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Leading or lagging: How well are climate change considerations being incorporated into Canadian fisheries management?

Daniel G. Boyce, Susanna Fuller, Chelsey Karbowski, Katie Schleit, and Boris Worm

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Abstract: In response to fisheries declines and delayed population recoveries, many management agencies globally are integrating alternative strategies that incorporate precautionary and ecosystem considerations, increasingly focusing on climate variability and change. Here, we quantitatively evaluate how these themes have been incorporated into the science and management plans for Canada's fisheries by analyzing the content of 905 research and management documents published by the Fisheries and Oceans Canada (DFO) for the Atlantic and Eastern Arctic regions. We found that the precautionary approach was mentioned much more frequently (44%) than climate change (11%) or ecosystem approaches to fisheries management (1%). Of research documents that mentioned climate change, 61% contained only a single reference to it, suggesting that it is not quantitatively evaluated in the science that informs the advisory and decision-making processes. Most references to climate change in the DFO research documents expressed high uncertainty of how climate change would impact the stock dynamics. We propose explanations for this and discuss approaches for increasing the incorporation of these themes into Canada's fishery management.

Résumé : En réponse aux déclins des ressources halieutiques et à la lenteur du rétablissement des populations, de nombreuses agences de gestion à l'échelle mondiale intègrent des stratégies nouvelles qui incorporent des considérations écosystémiques et de prévention, en mettant de plus en plus l'accent sur la variabilité et les changements climatiques. Nous avons réalisé une évaluation quantitative de la manière dont ces thèmes ont été incorporés aux plans de recherche et de gestion visant les ressources halieutiques canadiennes en analysant le contenu de 905 documents de recherche et de gestion publiés par le ministère des Pêches et des Océans du Canada (MPO) pour les régions de l'Atlantique et de l'est de l'Arctique. Nous constatons que l'approche de prévention est mentionnée beaucoup plus fréquemment (44 %) que l'approche axée sur les changements climatiques (11 %) ou l'approche écosystémique (1 %) de gestion des pêches. Des documents de recherche qui mentionnent les changements climatiques, 61 % ne le font qu'une seule fois, ce qui indiquerait que ces changements ne font pas l'objet d'une évaluation quantitative dans la recherche servant à éclairer les processus décisionnels et de formulation d'avis. La plupart des références aux changements climatiques dans les documents de recherche du MPO expriment une grande incertitude quant à l'incidence des changements climatiques sur la dynamique des stocks. Nous proposons des raisons pour expliquer cette situation et discutons d'approches permettant d'accroître l'incorporation de ces thèmes dans la gestion des ressources halieutiques du Canada. [Traduit par la Rédaction]

Introduction

Quantitative approaches to fisheries management, rooted in population modelling, serve as the foundation for current fisheries management practices in Canada and elsewhere. Traditionally, these models focused on fishing mortality as the focal variable that drove the dynamics of exploited populations. Yet, there has been increasing recognition of the importance of ecosystem dynamics (e.g., Cushing 1990), environmental variation (e.g., Mysak 1986; Hamilton 1987), climate change (Francis 1990; Healey 1990; Kennedy 1990) on fish population dynamics, and the associated need to adopt precautionary approaches to management (e.g., Garcia 1994). The uptake of these factors into current management strategies varies but is generally low and may be a contributing factor in the shortcomings of many fisheries management approaches around the world (Garcia and Grainger 1997; Worm et al. 2009; Brander 2010), associated fish population collapses (Myers and Worm 2003, 2005; Worm et al. 2009; Hutchings et al. 2010), and delayed recoveries (Frank et al. 2011).

Owing to its important and growing impacts on ocean ecosystems, climate change is becoming a dominant concern, reinforcing the need to include ecosystem factors, environmental variation, and precaution into fisheries management. Further, the effects of climate change are projected to increase in magnitude and extent over the next century, affecting food and economic security for billions of people worldwide (IPCC 2014; Gattuso et al. 2015; Boyce et al. 2020). Despite this, studies also indicate that effective management improves fisheries status (Hilborn et al. 2020) and can offset climate change effects, in some situations compensating for negative effects and amplifying positive effects (Le Bris et al. 2018). However, climate-related risks to fisheries will continue to increase and likely necessitate additional adaptation measures (Melvin et al. 2017). Consequently, there is an increased urgency to understand how fisheries can be

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D.G. Boyce and B. Worm. Ocean Frontier Institute, Dalhousie University, Halifax, NS B3H 4R2, Canada; Department of Biology, Dalhousie University, Halifax, NS B3H 4R2, Canada.

