability assessment (FSCVA) in the Arctic large aquatic basins marine system. Reasons for inclusion are a commercial or subsistence fishery species (F), bycatch to the fishery (B), or ecologically important species (E)

#	GROUP	COMMON NAME	SCIENTIFIC NAME	INC.
1	Diadromous	Arctic char – Cambridge Bay	*Salvelinus alpinus*	F
2	Diadromous	Arctic char – Cumberland Sound	*Salvelinus alpinus*	F
3	Diadromous	Arctic lamprey	*Lampetra camtschatica*	
4	Diadromous	Chum salmon	*Oncorhynchus keta*	F
5	Diadromous	Dolly varden	*Salvelinus malma*	F
6	Elasmobranchs	Arctic skate	*Amblyraja hyperborea*	B
7	Elasmobranchs	Greenland shark	*Somniosus microcephalus*	B
8	Groundfish	American plaice	*Hippoglossoides platessoides*	F
9	Groundfish	Arctic cod	*Boreogadus saida*	E
10	Groundfish	Greenland halibut	*Reinhardtius hippoglossoides*	F
11	Groundfish	Roughhead grenadier	*Macrourus berglax*	F
12	Pelagic	Capelin	*Mallotus villosus*	E
13	Pelagic	Northern sandlance	*Ammodytes dubius*	E
14	Pelagic	Pacific sandlance	*Ammodytes hexapterus*	E
15	Invertebrate	Northern shrimp	*Pandalus borealis*	F
16	Invertebrate	Pink shrimp	*Pandalus montagui*	F
17	Freshwater (GSL)	Inconnu	*Stenodus leucichthys*	F
18	Freshwater (GSL)	Lake trout	*Salvelinus namaycush*	F
19	Freshwater (GSL)	Lake whitefish	*Coregonus clupeaformis*	F
20	Freshwater (GSL)	Ninespine stickleback	*Pungitius pungitius*	E

Table 2. Species which are selected for future inclusion in the fish stock climate vulnerability assessment (FSCVA) in the Arctic large aquatic basins marine system. Reasons for inclusion are a commercial or subsistence fishery species (F), bycatch to the fishery (B), COSEWIC/SARA species (C), or ecologically important (E)

#	GROUP	COMMON NAME	SCIENTIFIC NAME	INC.
1	Diadromous	Arctic cisco	*Coregonus autumnalis*	F
2	Diadromous	Atlantic salmon	*Salmo salar*	F
3	Diadromous	Bering cisco	*Coregonus laurettae*	C
4	Diadromous	Broad whitefish	*Coregonus nasus*	F
5	Diadromous	Chinook salmon	*Oncorhynchus tshawytscha*	F
6	Diadromous	Coho salmon	*Oncorhynchus kisutch*	F
7	Diadromous	Least cisco	*Coregonus sardinella*	F
8	Diadromous	Pink salmon	*Oncorhynchus gorbuscha*	F
9	Diadromous	Round whitefish	*Prosopium cylindraceum*	F
10	Diadromous	Sockeye salmon	*Oncorhynchus nerka*	F
11	Elasmobranchs	Spinytail Skate	*Bathyraja spinicauda*	B
12	Elasmobranchs	Thorny skate	*Amblyraja radiata*	FB
13	Groundfish	Atlantic cod	*Gadus morhua*	FC
14	Groundfish	Atlantic hagfish	*Myxine glutinosa*	FE
15	Groundfish	Atlantic wolfish	*Anarhichas lupus*	C
16	Groundfish	Bering wolfish	*Anarhichas orientalis*	C
17	Groundfish	Deepwater redfish	*Sebastes mentella*	F
18	Groundfish	Fourhorn sculpin	*Myoxocephalus quadricornis*	C
19	Groundfish	Golden redfish	*Sebastes norvegicus*	F
20	Groundfish	Greenland cod	*Gadus ogac*	F
21	Groundfish	Longfin hake	*Urophycis chesteri*	F
22	Groundfish	Lumpfish	*Cyclopterus lumpus*	F
23	Groundfish	Marlin-spike	*Nezumia bairdii*	FB
24	Groundfish	Northern wolffish	*Anarhichas denticulatus*	F
25	Groundfish	Pighead prickleback	*Acantholumpenus mackayi*	F
26	Groundfish	Polar cod	*Arctogadus glacialis*	F
27	Groundfish	Rock grenadier	*Coryphaenoides rupestris*	F
28	Groundfish	Saffron cod	*Eleginus gracilis*	F
29	Groundfish	Snubnosed spiny eel	*Notacanthus chemnitzii*	F
30	Groundfish	Spotted wolffish	*Anarhichas minor*	C
31	Groundfish	Witch flounder	*Glyptocephalus cynoglossus*	F
32	Pelagic	Atlantic argentine	*Argentina silus*	F
33	Pelagic	Pacific herring	*Clupea pallasii*	F
34	Pelagic	Rainbow smelt	*Osmerus mordax*	FE
35	Invertebrate	Orange-footed cucumber	*Cucumaria frondosa*	F
36	Invertebrate	Green sea urchin	*Strongylocentrotus droebachiensis*	
37	Invertebrate	Iceland scallop	*Chlamys islandica*	F
38	Invertebrate	Atlantic deep sea scallop	*Placopecten magellanicus*	
39	Freshwater	Arctic grayling	*Thymallus arcticus*	
40	Freshwater	Burbot	*Lota lota*	
41	Freshwater	Emerald shiner	*Notropis atherinoides*	
42	Freshwater	Lake chub	*Couesius plumbeus*	
43	Freshwater	Longnose sucker	*Catostomus catostomus*	
44	Freshwater	Ninespine stickleback	*Pungitius pungitius*	
45	Freshwater	Northern pike	*Esox lucius*	

