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Incorporating knowledge of changes in climatic, oceanographic and ecological conditions in Canadian stock assessments

Pierre Pepin[1] | Jacquelyne King[2] | Carrie Holt[2] | Helen Gurney-Smith[3] | Nancy Shackell[4] | Kevin Hedges[5] | Alida Bundy[4]

[1]Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, St. John's, Newfoundland and Labrador, Canada

[2]Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, British Columbia, Canada

[3]Saint Andrews Biological Station, Fisheries and Oceans Canada, Saint Andrews, New Brunswick, Canada

[4]Bedford Institute of Oceanography, Fisheries and Oceans Canada, Dartmouth, Nova Scotia, Canada

[5]Freshwater Institute, Fisheries and Oceans, 501 University Crescent, Winnipeg, Manitoba, Canada

Correspondence
Pierre Pepin, Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, St. John's, NL, Canada.
Email: pierre.pepin@dfo-mpo.gc.ca

Abstract

Environmental impacts on fisheries are pervasive, yet methods to account for them in stock assessments and management decisions vary in rigour and quality. The prevalence and efficacy of methods to account for environmental impacts are not well documented, limiting our ability to adequately respond to future environmental and climate changes for adaptive resource management. In Canada, legislation now requires that environmental conditions are considered in the management of fish stocks, yet the current extent of implementation in assessment processes is poorly understood. We assessed the use of climate, oceanographic and ecological considerations in science advisory processes for 178 stock assessments by Fisheries and Oceans Canada. We evaluated whether these considerations were included in conceptual hypotheses about broad-scale mechanisms, quantitative or qualitative analyses, and the development of management advice on current or future stock status. Conceptual hypotheses were included in 46% of assessments; quantitative inclusions occurred in 21% of assessments, while qualitative interpretations appeared in 31% of assessments; and 27% of assessments included climate, oceanographic and/or ecological considerations in the advice. Assessments of salmonids, invertebrates and pelagic taxa more frequently made use of environmental data than those for groundfish and elasmobranchs. Comparing our findings with assessments in other jurisdictions highlighted a gap in Canada's ability to respond to environmental changes and a need to develop integrated management approaches, such as regional ecosystem assessments and approaches that combine modelling and empirical analyses, with socio-economic analysis within interdisciplinary teams.

KEYWORDS

climate change, ecosystem state, fishery management, prey–predator interactions, stock status evaluation

1 | INTRODUCTION

The importance of changes in environmental conditions (i.e., climate, oceanographic and ecological variables) on the distribution, abundance and productivity of aquatic resources is widely recognized (Punt, Szuwalski, & Stockhausen, 2014; Szuwalski et al., 2015). However, the application of such fundamental research in stock assessments remains limited globally (Bell et al., 2020; Marshall et al., 2019; Skern-Mauritzen et al., 2016), and is subject to error and breakdown (King et al., 2015; Myers, 1998; Szuwalski & Hollowed, 2016). Environmental effects are often implicit in management strategy evaluations (MSE) (Punt, A'mar, et al., 2014) although there are several instances in which the potential consequences of environmental effects are explicitly considered (Kaplan et al., 2021; Punt et al., 2022).

The ability of scientists to incorporate climate change or other environmental information into the advisory process relies on fundamental research. For environmental information to be effectively included in an advisory process, a high degree of confidence is required in our knowledge of how environmental drivers affect changes in the state of one or several features of the taxa's biology, and the mechanism(s) involved (Edwards et al., 2017). Many are reluctant to include environmental considerations because the implications often lead to advice that requires greater precaution in stock management, and the threshold for acceptance of new approaches often exceeds that of established methods. Environmental conditions can act directly or indirectly on life-history parameters (i.e., growth, condition, mortality, phenology, maturation and energy allocation) or can affect the ability of scientists to quantify abundance through changes in behavior (e.g., catchability, the timing of migration and shifting distribution). Also, these impacts can act at various time scales and with different levels of consistency (e.g., episodic events impacting pre-recruit survival, cumulative conditions over the growing season or over multiple years).

The methods that can be used to incorporate environmental variables into population assessments are likely to differ among taxa, stocks and regions because of differences in uncertainty regarding system dynamics, and the relative importance of potential drivers of change, or the relative strength of environmental change has less effect than that of other factors (e.g., harvest rates). The extent of these differences is currently unknown, as are possible opportunities for sharing methodical advances among taxa, stocks and regions. Skern-Mauritzen et al. (2016) reported that approximately only 2% of international assessments included considerations of environmental or ecosystem change in the provision of advice. They focused on stock assessments produced by international regional fishery bodies and by the United States and Australia, two countries considered to be at the forefront of ecosystem approaches for fisheries management. Marshall et al. (2019) found that in 206 US stock assessments, ecosystem considerations were more widespread (25%) than reported in Skern-Mauritzen et al. (2016) and occurred more often if a regional science center had a long-term program on predator–prey interactions or when stocks were designated as overfished. Reviewing the ways stock assessments have considered ecosystem variables is a foundation for developing recommendations on when and how to expand a stock assessment to include those factors.

Canada's *Fisheries Act* (R.S.C., 1985, c. F-14, https://laws-lois.justice.gc.ca/eng/acts/f-14/FullText.html) was revised in 2019 and states that environmental conditions affecting the fishery stock shall be taken into account when maintaining and rebuilding stocks. Scientific advice concerning the status of aquatic renewable resources and the potential consequences of management actions are developed through a peer-review process overseen by the Canadian Science Advisory Secretariat (CSAS) of Fisheries and Oceans Canada (DFO). In addition, DFO is currently developing a national strategy to initiate an ecosystem approach to fisheries management (EAFM) for the development of single-stock advice. Including ecosystem considerations in single-species stock assessments is one way to provide ecosystem-based management advice. The aim of this review is to provide an evaluation of recent Canadian fish stock assessments to determine the state of application of environmental parameters in models, assessments or management advice, identify common barriers to inclusion of environmental information and opportunities for its further incorporation in assessments and advice. All stock assessments reviewed have provided scientific advice to fisheries managers and are critical to DFO's mandate to sustainably manage fisheries. We aim to describe the points in the assessment processes at which environmental information is applied, and how this has been used to frame tactical and strategic advice for decision-makers.