S. Fuller, C. Karbowski, and K. Schleit. Oceans North, Halifax, NS B3J 1E6, Canada.

Corresponding author: Daniel G. Boyce (email: dboyce@dal.ca).

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managed in a climate-smart manner (Pinsky and Mantua 2014; Gattuso et al. 2015; Busch et al. 2016). Nations such as the USA (Gregg et al. 2016), the UK (Defra 2013), Ireland (Kopke and O'Mahony 2011), and Australia now include explicit strategies intended to increase the resilience of fisheries to climate change (refer to Bryndum-Buchholz 2020 and Pepin et al. 2020 for reviews on this topic). Regional management organizations in the North Atlantic, including the Northwest Atlantic Fisheries Organization (NAFO) and the International Council for the Exploration of the Sea (ICES), are now developing approaches to incorporate climate change, uncertainty, and ecosystem effects into the management of fisheries (Garcia et al. 2003; Busch et al. 2016; FAO 2018; Koen-Alonso et al. 2019).

Despite the above-average climate change rates in its waters, Canada has not yet established a clear climate change adaptation strategy for its fisheries. Expert assessments have reported a high probability of substantial climate change impacts in all of Canada's marine and freshwater basins and that the effects will generally increase over time (DFO 2012*a*, 2012*b*). Peer-reviewed studies also project considerable climate-driven marine animal biomass changes across much of the Canadian Exclusive Economic Zone (Shackell et al. 2014; Lotze et al. 2019; Bryndum-Buchholz et al. 2020; Boyce et al. 2020). However, despite the lack of an explicit adaptation strategy, climate change and related themes around precautionary approaches and ecosystem considerations have been introduced by Fisheries and Oceans Canada (DFO) as key priorities in managing Canadian fish stocks. In 2003, a federal framework for a precautionary approach became government policy, leading in 2006 to more formal implementation of precautionary approaches to fisheries management (DFO 2006) and the 2009 precautionary approach policy (DFO 2021*a*). In 2007, the Science Management Board promoted the implementation of an ecosystem approach to fisheries management (EAFM; DFO 2007) and wrote, "...the highest priority for DFO Science is providing scientific support for ecosystem-based management." This shift led to targeted funding for applied ecosystem research under the Strategic Program for Ecosystem-Based Research and Advice (SPERA) in 2012 and the Sustainable Fisheries Framework, the foundation of the ecosystem-approach to fisheries (EAF). In 2011, directed climate change research began under the Aquatic Climate Change Adaptation Services Program (ACCASP). According to DFO, the priorities of ACCASP include "...to advance knowledge and understanding of the risks, impacts and opportunities created by climate change for Fisheries and Oceans Canada's mandated areas of responsibility and to begin to develop science-based adaptation tools necessary to support the consideration of climate change in departmental decision-making." However, despite the understanding that climate change poses a severe and growing threat to Canadian marine resource use (DFO 2012*a*, 2012*b*) and the availability of funding for directed climate change research under ACCASP, the extent to which climate change and these other related themes are being incorporated into decisions related to fisheries management is not currently well known.

Here we evaluate the extent to which relevant management priorities (climate change, the precautionary approach, and EAF) are considered in DFO fishery assessment and decision-making over the last two decades. Our analysis focused on fisheries in the Canadian Atlantic and Eastern Arctic because they support the majority of the total landings in Canada (mean = 80%, range = 70%–85% between 1990 and 2018) and are experiencing rapid climate impacts and associated ecosystem restructuring (Frank et al. 2011; Le Bris et al. 2018; IPCC 2019), a trend that is projected to continue (Saba et al. 2016; Bryndum-Buchholz et al. 2020; Boyce et al. 2020). We compiled 905 research and management documents for commercially harvested marine species between 2000 and 2020. The documents' text was quantitatively analyzed to identify the frequency with which relevant management priorities arose and how this varied among species, regions, document types, and over time. Given the nested interrelatedness of these management priorities, we also evaluated the extent to which they were considered jointly versus separately in fisheries management documents. Finally, we assessed whether the availability of relevant data was a limiting factor by evaluating the extent to which the primary ecosystem monitoring data sources available to DFO were used in the fishery management documents.