46	Freshwater	Round Whitefish	*Prosopium cylindraceum*
47	Freshwater	Slimy sculpin	*Cottus cognatus*
48	Freshwater	Spottail shiner	*Notropis hudsonius*
49	Freshwater	Threespine stickleback	*Gasterosteus aculeatus*
50	Freshwater	Trout-perch	*Percopsis omiscomaycus*
51	Freshwater	Walleye	*Sander vitreus*

Table 3. Summary of biological sensitivity factors to be used to score the sensitivity of each species to climate change. Table is copied from Hare et al. 2016, with the addition of 'low oxygen tolerance inputs' as a sensitivity factor

SENSITIVITY FACTOR	GOAL	LOW SCORE	HIGH SCORE
Habitat Specificity	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.	Habitat generalist	Habitat specialist
Prey Specificity	To determine, on a relative scale, if the stock is a prey generalist or a prey specialist.	Prey generalist	Prey specialist
Adult Mobility	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.	High mobility	Low mobility
Dispersal of Early Life Stages	To estimate the ability of the stock to colonize new habitats when/if their current habitat becomes less suitable.	High dispersal	Low dispersal
Early Life History Survival and Settlement Requirements	To determine the relative importance of early life history requirements for a stock	Generalist with few requirements	Specialists with specific requirements
Complexity in Reproductive Strategy	To determine how complex the stock's reproductive strategy	Low complexity, broadcast spawning	High complexity; aggregate spawning
Spawning Cycle	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.	Year-round spawning	One event per year

Sensitivity to Temperature	To use the distribution of the species (not stock) as a proxy for its sensitivity to temperature	Broad thermal limits	Narrow thermal limits
Sensitivity to Ocean Acidification‡	To estimate a stock's sensitivity to ocean acidification based on its relationship with "shelled species." (followed Kroeker et al. 2012)	Sensitive taxa	Insensitive taxa
Population Growth Rate	To estimate the relative productivity of the stock.	High population growth	Low population growth
Stock Size/Status	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.	High abundance	Low abundance
Other Stressors	To account for conditions that could increase the stress on a stock and thus decrease its ability to respond to changes.	Low level of other stressors	High level of other stressors
‡ Marine assessment only			

Table 4. Definitions of data quality scores modified from Hare et al. (2016). Data quality scores are assigned to each sensitivity attribute.

Data Quality Score	Description
5	**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 *within the study area*.
4	**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 but is *outside the study area*.
3	**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 or the reliability of the source may be limited, but the available data is *within the study area*.
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 or the reliability of the source may be limited, and the available data is *outside the study area*.
1	**Expert Judgement**. The attribute score reflects the expert judgement of the reviewer and is based on their general knowledge of the species, or related species, and their relative role on 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 5. Scoring logic rule from Hare et al. 2016

Overall score	Numeric score	Logic Rule
Very High	4	3 or more means ≥3.5
High	3	2 or more mean ≥3.0
Moderate	2	2 or more ≥2.5
Low	1	All other scores