2 | METHODS

The linkage between climate change and variability in fish population dynamics is mediated through physical and biogeochemical oceanographic and ecological drivers, therefore any evaluation of the incorporation of climate information in single-species stock assessments should account for that broader suite of drivers. For the purposes of this review, climate, oceanographic and ecological drivers as a group are referred to as environmental variables, and are defined here as:

1. Climate (C) drivers characterize multi-year or multi-decadal variations and trends in regional or large-scale atmospheric processes or drivers of broad-scale physical properties (e.g., Atlantic multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and Pacific Decadal Oscillation (PDO)) that are often associated with important changes in ecosystem characteristics (e.g., primary production, community structure and distributional shifts). Climate variables also include shorter-term processes acting at large spatial scales, such as the El Niño Southern Oscillation (ENSO). Sea ice indices were included as climate variables because of their large spatial scale and long-term declines due to atmospheric warming. Climate variables are often linked to oceanographic processes but the indicators are generally applicable over large spatial scales and temporal variations are on the order of decadal rather than interannual.
2. Oceanographic (O) drivers can be strongly associated with climatic variability, but also often include short-term and regional variability in ocean conditions. These variables can reflect the cumulative effects of changes in weather patterns or departures from the average seasonal cycle. Oceanographic variables are physical and biogeochemical drivers and include upwelling indices, temperature, salinity, dissolved oxygen content and pH.
3. Ecological (E) drivers include a broad range of ecosystem features, trophic interactions (i.e., predator–prey relationships) and habitat requirements. Variability in ecological drivers is often similar to that of oceanographic variables but can exhibit independent changes as a result of perturbations to one or several ecosystem components. Ecological variables include predator and prey indices, and thermal habitat requirements.

Four main questions were evaluated in the review of each stock assessment (Figure 1). Question 1 addressed whether, and where within the stock assessment document conceptual hypotheses between environmental variables and the stock were identified. Question 2 addressed whether environmental variables were included *quantitatively* in the assessment, and how they were included. We considered stock assessments that included time-varying biological parameters, such as natural mortality or growth, as examples that quantitatively included climate, oceanographic and/or ecological variables when rationale was provided linking it to a relevant variable or process. For example, the rationale for including time-varying natural mortality could be due to varying predation rates (i.e., ecological considerations) or may reflect broader changes in ecosystem status. Question 3 addressed whether environmental variables were included *qualitatively* in the assessment, typically by considering those variables used to interpret status, trends or anomalies in stock indices, such as survey catch per unit effort. Question 4 addressed whether the final recommended scientific advice included climate, oceanographic and/or ecological considerations. Many assessments may have considered environmental variables during deliberations, but the final consensus for recommended advice may not have utilized those analyses. In cases where no climate, oceanographic or ecological information was included in the advice, the reasons were identified where possible and categorized (e.g., not a concern, unknown mechanism and data limitations) to identify impediments to inclusion. For each question, we documented the specific environmental variables or a combination thereof, and identified the associated variables.

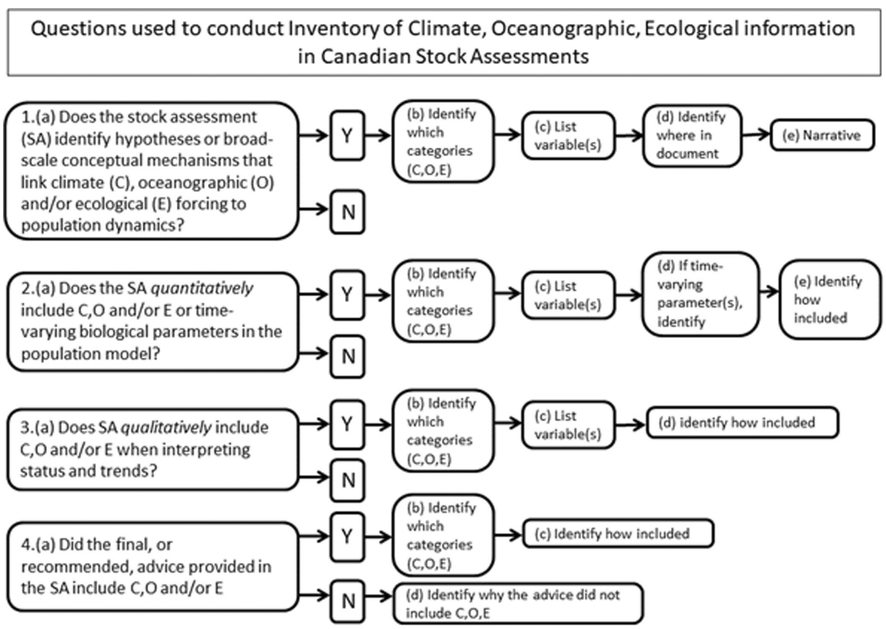

FIGURE 1 Flowchart used to review the use of climate (C), oceanographic (O) and ecological (E) variables or considerations in DFO fisheries stock assessments. Question sub-headings (a) to (e) provide the order in which the review was conducted

DFO is responsible for providing advice for stocks in the Pacific, Atlantic and Arctic Oceans, the Gulf of St. Lawrence and some large freshwater systems. Responsibility for assessments generally rests with the DFO institutions in closest geographic proximity to the bioregion (DFO, 2009) in which the stock occurs, although some assessments are carried out jointly by multiple institutions (outside of DFO). Therefore, we included stock assessments conducted by DFO for Canadian fisheries, for North Atlantic Fisheries Organization (NAFO) stocks and by the Transboundary Resource Assessment Committee (TRAC).

We reviewed published CSAS Science Advisory Reports, Science Responses and Proceedings Series (http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm). Exceptions to this were for stock assessment advice provided for some Pacific salmon (*Oncorhynchus* spp.) stocks which are often provided within Fishery Bulletin notices, Salmon Outlook Reports and Canadian Technical Reports of Fisheries and Aquatic Sciences. For Pacific salmon, the review was not comprehensive because numerous assessments exist that are not highly circulated and not publicly accessible. In conducting this review, we recognize that although it is not exhaustive, it does capture the majority of stocks for which DFO Science advice is provided.

A total of 178 stock assessments were considered (Table S1). For each stock assessment, we used the most recently published document upon which current advice, or a framework for the provision of advice, was based. If the most recently published document was an update of a previously published stock assessment model, we referred to the full assessment document for details. Publication dates ranged from 2000 to 2017 although the majority (88%) of documents considered were published after 2009. Our protocol for review of stock assessments did not provide an evaluation of historical patterns in the inclusion of environmental variables as only the most recent assessment for each stock was considered. We did not evaluate the accuracy, rigour or efficacy of the inclusion of these variables in projections or forecasts.

3 | RESULTS

Of the 178 assessments reviewed in this evaluation, 46% (81/178) identified conceptual hypotheses that link environmental variables to population dynamics (Figure 2). However, only 21% (38/178) of the assessments included environmental variables quantitatively in the population model or used time-varying biological parameters thought to be related to such drivers. Thirty-one percent (31%, 55/178) of assessments qualitatively included environmental variables when interpreting status and trends. Advice and/or recommendations that included the importance or effects of environmental variables appeared in 27% (48/178) of stock assessments.