Methods

Data

A database of documents related to the science and management of marine species in Quebec, the Atlantic Provinces, and Eastern Arctic published between 2000 and 2020 was compiled. Three publicly available DFO document types were used (refer to online Supplementary Information, Fig. S1[1]):

1. DFO research documents (RES-DOCs) that form the scientific basis for management (n = 729). These included research documents, stock status reports, science advisory reports, and science responses.
2. DFO integrated fisheries management plans (IFMPs) that outline the process through which fisheries are managed for a prespecified duration and are "evergreen", meaning they are only updated as needed (n = 68). In theory, these include the planning cycle, fishery objectives, management decisions, control measures, and Indigenous participation. They are developed by DFO after consultation with the fishing industry, the provinces, and other stakeholders and are informed by the RES-DOCs.
3. Peer-reviewed publications (PR-DOCs) related to fisheries dynamics authored or co-authored by DFO scientists and published in scientific journals (n = 108).

The DFO RES-DOCs and IFMPs are publicly available through the DFO Canadian Science Advisory Secretariat website. Where IFMPs were not publicly available, they were obtained through a request from DFO personnel. For each document, metadata was entered into a database that contained the title, year, species, species group, and region of the document. Where possible, only the most recent documents for each species were retained, although older ones may also be included. The PR-DOCs were obtained by searching the Clarivate Analytics Web of Science, which provides subscription access to peer-reviewed studies published in over 21 100 journals since 1900. Supplementary Table S1[1] contains the search criteria that were used to identify peer-reviewed studies of relevance to this study. Documents pertaining to freshwater species or species outside of the geographic area of interest were excluded.

Analyses

The text within the documents was analyzed to understand how eight primary and secondary themes were represented in fisheries research and management in Canada. The three primary themes included climate change, EAF, and the precautionary approach. The five secondary themes included oceanographic factors, trophic dynamics, exploitation, climate vulnerability, and forecasting. Each theme was associated with a set of keywords or phrases (terms). For example, the fishing theme was associated with the following terms: "exploitation", "fishing", "landings", "harvest", "hunting". The software searched the text of the documents for these terms and, upon occurrence, associated them with the fishing theme. The frequency with which these

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2020-0394.

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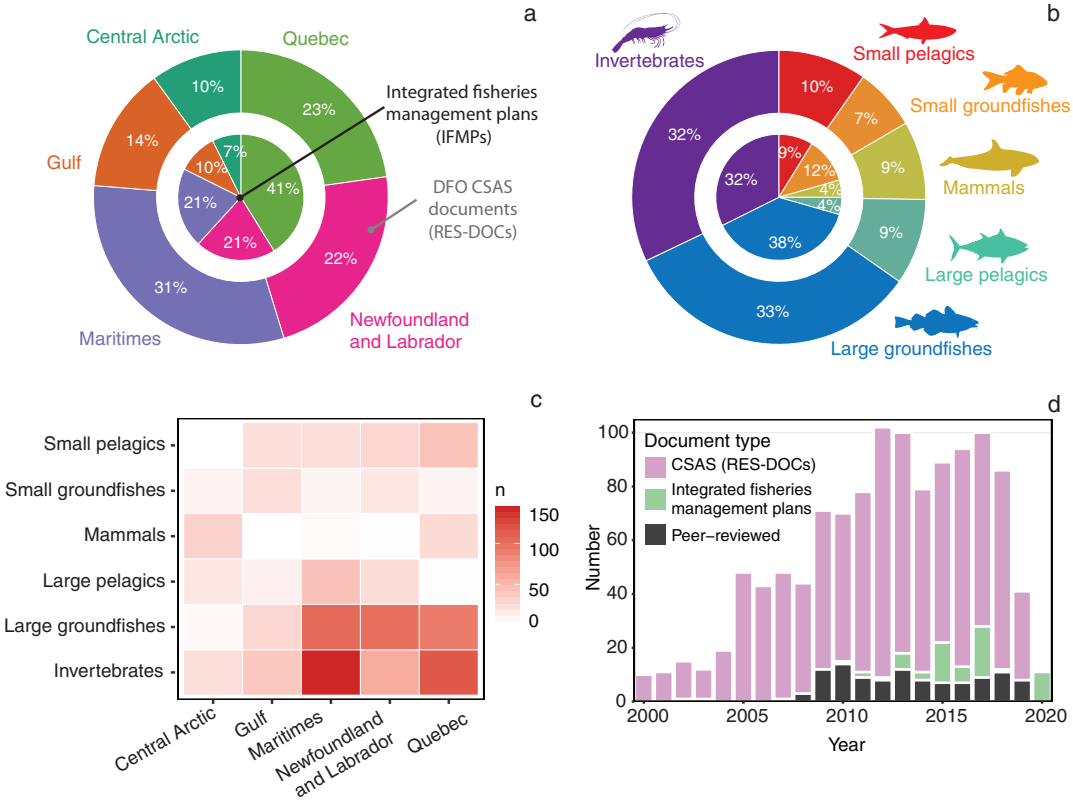
Fig. 1. Summary of Fisheries and Oceans Canada (DFO) documents used in this analysis. (*a*–*b*) The proportion of available DFO documents for each document type, administrative region (*a*), and species group (*b*). Colours depict the different regions (*a*) and species groups (*b*). The inner circles show integrated fisheries management plans (IFMPs) and the outer research documents (RES-DOCs). (*c*) Availability of DFO documents according to their functional group (*y* axis) and administrative region (*x* axis). Dark red denotes a greater number of available documents. (*d*) The availability of all document types over time are shown as colours: RES-DOCs are purple (CSAS = Canadian Science Advisory Secretariat), IFMPs are green, and peer-reviewed publications (PR-DOCs) are black.