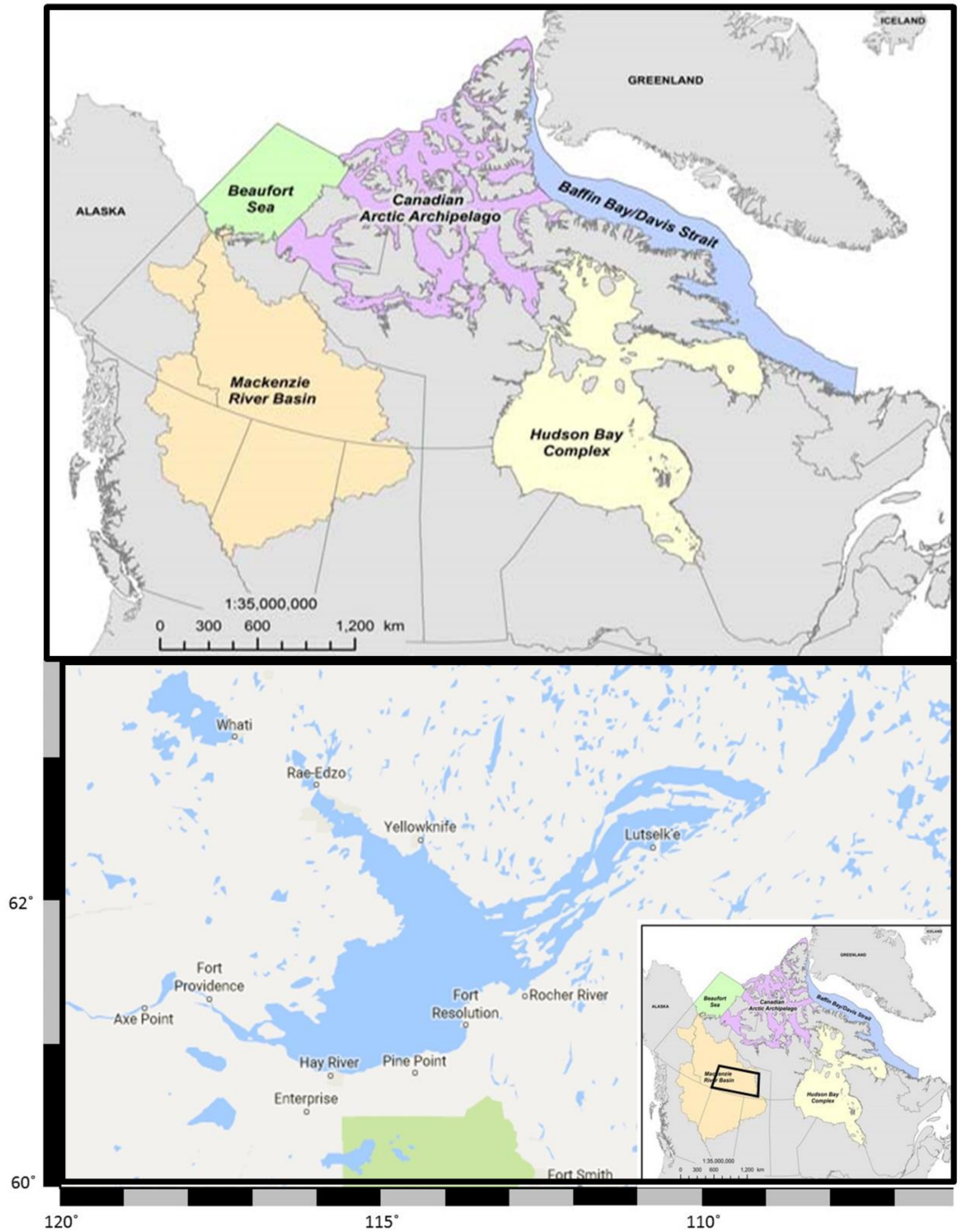


Figure 1. Map of the Canadian Arctic large aquatic basin (LAB; top) and Great Slave Lake, NWT (bottom)

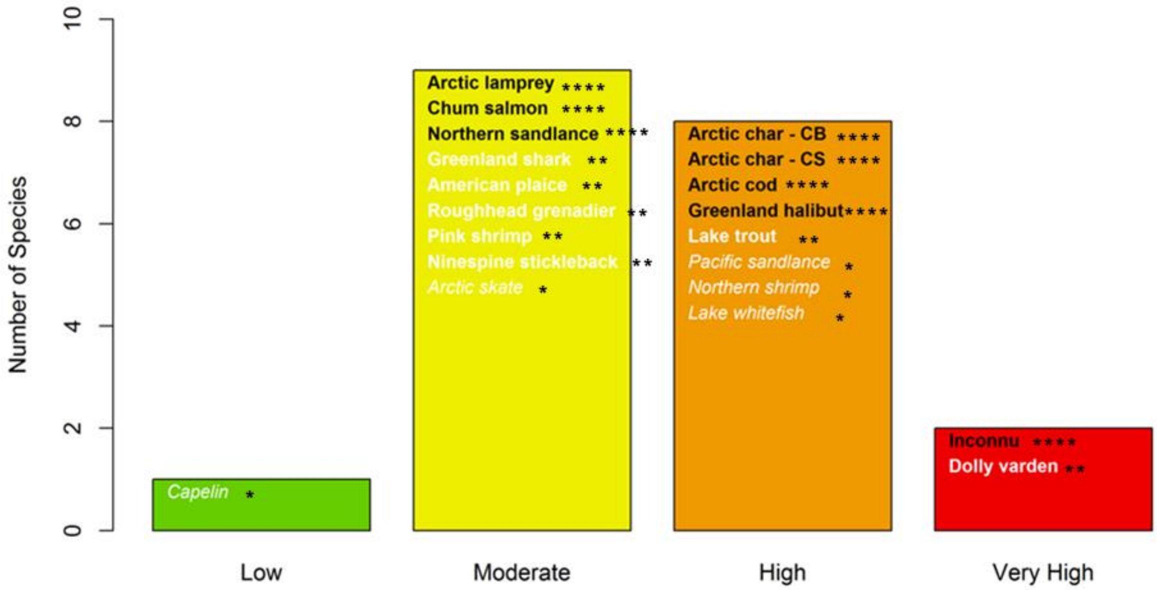


Figure 2 Biological sensitivity of Arctic fish species based on 12 attributes. Certainty in classification category is denoted by text colour and font based on results of 10000 bootstrap iterations. Very high certainty (>95% ; black, bold, ****), high certainty (<95% & >90%; black, italic, ***), moderate certainty (<90% and >66%; white, bold, **) and low certainty (<66%; white italic *)