3.1 | Q1 – Conceptual hypotheses and broad-scale mechanisms

Of the 81 stock assessments that identified hypotheses or broad-scale conceptual mechanisms as background information or in the interpretation of potential population drivers, oceanographic variables were considered in 74% of assessments, either on their own or with other variables, whereas ecological variables were considered in 46% of assessments, and climate variables were considered in 22% of assessments. These numbers exclude instances in which environmental variables were explicitly or implicitly included as drivers in the assessment of stock status.

Stock assessments for salmon and other anadromous fishes considered environmental variables most frequently (58%, Figure 2). Overall, the proportion of stock assessments considering environmental variables was lowest for marine mammals (21%) and elasmobranchs (14%).

Within the category of oceanographic variables, the water temperature was most frequently considered (69%; Figure 3). Among climate variables, large-scale forcing and cycles (e.g., Atlantic Multidecadal Oscillation, NAO, PDO, long-term changes in sea ice; 38%) were considered more frequently than short-term forcing (e.g., ENSO) (5%). Among ecological variables, trophic interactions were the dominant consideration (35%), but habitat changes were also included (5%). The general pattern of consideration of environmental variables in conceptual hypotheses was also apparent in the application of quantitative and qualitative approaches to assessments, and consequently in the provision of advice.

3.2 | Q2 – Quantitative analyses

Only 21% of the stock assessments examined (38/178) used environmental variables quantitatively (Figure 2). Most quantitative approaches involved the estimation or interpretation of a time-varying parameter within a population model (37% of the 38 assessments), which is considered a catch-all for a complex set of processes. The time-varying parameter was typically natural mortality to account for predation, or growth or catchability/selectivity to account for changes in ocean conditions (Figure 4). Secondly, in 16% of the 38 assessments, environmental variables were included as co-variates in statistical models used to predict recruitment (e.g., in stock-recruitment relationships), or population productivity, typically spawning stock biomass (also used in 16% of cases; Figure 4). In most of those instances, an assessment of habitat availability, mainly based on bottom temperature, was linked to productivity or biomass estimation of the stock or year-class. Catch Per Unit Effort (CPUE) standardization occurred in fewer instances (11%) and were mainly used to tune fishery or survey indices of abundance, including time-varying catchability/selectivity. Environmental variables were also used to assess variations in the timing, migration or habitat available for spawning (11%). In a few instances (11%), environmental variables were applied to adjust harvest rates, biological benchmarks or outline other harvest strategies (Table S2). Finally, in the fewest instances (8%) growth, either time-varying or period averaging estimation, was linked to environmental covariates.

When stock assessments did include environmental variables in a quantitative approach, the majority included oceanographic (61%) or ecological (53%) considerations, while only 24% included climate

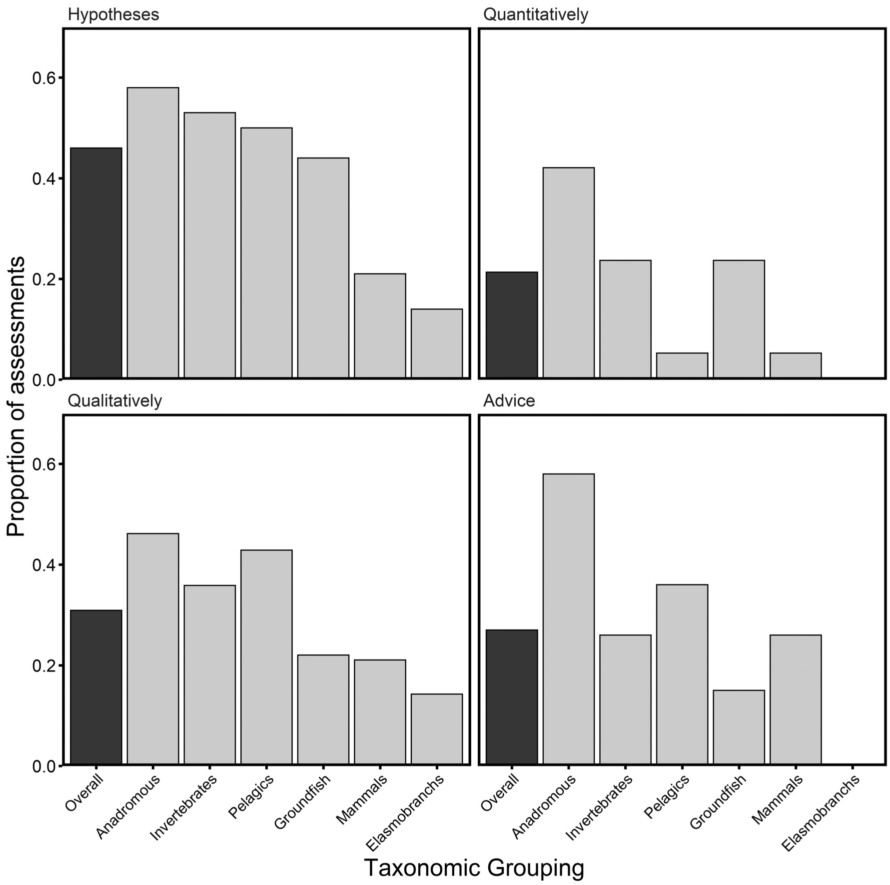

FIGURE 2 Proportion of assessments ($n = 178$) overall and by taxonomic grouping that incorporated climate (C), oceanographic (O) and/or ecological (E) variables to develop conceptual hypotheses, quantitatively assess status, qualitatively interpret trends or status and provide advice. The total number of assessments by taxonomic grouping are anadromous, $n = 26$; invertebrates, $n = 53$; pelagic fish, $n = 14$; groundfish, $n = 59$; marine mammals, $n = 19$; and elasmobranchs, $n = 7$

forcing variables (Figure 3). Trophic interactions (31%) were most common in groundfish assessments, particularly for stocks in the Gulf of St. Lawrence. The broad-scale ecological change was also indirectly included (21%), namely as a rationale for varying productivity or recruitment (Figure 3).

Climate variables were usually included quantitatively using indices of long-term atmospheric forcing or short-term climatic processes (namely ENSO events) combined with long-term atmospheric forcing (Figure 3). Long-term atmospheric forcing was quantitatively included most often in the Pacific region anadromous assessments using the PDO index. It is likely that ENSO indices are not included in more Pacific stock assessments because the teleconnection patterns to the Pacific are well captured in sea surface temperature time series (Trenberth & Hurrell, 1994).