themes appeared in the documents was then analyzed to understand patterns in theme occurrence in relation to document types (RES-DOCs, IFMPs, PR-DOCs), species groups, regions, and over time. The Supplementary Information contains a detailed description of the methods used to undertake this analysis, and Supplementary Table S2[1] includes the words and phrases used to define the themes. Additional information was obtained by reading the documents identified as being of particular interest — for example, those that discussed climate change.

To understand the associations between these primary themes across research and management documents, we matched 137 RES-DOCs to 37 corresponding IFMPs according to the focal species, management region, and publication year. From these matches, a co-occurrence analysis was undertaken (Griffith et al. 2016) to determine the frequency with which the themes were coincidentally present or absent in RES-DOCs and IFMPs. Themes that are more strongly associated across RES-DOCs and IFMPs appear closer in the multidimensional plot.

The text within the documents was analyzed to understand how the ecosystem and climate-relevant data sources were being used in fisheries research and management in Canada. Data source themes were defined by the primary observational datasets that are available to DFO researchers, including fishery landings, Array for Real-Time Geostrophic Oceanography floats, gliders, Atlantic Zone Off-Shelf Monitoring Program, conductivity temperature depth profiles, remote sensing, Atlantic Zone Monitoring Program, continuous plankton recorder, DNA, larval surveys, acoustics, and research vessel surveys. As with management themes, each data theme was associated with a set of keywords or phrases (terms). For example, the acoustic theme was associated with the following terms: “acoustic”, “backscatter”, “target strength”, and “acoustics”. The software searched the text of the documents for these terms and, upon occurrence, were associated with the data theme. The frequency with which these themes appeared in the documents was then analyzed to understand the frequencies with which different data types were being used and whether different data types were used in combination.

Analyses were undertaken to determine whether the targeted government funding for ecosystem-based (SPERA) and climate (ACCASP) research was being incorporated into the scientific basis for DFO fisheries management (RES-DOCs). To accomplish this, we searched the text within the RES-DOCs for citations to PR-DOCs (n = 108), as well as to peer-reviewed research that was funded through SPERA or ACCASP. PR-DOCS$_{SPERA}$ (n = 29) and PR-DOCS$_{ACCASP}$ (n = 64) were identified using the Clarivate Analytics Web of Science and searching for the appropriate funding sources.

Results

Database summary

A total of 905 documents were compiled. RES-DOCs comprised 81%, with IFMPs and PR-DOCs representing 8% and 12%, respectively. The RES-DOCs comprised 43% Research Documents, 40% Science Advisory Reports, 13% Science Responses, and 5% Stock