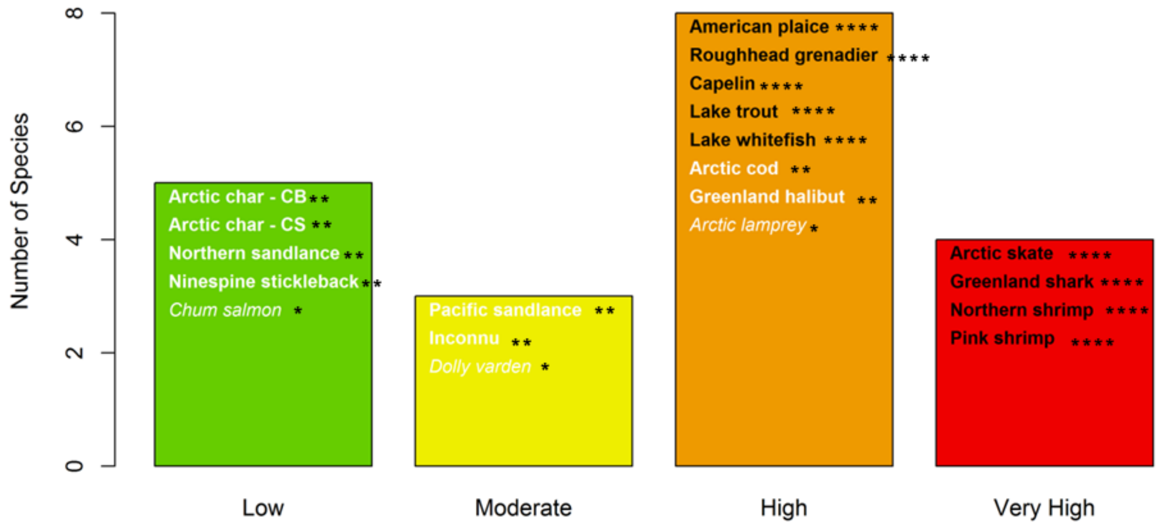


Figure 3. Potential for distribution change of Arctic species based on a subset of the sensitivity attributes. Certainty in classification category is denoted by text colour and font based on results of 10000 bootstrap iterations. Very high certainty (>95% ; black, bold ****), high certainty (<95% & >90%; black, italic ***), moderate certainty (<90% and >66%; white, bold **) and low certainty (<66%; white italic *)