Among those stock assessments that included environmental variables quantitatively, a high proportion (87%) provided science advice that was based on these considerations. This suggests that when quantitative analyses are undertaken, the inclusion of climate, oceanographic or ecological variables can provide useful management advice. There has been considerable progress in the approaches used to include and evaluate environmental variables in modelling recruitment (Haltuch et al., 2019; Maunder & Thorson, 2019). However, it is equally plausible that attempts to quantitatively include those variables are only reported in a stock assessment document when results are statistically significant or reduce uncertainty, thereby improving advice.

3.3 | Q3 – Qualitative interpretation

Qualitative analyses consist of instances in which environmental variables are not explicitly included in the assessment model but serve as an additional source of knowledge about stock status and its potential relationship with ecosystem conditions. We found that 31% (55/178) of stock assessments qualitatively considered environmental variables when interpreting status or trends (Figure 2). Environmental variables were most often considered qualitatively for anadromous species (46%) and relatively infrequently for groundfish, mammals and elasmobranchs (22%, 21% and 14%, respectively; Figure 2). Most frequently, environmental variables were used qualitatively to explain historical trends in biological processes (e.g., abundances, growth, maturation and distribution derived from habitat suitability models). Environmental variables were also used qualitatively to explain anomalies in specific years, explain current stock status, account for uncertainties in assessments and forecast future status and trends using multi-indicator frameworks (Figure 4).

Among stock assessments with qualitative use of environmental variables, 25% considered climate forcing, 73% oceanographic variables, 62% ecological variables and a large proportion of assessments considered variables from multiple categories (Figure 3).

Oceanographic variables were more often considered than climate or ecological variables for most regions, but ecological variables were more frequently considered in assessments performed in the Atlantic Ocean (53%). Climate forcing was more frequently

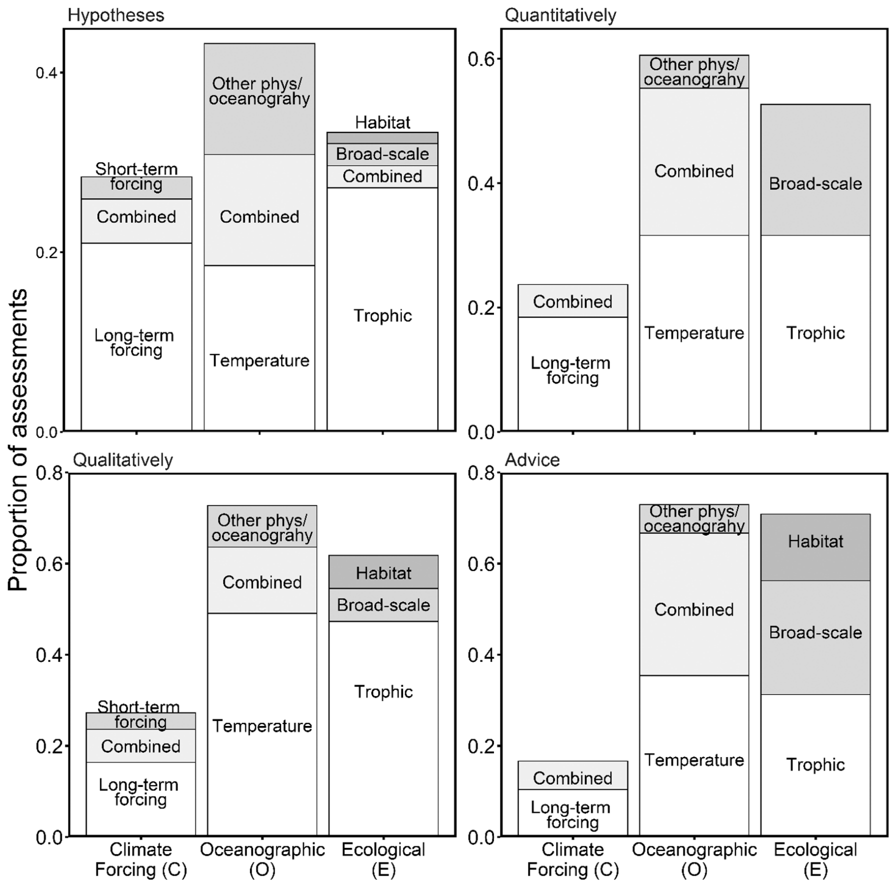

FIGURE 3 Proportion of assessments that used long-term or short-term climate forcing (C) variables; temperature or other physical and oceanographic (O) variables; trophic interactions, broad-scale changes or habitat ecological (E) variables. Proportions are based on the number of assessments that incorporated climate (C), oceanographic (O) and/or ecological (E) variables to develop conceptual hypotheses, quantitatively assess status, qualitatively interpret trends or status and provide advice

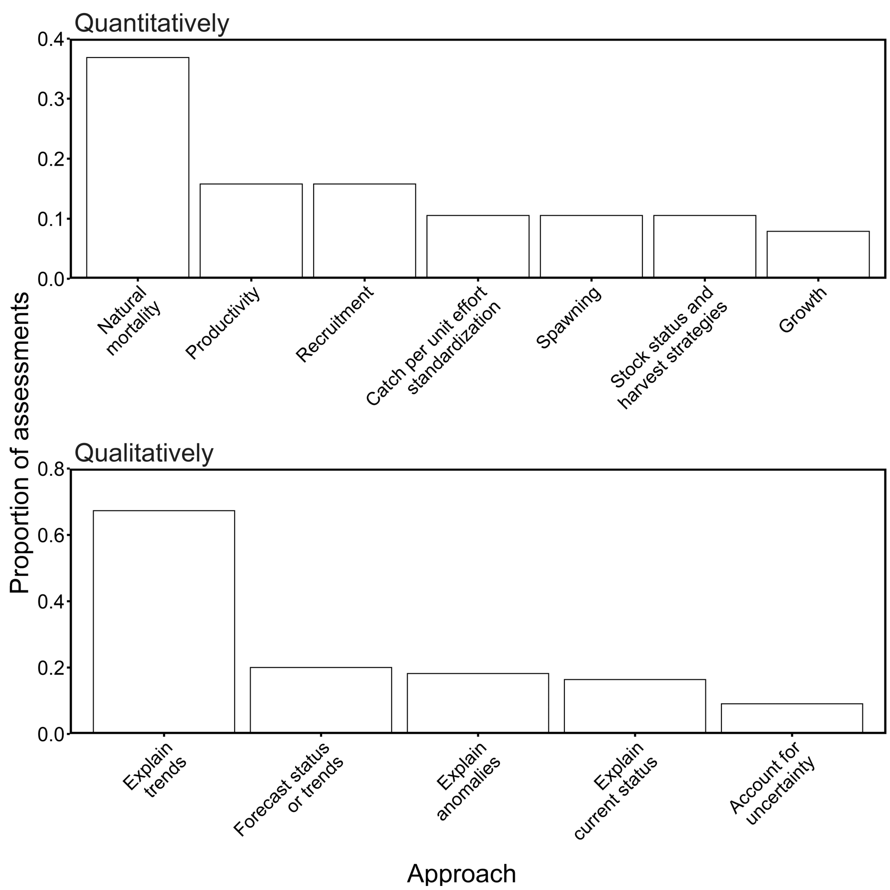

FIGURE 4 Proportions with which analytical approaches were used in assessments. Values were calculated as proportions of stock assessments that incorporated environmental variables either quantitatively or qualitatively, respectively

considered in assessments of Canadian stocks in the Pacific Ocean, where most of the anadromous stocks are located (37%).