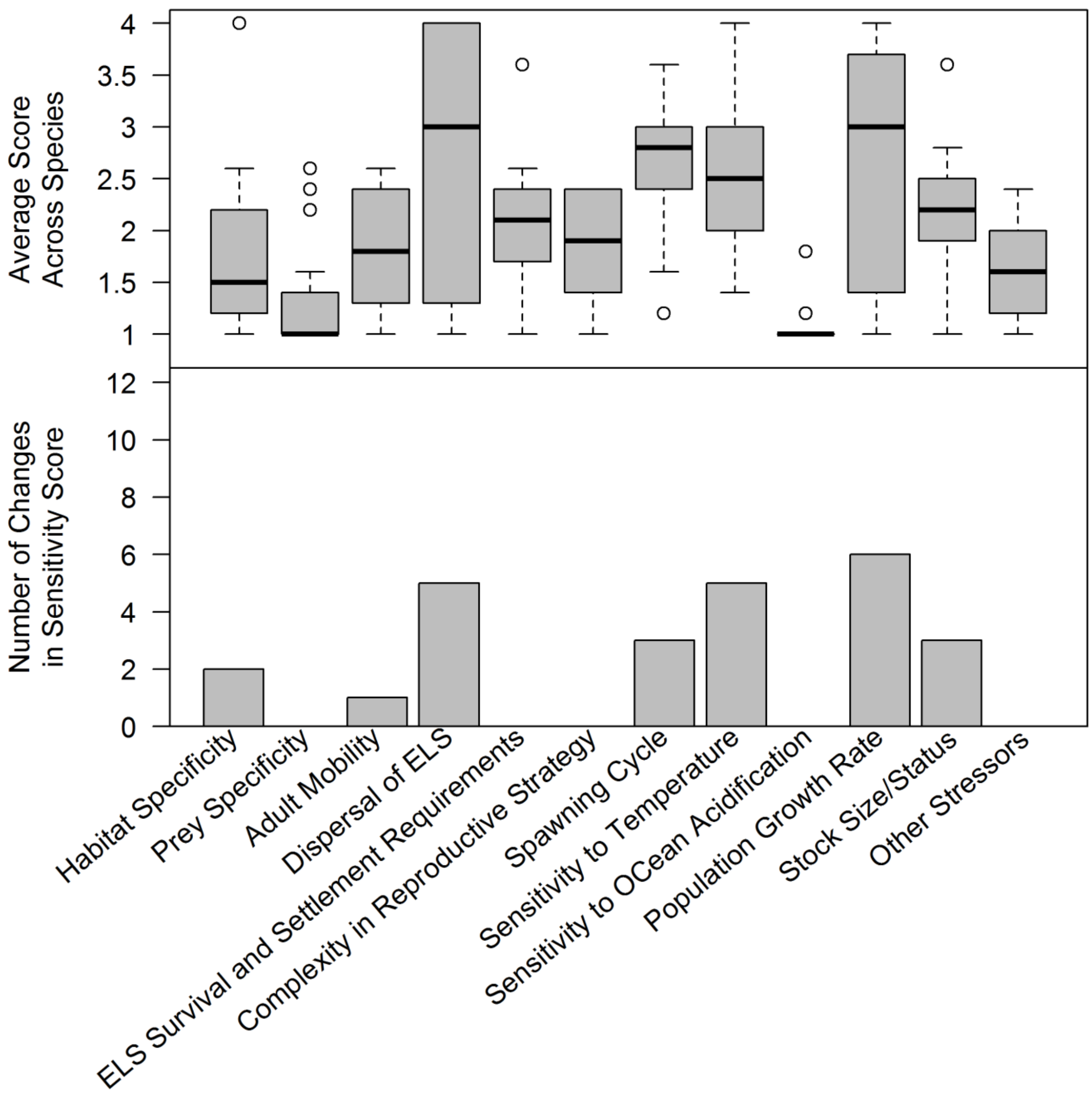


Figure 4. Average sensitivity scores for each of the twelve attributes across all species (top) and number of changes in sensitivity score when individual attributes are removed from analysis (bottom). Sensitivity to ocean acidification was only included for non-freshwater species, while sensitivity to low oxygen was only included for freshwater species.

	habitat	prey	mobility	earlydisp	lifehist	repstrat	spawn	temp	sensOA	growth	stock	stress
Arctic char - CB	5	3	5	3	3	5	3	5	5	5	3	1
Arctic char - CS	5	5	5	3	3	5	3	5	5	5	3	1
Arctic lamprey	5	4	5	5	4	5	5	4	5	4	0	0
Chum salmon	5	5	5	5	3	5	3	4	5	5	3	3
Dolly varden	5	5	5	5	5	5	5	5	5	5	5	5
Arctic skate	5	4	5	3	5	3	3	5	2	3	2	3
Greenland shark	5	5	5	5	5	1	1	5	5	5	1	0
American plaice	5	4	4	4	4	4	4	4	4	4	3	2
Arctic cod	5	5	5	3	5	2	2	5	5	5	1	1
Greenland halibut	5	5	5	5	4	3	3	5	5	4	5	2
Roughhead grenadier	4	4	2	0	1	2	4	4	4	4	5	3
Capelin	5	5	5	5	5	4	5	5	5	5	3	1
Northern sandlance	4	4	4	4	4	4	4	4	4	4	0	2
Pacific sandlance	4	4	4	4	4	4	4	4	4	4	1	2
Northern shrimp	4	4	4	4	4	4	4	4	4	3	3	0
Pink shrimp	4	5	4	5	3	5	5	5	5	2	5	3
Inconnu	5	5	5	5	3	5	5	4	5	5	3	3
Lake trout	5	5	5	5	5	5	3	5	5	5	1	3
Lake whitefish	5	5	5	5	4	4	5	4	5	5	1	1
Ninespine stickleback	5	5	5	5	3	5	5	3	5	5	1	1

Figure 5. Data quality scores (numbers) and attribute sensitivity score (colour) for each of the 12 attributes and 20 species. Color is one of green (low; mean score <2.5), yellow(moderate; mean score 3.0>2.5), orange (high; mean score 3.5>3.0), red (very high; mean score >3.5), or grey (not scored). Data quality is scored as 5 (adequate data from the Canadian Arctic), 4(adequate data from outside the Canadian Arctic), 3 (Limitied data from the Canadian Arctic), 2(Limited data from outside the Canadian Arctic), 1 (Expert judgement), or 0 (No data).

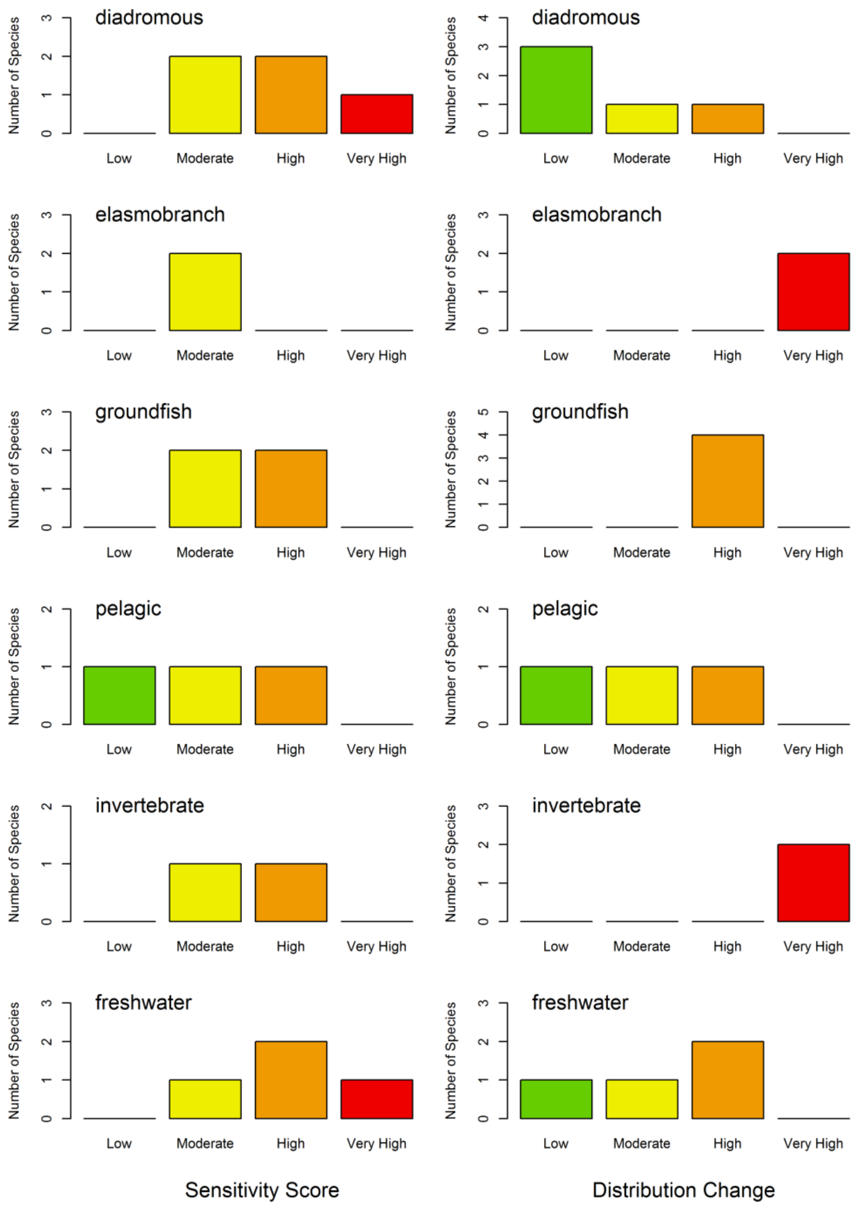


Figure 6. Functional group scores for Arctic fish species for sensitivity and potential for distribution change. See figure 2 and X for aggregated results.