3.4 | Q4 – Advice and recommendations

Of the 178 assessments evaluated in our analysis, 48 (27%) made recommendations or provided advice based on environmental considerations (Figure 2), which is substantially less than the 81 (46%) documents that identified hypotheses or broad-scale conceptual mechanisms. However, approximately one-quarter of the assessments that made recommendations did not identify hypotheses or conceptual mechanisms as the basis for the assessment, raising questions concerning the basis of the advice. This lack of clarity illustrates the need to fully document all hypotheses or conceptual mechanisms in each assessment report.

More than two-thirds (69%) of assessments that included environmental variables in advice also included those variables quantitatively in the assessment, whereas three-quarters included environmental variables qualitatively. More than half of the instances with recommendations that included environmental considerations (61%) were based on instances where both quantitative and qualitative results were applied in the interpretation of population dynamics. This reflects that multiple approaches (or models) can be applied in the assessment process.

The consideration of environmental variables in advice was greatest in anadromous species (58%, Figure 2), with the predominance in Pacific salmon species. Only 15% of groundfish stock assessments included environmental considerations in the advice and only one of the seven assessments for elasmobranchs provided advice based on environmental variables. The contrast among taxa may partly reflect the extent to which variations in environmental conditions are likely to be encountered in the upper water column, but they may also reflect differences in longevity. Differences in the histories of the various ecosystems, such as the collapse of Atlantic groundfish in the late 1980s and early 1990s, may also contribute to these differences.

Overall, oceanographic variables appeared in 73%, and ecological considerations appeared in 71% of the scientific recommendations (Figure 3). Climate considerations appeared in 18% of assessments in which environmental conditions were included in the advice, and generally in combination with oceanographic and ecological considerations.

Environmental considerations were used in the advice relevant to harvest control rules in 43 of the 48 assessments (90%). The consequences of time-varying parameterization to expectations concerning stock productivity, principally in terms of changes in natural mortality rates, occurred in 31% of these assessments. Links between population trends and climate, oceanographic and ecological variables were noted in 14% of assessments, and generally provided context to explain expectations of future population state and production potential relative to management objectives. Climate, oceanographic and ecological considerations were identified as a source of uncertainty in 8% of assessments as contextual information pertinent to recommendations about harvest control rules.

Of the assessments where environmental considerations were not included in the recommendations, 49% (64/130) did not include a section pertaining to variations in environmental conditions despite 34% of them having explicitly identified hypotheses or broad-scale conceptual mechanisms that linked environmental forcing to population dynamics. In 39% of the remaining 66 assessments with no environmentally based recommendations, a lack of clear understanding of the mechanisms by which environmental conditions would affect the population was cited as the reason for not incorporating environmental variables. Data limitations or uncertainty were cited in 45% of these assessments. Seventeen percent of these assessments identified other factors as having a greater influence on populations than environmental variables. A lack of quantifiable benefit to the analysis or projection of stock status was cited in 17% of these assessments.

4 | DISCUSSION

Progress towards implementing an EAFM, measured by the incorporation of environmental variables into stock assessments is being made in Canada, but it is varied and incomplete. The *status quo* does not provide sufficiently consistent informed advice to meet new legislative requirements in Canada to consider environmental variables in assessments. Our review of 178 stock assessments representing fisheries across Canada's extensive coastline revealed that although 46% of examined assessments identified hypotheses or broad-scale conceptual mechanisms concerning environmental variables and population dynamics, only 21% used environmental variables quantitatively and 31% considered environmental variables qualitatively, with only 27% including environmental considerations in the final science advice provided to fisheries managers. The consideration of environmental variables varied among taxa and the type of environmental variable. Assessments of salmonids, invertebrates and pelagic taxa were more likely to include environmental data than assessments of groundfish, marine mammals or elasmobranchs. Oceanographic and ecological factors were considered more often than climate variables, although the latter was of particular importance in the Pacific and Arctic Oceans. Furthermore, the inclusion of environmental variables into an assessment is more likely to be successful for species with a strong bottleneck in their life history during which environmental variables play a significant role in population dynamics, such as anadromous species of salmon (Haltuch et al., 2019; Maunder & Thorson, 2019). This is consistent with more recent findings of climate change considerations in Atlantic and eastern Arctic fisheries management (Boyce et al., 2021). The low proportion of advisory documents that include environmental variables highlights a gap in DFO's ability to provide comprehensive fisheries science advice, with potential impacts on Canadian marine resource management and livelihoods. In the age of the Anthropocene, scientific knowledge gaps must be filled to reduce pressure from cumulative stressors such as climate change and overfishing.

4.1 | Requirements for the inclusion of environmental variables in assessments

From our review of Canadian assessments, and multiple examples from other jurisdictions, we identified four requirements for the inclusion of environmental variables: (1) basic core research, (2) frequent re-assessment of relationships with environmental variables, (3) rigorous evaluation of the inclusion of environmental variables and (4) a risk-based approach for considering impacts of environmental variables that goes beyond statistical significance (*sensu* Dorn & Zador, 2020; Duplisea et al., 2021). Despite the observed differences in the consideration of environmental variables among taxonomic groups and regions within Canada, a clear pattern is evident. Environmental variables are incorporated into stock assessments as a result of core research. In many cases, this research occurs when the impact of environmental variables has become apparent through correlations or larger changes have been observed in environmental variables and the population under consideration. In general, information on forecasted environmental impacts in fisheries is limited (FAO et al., 2021) and there is a need to account for the impacts of uncertainty on the inferences presented to managers (FAO et al., 2021). Considerable background research is required to understand the linkages and pathways of effects between environmental variables, stock productivity and status to predict the impact of current and proposed management actions in a changing environment. This highlights the importance of basic research to reduce scientific uncertainty in fisheries decision-making when populations are subject to environmental change. Differences in the frequency and method of incorporating environmental variables reflect differences in the strength of mechanistic understanding of pathways of effect and the level of confidence in statistical relationships.