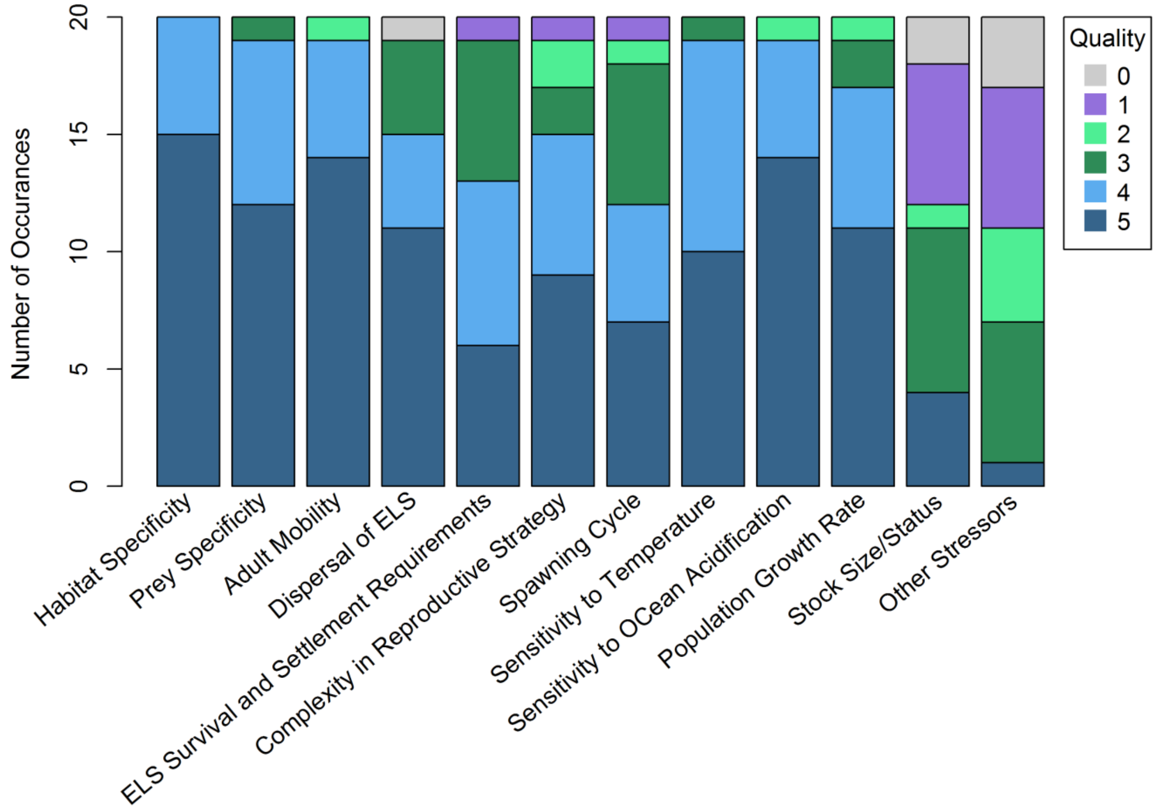


Figure 7**.** Data quality scores by sensitivity attribute. Data quality is scored as 5 (adequate data from the Canadian Arctic), 4(adequate data from outside the Canadian Arctic), 3 (Limitied data from the Canadian Arctic), 2(Limited data from outside the Canadian Arctic), 1 (Expert judgement), or 0 (No data).

APPENDIX 1 – Sensitivity attributes from Hare et al. (2016)

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: Stocks that are reliant on specific habitat types may be more vulnerable to climate change because they are dependent on not only their own response to climate change, but also the impact on their habitat (EPA 2009). Note: the type (biotic vs. abiotic) 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. 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. Stocks 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, 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, 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 physical habitats.** Occurrences of the stock have been documented in diverse habitats. Also, included in this bin are stocks that are restricted to one physical 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: Understanding how reliant a stock is on specific prey species could predict its ability to persist as the climate changes. Generalists (who feed across a wide spectrum of prey types) should have a better chance to persist in response to a changing environment. Alternatively, 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.

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, 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.

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. 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. 2008, Hare and Richardson in press). 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 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. For elasmobranchs that have evolved life history strategies that produce a smaller number of well-developed offspring, the impact of this attribute will be reduced. For elasmobranchs with live birth, dispersal will occur while in utero and should be scored as low to moderate. 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. Bins were modified from Pecl et al. (2014).

Dispersal of Early Life Stages Bins:

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.

Background: Close to 100 years ago, fisheries scientists recognized the importance of recruitment variability in fish populations (Hjort 1914). Since then, multiple hypotheses have been developed to explain this variability, but 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 that are dependent on specific physical conditions to survive (e.g., temporary gyres that provide food and retention, calm conditions that allow for concentration of prey, specific transport pathways to nursery habitats, etc.).
- Larvae that are dependent on a settlement habitat or cue that could be impacted by a changing climate.

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 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 specificity of these conditions varies between stocks. If no citable reference is available, 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.

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 at low stock sizes due to depensation/allee effects. If this is not known, does the stock share life history characteristics that would predict strong alee effects (e.g., at low densities, urchins can experience decreased fertilization and thus reduced recruitment)?
- The reproductive success of the stock requires the use of vulnerable habitats (freshwater, estuaries, mangroves, salt marshes, coral reefs) 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:

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 over an extended period of time will be more likely to be successful in a changing environment. 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, a type of bet hedging, 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 considered to be at the lowest risk of suffering from adverse effects of climate change. 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 risk. 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 high risk of being effected 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 queues to initiate spawning and that only spawn once per year are at the highest risk level for 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. Note: that this attribute uses species (vs. stock) distributions as they better predict thermal requirements.

Relationship to climate change: Species that experience a wide range of temperature regimes are more likely to persist in a warming ocean (Chin et al. 2010).

Background: The distribution of a species within or across provinces provides an estimate of its temperature requirements. Spalding et al. (2007) 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 Spalding et al. (2007) 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).

Temperature Sensitivity Bins:

1. **Low: Large temperature range.** Species occurs in a wide range of temperatures (>15ºC), or is found across 3 or more provinces.

2. **Moderate: Moderate temperature range.** Species occurs in a moderately wide range of temperatures (10-15ºC), or is found across 2 provinces.

3. **High: Somewhat limited temperature range.** Species occurs in a moderately narrow range of temperatures (5-10ºC), 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 (<5ºC), or is found within one province and has a limited depth distribution (i.e., depth range is <100 m).

SENSITIVITY TO OCEAN ACIDIFICATION (OA)

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

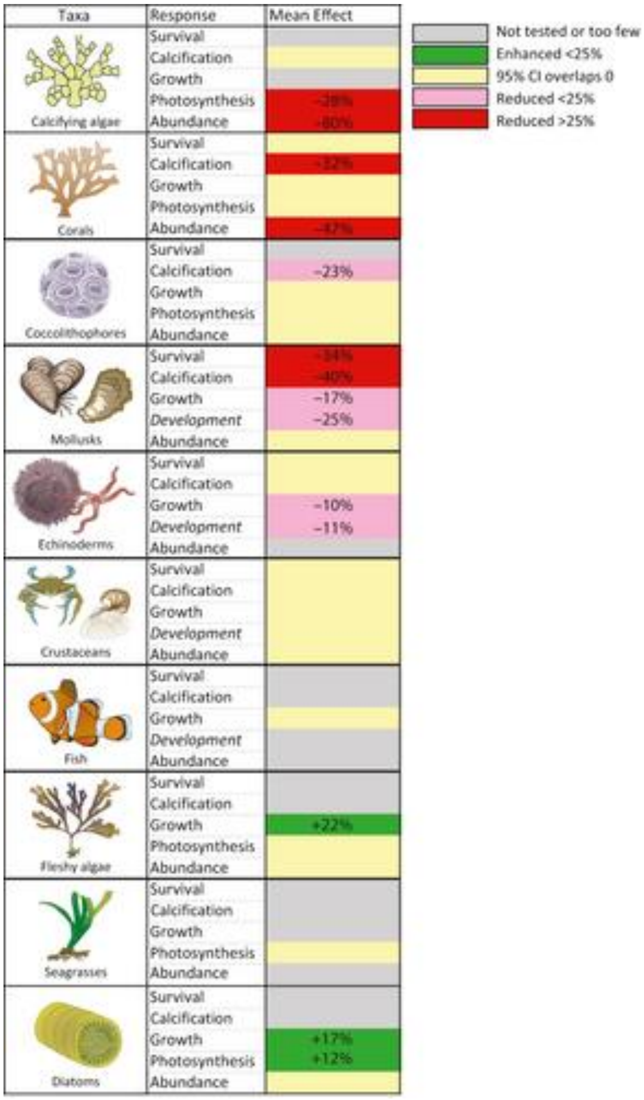
Relationship to climate change: Impacts of OA on marine organisms can be highly variable, with considerable variability between taxa and species (Kroeker et al. 2013). Therefore, we are estimating impact of OA by examining the dependence of the stock on sensitive taxa. For example, current research shows a consistent negative impact of OA on mollusks and corals, so species in either of 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 (see Figure 4 from Kroeker et al. below). 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 may also be affected (Mundy et al. 2009).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 the results presented in Figure 4 from Kroeker et al. 2013 (or other relevant information) 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.

Sensitivity to Ocean Acidification Bins:

1. **Low: Stock not reliant on sensitive taxa.** 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. 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 highly 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 corals or mollusks) that have been shown to have a consistent negative impact of OA on survival, growth or abundance.



From Kroeker et al. 2013
Fig. 4 Summary of effects of acidification among key taxonomic groups. Effects are represented as either mean percent (+) increase or percent (?) decrease in a given response. Percent change estimates were back transformed from the mean LnRR, and represent geometric means, that are conservative of the arithmetic means.

POPULATION GROWTH RATE

Goal: To estimate the relative productivity of the stock.

Relationship to climate change: More productive stocks are, in general, better suited to rebound after the population is stressed by changes in the environment, such as climate change.

Background: Population growth rate is defined as the maximum population growth that would be expected to occur under natural conditions (e.g., no fishing). The amount the population changes over time can be attributed to births, deaths, emigration, or immigration of individuals between separate populations (EPA 2009). If direct measurements of population growth rate (r) are 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 and natural mortality. Scoring bins for these proxies were modified from Musick (1999) by an analysis of 141 marine fish species that were considered to be representative of U.S. fisheries (Patrick et al. 2009).

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**
Intrinsic rate of increase (r)	> 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

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 (BMSY) and is a commonly used biological reference point for federally managed stocks. Use the following link for information on current estimates of B/BMSY: 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 (Musick 1999) set a level of <10,000 individuals as the criteria for a stock being considered vulnerable to the risk of extinction. 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 "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. Also, if a stock has known low genetic diversity, adjust your ranks accordingly.

Stock Size/Status Bins:

1. **Low:** B/BMSY ≥ 1.5 (or proxy)

2. **Moderate:** B/BMSY ≥ 0.8 but < 1.5 (or proxy)

3. **High:** B/BMSY ≥ 0.5 but < 0.8 (or proxy)

4. **Very High:** B/BMSY < 0.5 (or any stock below <10,000 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: 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.

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. 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 stressors the stock may be experiencing:

- The habitat on which the stock depends is degraded. Examples include anthropocentric 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:

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.

Very High: Stock is experiencing high stress other than fishing. Stock is experiencing four or more known stressors.