4.2 | Challenges in applying environmental variables to assessments

Our review highlights the high standards of the peer-review process for the incorporation of environmental knowledge in the provision of scientific advice where concern over scientific uncertainty in understanding underlying mechanisms is often cited as a limitation. Stock assessments rely on reconstructing the past to understand the drivers of change in population abundance and to project into the short-term future, typically 3 years or less. The quality and quantity of information and knowledge available can limit our ability to evaluate the relative contributions of environmental variables to population dynamics in the short term. The advisory documents studied herein highlighted the importance of "weight-of-evidence" in providing a demonstrable impact of environmental drivers on population dynamics to meet the standards of the peer-review process.

Drivers of fisheries population abundance may change over time, where complex interactions among environmental variables can result in shifts in relative driver dominance, which necessitates the regular re-assessment of environmental relationships through basic research. For example, a relationship between projected catches of Newfoundland Snow Crab (*Chionoecetes opilio*, Oregoniidae) and the extent of a climate-related thermal habitat index (based on conditions 6–8 years prior to the fishery) appeared to break down consequent to recovering groundfish stocks, forcing a reassessment of the variables included in projections (DFO, 2017a). Such occurrences are likely to become more common with increasing climate change and can result in the breakdown of models based on relationships that had previously appeared reliable because other factors may become more important drivers of a population's dynamics, as was the case for Bay of Biscay Anchovy abundances and an upwelling index (Allain et al., 2001; Borja et al., 1998; ICES, 2001, 2005). A recent example is provided by the US Pacific Sardine (*Sardinops sagax*, Clupeidae) where there is a sophisticated integration of environmental variables into the assessment and provision of advice for management (Hill et al., 2017; Kilduff et al., 2015; Mantua, 2015; Mueter et al., 2005; Oke et al., 2020). Initially, sea surface temperature (SST) was included in the harvest control rule in 1998, but recruitment failures from 2006 to 2012 (in spite of high SST values) led to the removal of SST (Zwolinski & Demer, 2014). SST averaged over the spawning grounds was then reapplied in the harvest control rule with a buffer (Hill et al., 2017) as well as a recommendation that models would need to be re-assessed frequently for validity. Detecting changes in relative driver dominance is essential to foster confidence in the inclusion of climate, oceanographic or ecological variables into the advisory process. In addition, sudden system losses or shocks caused by short-term factors such as extreme weather events are increasing (Cottrell et al., 2019; Mills et al., 2013), and will need rapid management responses to reduce long-term effects on stock productivity (e.g., marine heat waves [Cheung & Frolicher, 2020]). Climate change effects are resulting in the increasing occurrence of conditions outside the range of past observations. Certain taxa may not be able to react to localized extreme conditions as a result of physiological stress, poor condition or reduced survival. The increasing frequency of extreme events will lead to a greater need for rapid changes in management actions and will likely require a rethinking of what constitutes sustainable practices.

Our results indicate that the inclusion of environmental variables in the provision of advice was often not rigorously evaluated a priori in many Canadian assessments, which may lead to advice that does not accurately consider current conditions. For example, when environmental variables were included as covariates in assessment models, the model fits rarely included cross-validation methods, typically being based on correlation coefficients between modelled and observed data or information criteria (e.g., Akaike or Deviance information criteria) which do not evaluate out-of-sample prediction accuracy. Even if including environmental metrics in assessments improves model fit, their inclusion can reduce the quality of decisions if correlations among variables change over time and these changes are not taken into account. In a few cases more rigorous evaluations were performed by re-evaluating statistical model fits with re-sampled data (e.g., Fraser River sockeye pre-season forecast [DFO, 2016, 2017b]). However, these processes did not evaluate whether the inclusion of those metrics improved scientific advice or management outcomes. For example, De Oliveira and Butterworth (2005) found that fisheries management for the South African Anchovy (*Engraulis encrasicolus*, Engraulidae) only benefited from the inclusion of environmental variables in terms of summary performance and catch when the environmental variables explained at least 50% of the variation in recruitment.

Another challenge facing EAFM is that information on forecasted environmental impacts in fisheries management is frequently limited, creating the need to account for uncertainty (FAO, 2021). At the same time, the peer-review process may be subject to institutional conservatism (Marshall et al., 2019) that requires a high burden of proof before the role of environmental variables may be recognized and incorporated into management plans, which may occur only after the cumulative impacts of environmental and fishery pressures result in a decline in the stock's status. However, this burden of proof ignores the general patterns of change in marine ecosystems that are highly likely to affect the future stock status and potentially alter a precautionary exploitation rate. It also discounts the risk associated with management decisions that treat uncertainty as a random factor in stock trends. This challenge reinforces the need for basic research as well as the requirement to reassess relationships between stock dynamics and environmental variables. We recommend that the quantitative inclusion of environmental variables in assessments be rigorously evaluated and uncertainties are quantified to determine whether greater accuracy is achieved and management objectives are better met relative to instances when environmental variables are excluded. In cases where the inclusion of environmental variables does not improve accuracy or the ability to achieve management objectives, the efforts taken to consider environmental variables in the stock assessment need to be fully documented and a summary included in the scientific advice to ensure fisheries managers are aware that environmental variables were considered and that this information is not lost.

A common approach in fisheries assessments is to fit a particular model parameter (e.g., mortality) as a random effect through a time-varying autocorrelated process, which does not require a mechanistic understanding of the key drivers, but which captures the overall effect of varying environmental conditions on stock dynamics. Projections of future population state, however, are associated with widening variance when the time-varying autocorrelated process is not associated with underlying mechanisms. When relationships between environmental variables and population responses (e.g., growth, mortality and recruitment) can be identified, it may be possible to provide indications of past or future possible population status in relation to a covarying environmental factor. This can be particularly useful in instances in which future environmental states can be forecasted, such as through climate change projections or expected changes in predator populations. Duplisea et al. (2021) proposed the use of empirical or phenomenological models to provide broad predictive capacity to quantify future states to manage risks associated with management decisions under plausible future environmental conditions and fishery objectives. Similar to environmentally conditioned MSEs (Kaplan et al., 2021; Punt et al., 2022), Monte Carlo simulations based on the underlying environmental effect on population response provide projections of the probability of achieving the objectives through time while allowing an assessment of the importance of environmental change on stock dynamics but without the complexity of an MSE. Successive and consistent departures from projections can serve to assess whether other factors may be driving stock dynamics or that changes in baseline conditions may require a re-evaluation of the stock's production potential and fishery objectives.

The development and application of standards for the detection of climate, oceanographic or ecological effects would increase the rigour and credibility of assessments that include those variables. Such analytical tools should be applied in a systematic manner as part of the stock and ecosystem assessment process(es) that include the use of such variables. This would be similar to the approach by the Intergovernmental Panel on Climate Change (IPCC) in the detection and attribution of climate change effects (Bindoff et al., 2013), where evidence-based assessments are used to analyze certainty or uncertainty in scientific knowledge. This contrasts with the current, more common *ad hoc* approach that can be affected by the variations of the peer-review process.

4.3 | Limitations of this study

Our review did not evaluate whether the inferences of future population state were improved by the addition of the environmental variables into the advice, nor the potential cumulative effects of variables over life stages. While there are several examples of Canadian stock assessments that quantitatively considered environmental variables in the provision of advice, there were few examples that explicitly compared results from models with environmental variables inclusion to those without. Such an evaluation for all 178 assessments would have required retrospective analyses of the projections, which was well beyond the scope of this review.

In addition, our review did not evaluate whether the use of environmental variables was influential in the decision-making processes because that information is rarely available. Although records of the scientific peer review process are publicly available (http://www.meds-sdmm.dfo-mpo.gc.ca/csas-sccs/applications/publications/index-eng.asp), explicit records of how science advice (including information regarding environmental variables), economic analyses and consultations with stakeholders and co-management bodies (when applicable) are weighted in the decision-making process by fisheries managers, are not readily available. The lack of fully open, transparent and documented steps throughout decision-making processes that lead to the allocation of Canadian natural resources is a major shortcoming, particularly when DFO has a mandate for transparency and evidence-based decision-making (https://www.dfo-mpo.gc.ca/rpp/2020-21/dp-eng.html#B2). Without knowledge of the options considered for the various management decisions and the trade-off among drivers (e.g., conservation constraints vs.

socio-economic impacts) that led to the applied management action, the current evaluation of the "value" of environmental considerations to future states of the fishery and ecosystem could be regarded as largely conjectural or speculative.

4.4 | The need to move towards broad application of EAFM principles

It is somewhat surprising, given the large amount of published literature linking climate and environmental drivers to fish population dynamics (Lindegren & Brander, 2018), that relatively few examples exist globally where indices of those drivers are included, either quantitatively or qualitatively, in stock assessments. A global review concluded that the direct inclusion of ecosystem drivers in assessments was rare, but consideration of ecosystem state often offered context for changes in stock status (Skern-Mauritzen et al., 2016). A review of stock assessments in the United States, however, showed that, similar to Canada, ecosystem factors were being considered in the analysis in 25% of stock assessments, quantitatively, qualitatively or as contextual information (Marshall et al., 2019). The value of quantitatively including environmental variables in short-term tactical forecasts (1–2 years) may be of limited value unless the stock status is highly responsive to year-to-year variations in environmental conditions, as is the case for blue whiting in Europe (Miesner & Payne, 2018). Moderate-term strategic projections, when possible, may be more strongly affected if changes in population state are linked to climate, oceanographic or ecological covariates. Population responses are likely to be linked to the strength and rapidity of environmental change(s) experienced, and extreme events may further influence population productivity.

In the United States, the overarching national Fisheries Climate Science Strategy (Link et al., 2015) has helped develop Regional Action Plans for local implementations. Qualitatively the United States considers environmental variables in management advice through detailed Ecosystem Status Reports for large marine ecosystems (Craig et al., 2021; Ferriss & Zador, 2021; Gove et al., 2019; Harvey et al., 2021; Ortiz & Zador, 2021; Siddon, 2021). Ecosystem "report cards" or overviews are also used in Australia (Gaughan & Santoro, 2018), Europe (AORA, 2017; ICES, 2016a, 2016b, 2016c, 2016d, 2017a, 2017b), and have been developed for internationally managed species such as Atlantic tunas (Juan-Jordá et al., 2018; Juan-Jordá et al., 2020). The development of comprehensive Ecosystem Status Reports represents a critical step in the incorporation of climate, oceanographic and ecological considerations in Canadian stock assessments. Challenges in developing ecosystem summaries include limited resources, resolution of spatial and temporal data at appropriate scales, data management and lags between the timing of data compilation and report release. Furthermore, there as seldom clear objectives and policies available to managers about how to incorporate changes in ecosystem status into decision-making.

Incorporating the influence of environmental variables relative to the effects of fisheries in recommendations from single-species stock assessments represents an important step towards the implementation of an EAFM (Patrick & Link, 2015). In most of the assessments considered in this review, environmental drivers consisted of a single dominant feature of the ecosystem that had undergone substantial change over the stock's history, although sometimes correlated with other features or metrics for the region of interest (e.g., climate and oceanographic indices). Many have advocated for the development of a systematic framework to ensure a comprehensive evaluation of the potential effects of anthropogenic and environmental drivers on aquatic stocks (Koehn et al., 2020; Link et al., 2020; Marshall et al., 2019) and while such proposals have often been aimed in the context of the more holistic ecosystem-based fisheries management, which is focussed at the multispecies level, the basic principles could serve as a base for the broader application of an EAFM in the Canadian system.

As a first step, an incremental and pragmatic approach to conducting an evaluation of the potential relationship between stock status (e.g., biomass, abundance, growth, mortality and recruitment) and environmental variables based on a structured checklist of environmental drivers to be applied to all stocks would represent an organized foundation to ensuring greater consistency within the organization. Because the incorporation of oceanographic and ecological variables was approximately equal in the provision of advice for Canadian stocks, integrated trend analysis (ICES, 2019; Szalaj et al., 2021) could provide a solid foundation for stock assessments across Canada's three Oceans and when developed and applied consistently to all stocks subject to the revised *Fisheries Act*. The development of a systematic framework appropriate to the operational constraints of DFO could also provide a tool to better coordinate assessments among stocks and species within each region. The framework could include a fuller spectrum of climate change impacts that were not considered in our review, for example, stock distribution across management borders.

Canada's Arctic, Atlantic and Pacific oceans are projected to see entrances of new commercial species in their territories as a result of climate change with minimal exits (Oremus et al., 2020), therefore adaptive management will likely involve increasing transboundary management agreements and spatial forecasting (FAO et al., 2021; Maureaud et al., 2021). A key consideration about the potential impact of climate change involves shifts in distributions that could impact the availability of species to harvesters. General expectations are for a gradual poleward shift for many species (Cheung et al., 2009; Fogarty et al., 2017). However, local processes may result in complex changes in habitat availability that would affect a stock's vulnerability to climate change, as Le Corre et al. (2021) demonstrated for northern shrimp (*Pandalus borealis*, Pandelidae) off eastern Canada and McHenry et al. (2019) for species on the Northeast Shelf of the United States. In Australia, the harvest control rule for western rock lobster (*Panulirus cygnus*, Palinuridae) includes the ENSO-related Southern Oscillation Index, local ocean currents, rainfall, sea level height and SST (de Lestang et al., 2012) and climate projections to 2030 were factored into an MSE for sea cucumbers (Plagányi et al., 2013). Internationally, changes in the spatial distributions of species primarily due to ocean warming are expected to affect national catch potential in exclusive economic zones and international waters (Hare et al., 2016; Hollowed et al., 2013; Maureaud et al., 2021; Mills et al., 2013; Pinsky & Fogarty, 2012; Shackell et al., 2014; Shackell et al., 2021) and have already led to social conflicts within and between countries (Barange et al., 2018; Daw et al., 2009; Grafton, 2010; Østhagen et al., 2020; Pinsky et al., 2018; Spijkers & Boonstra, 2017). Environmental variables are being used to inform short-term spatial forecasting of the spawning habitat of blue whiting (*Micromesistius poutassou*, Gadidae) in the eastern Atlantic and to improve catchability (SST and climatology models) of southern bluefin tuna (*Thunnus maccoyii*, Scombridae) on seasonal scales (Eveson et al., 2015; Hobday et al., 2011). Factoring in the effects of shifting distributions and catchability into stock assessments should be a key consideration in guiding improvements to current assessment models and methods.

There are a number of key actions that can facilitate the successful implementation of environmental considerations and fisheries adaptation (Duplisea et al., 2021; FAO et al., 2021; Free et al., 2020; Link et al., 2015; Ojea et al., 2020):

- Increase basic research in environmental monitoring and early warning systems to reduce uncertainty in rates of change to be applied to assessments.
- Fill knowledge gaps of cumulative species vulnerability assessments over different life stages, addressing uncertainty in projected impacts.
- Development and implementation of best practice principles, methodologies for data-poor stock assessments and MSE evaluations where sufficient data is available.
- Provision and use of regular ecosystem assessments and summaries for informing stock assessments.
- Creation of interdisciplinary teams for stock evaluations to facilitate data sharing and action.
- Iterative cycles assessment that determine the robustness of environment–fisheries relationships, creating tiered classifications of assessments to deal with risk, uncertainty and the cost of inaction.
- A national fisheries climate and ecosystem science strategy to provide overall guidance on the implementation of environmental considerations and to reduce institutional inertia.
- Flexible and adaptable management that can be responsive to in-season changes or to extreme events (e.g., marine heat waves) that may affect phenology and recruitment.
- Spatially dynamic ecosystem models to address shifting stocks, with projections of climate velocities to enable resilient co-management of transboundary stocks.

This fisheries strategy should involve early stakeholder engagement and the inclusion of Indigenous and local knowledge. Moving towards further consideration of the role of the ecosystem state on fisheries would require the assessments to consider social and economic issues to provide a comprehensive evaluation of the factors needed to balance conservation needs and human use of marine ecosystems. Scenario-driven ecological-economic modelling exercises have shown that governance and trade decisions were more significant in determining the outcomes of management decisions than the effects of climate change alone (Mullon et al., 2016), and that policymaker confidence uncertainties may have previously prevented incorporation of environmental considerations (Burden et al., 2017). This demonstrates the complexity of factors around management actions that will affect resource resiliency.

Failure to explicitly deal with uncertainties as the cost of inaction may be greater than the risk of implementation (FAO et al., 2021). Currently, DFO's consideration of environmental variables in assessments and advice has been relatively *ad hoc*, with applications often dependent on the efforts of an individual or small groups of scientists, a pattern identified in other jurisdictions by Skern-Mauritzen et al. (2016). There may also be differences in local expertise as well as perspectives for the inclusion or exclusion of environmental variables which could be avoided through the development of multidisciplinary teams to conduct assessments. This will have to change within Canada because of revised *Fisheries Act* regulations that require stronger evidence-based decision-making. Given the important changes that have taken place in all of Canada's oceans (Bernier et al., 2018; Boldt et al., 2020), experiences from other jurisdictions highlight that priority should be given to maintaining and improving the scientific support within DFO for ecosystem-based research, particularly the process-oriented research that postulates conceptual mechanisms, and provides the empirical-basis for linking climate and environmental drivers to fish stock productivity. Simulation testing and sensitivity analyses in assessments could test the assessment assumptions along with conceptual mechanisms within an MSE framework to evaluate the cumulative risk associated with exploitation strategies under changing environmental conditions. Doing so would help define the main ecosystem drivers, the ecosystem monitoring support required and identify how to modify stock assessment models to incorporate those drivers.

The impetus for the inclusion of environmental variables in stock assessments is fundamentally driven by the terms of reference for stock assessments, which are dependent on the request for advice from resource managers. Climate change is upon us and reliance on evaluating the effects of environmental variables in reaction to crises created by unresponsive management practices may not be effective or precautionary for the future of aquatic renewable resources. Lack of governmental prioritization of climate-informed resource management can lead to maladaptive policies that increase the risk of adverse impacts and increase both the cost and efficacy of adaptation options for the future. We propose that it would be better to be proactive, and risk the potential for false positives, rather than ignore our core understanding that ecosystems and environmental conditions are not stationary and that there will likely be consequences to sustainable fishery practices. Fogarty et al. (2020) highlight that consideration of the risk associated with environmental change should be required and formalized as part of management plans given that these serve as the foundation for decision-making in terms of harvest control rules and/or the determination of total allowable catches. A more proactive approach to the inclusion of environmental considerations would also likely require that the assessment process be guided to a greater extent by concerns around environmental and ecosystem changes. At the same time, there would be a need to partly alter the philosophical approach to the peer-review process by taking greater consideration of how environmental variables can affect the accuracy with which we can describe or predict population fluctuations rather than focusing on the precision with which we can model them.

5 | CONCLUSIONS

Given Canada's high sensitivity to climate change because of its extensive coastline and northern exposure, incorporating climate, oceanographic and ecological variables will become increasingly important to enable sustainable resource management. Scientific uncertainty from a lack of mechanistic understanding of the variable influence on abundances can be partially mitigated through the provision of qualitative ecosystem indicator reports, processes to deal with uncertainty and tool assessment in iterative cycles, where identified knowledge gaps can be used to prioritize research needs. This will facilitate meeting the requirements of Canada's revised *Fisheries Act*, altering risks and providing science-informed advice for dynamic management under environmental change.

AUTHOR CONTRIBUTION

All authors contributed to the conceptualization, analysis and writing of the study reported in the manuscript. PP coordinated the working group.

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CONFLICT OF INTEREST

The authors do not have any interest or relationship, financial or otherwise, that might be perceived as influencing an author's objectivity and that might be considered a potential source of conflict of interest. The contents of this manuscript represent a critical evaluation of the use of climatic, oceanographic or ecological variables in Canada's stock assessments.

DATA AVAILABILITY STATEMENT

The datasets generated for the current study are available from the corresponding author on request. The data were compiled from freely accessible Canadian Science Advisory Secretariat reports.

ORCID

Pierre Pepin https://orcid.org/0000-0003-4555-4843

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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