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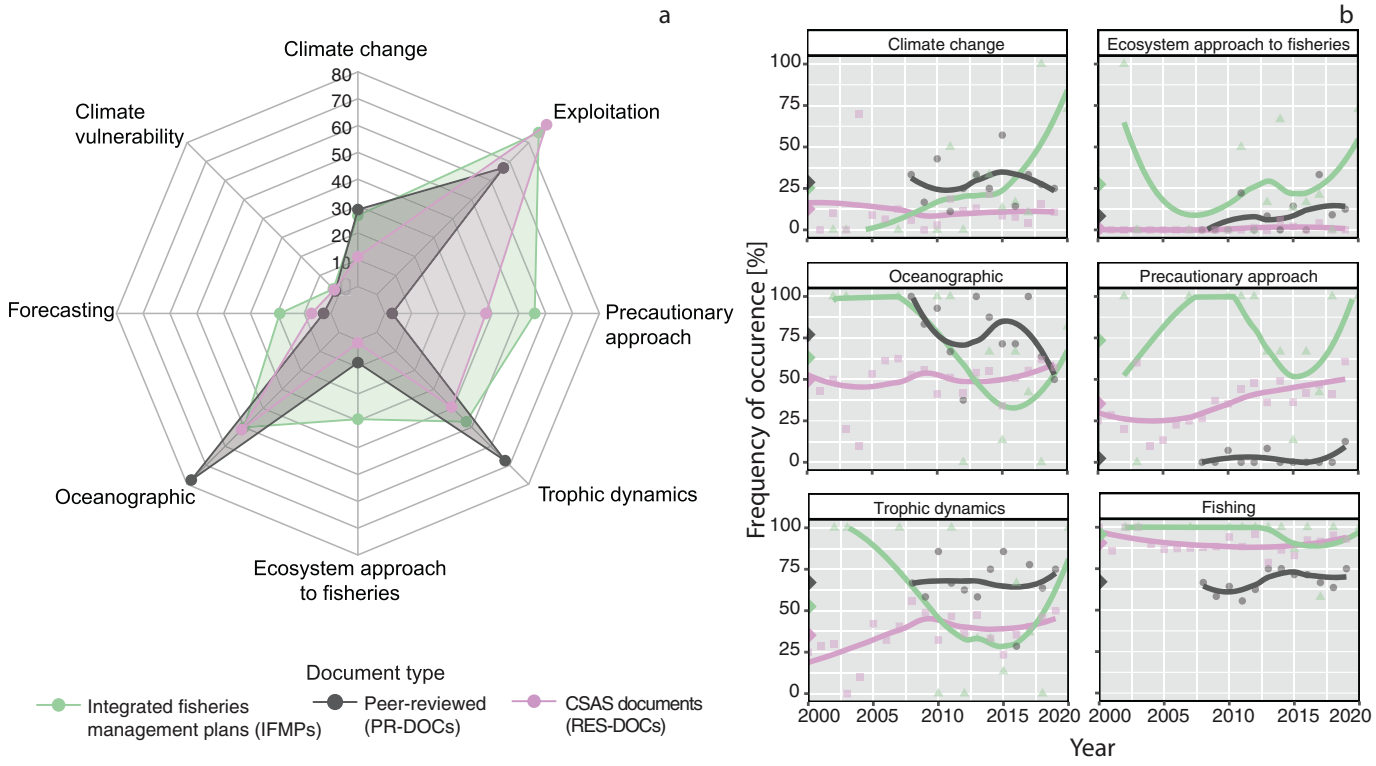
Fig. 2. Frequencies (%) of themes occurring across documents (*a*) and over time (*b*). (*a*) The average frequency of occurrence of the themes for each document type; axes begin at the center of the plot and extend outward. (*b*) Time trends in the frequency of occurrence for themes of interest. Average frequencies over the time series are displayed as points along the *y* axes. Colours denote the document types: RES-DOCs are purple, IFMPs are green, and PR-DOCs are black.



Status Reports. Most DFO documents originated from the Maritimes, Newfoundland and Labrador, and Quebec (Fig. 1*a*), which accounted for 59%, 33%, and 7.5% of all Atlantic fishery landings in 2018, respectively. However, Quebec had a notably higher percentage of IFMPs (41%) relative to RES-DOCs (23%), whereas the Maritimes had a higher percentage of RES-DOCs (31%) relative to IFMPs (21%). The representation of species groups in DFO IFMPs and RES-DOCs were comparable (Fig. 1*b*). Overall, DFO documents related to large groundfish (33%–38%) and invertebrates (32%) were most common, followed by small pelagic fish (9%–10%), small groundfish (7%–12%), mammals (4%–9%), and large pelagic fish (4%–9%). There was an increase in the number of documents over time, with most published after 2011 and very few before 2005 (Fig. 1*d*). There was an increased frequency of documents related to invertebrates over time and a reduction in those related to large groundfish.

Frequencies of theme occurrence

The exploitation theme occurred almost ubiquitously across all document types, reflecting a continued strong focus on the impact of exploitation on target species (Fig. 2*a*). The theme occurred more frequently in the RES-DOCs (89%) and IFMPs (85%), relative to peer-reviewed studies (67%), and was consistent over time (Fig. 2*b*) and across regions or functional groups. The EAF theme arose in 29% of IFMPs, 8% of PR-DOCs, and 1% of RES-DOCs. However, the related trophic dynamics theme emerged much more frequently in PR-DOCs (68%), IFMPs (47%), and RES-DOCs (39%). Trophic dynamics often occurred in association with invertebrates and groundfish as a mechanism to explain past ecosystem shifts. The precautionary approach theme frequently occurred in both RES-DOCs (38%) and IFMPs (56%) and less in PR-DOCs (3%). The frequency of occurrence increased over time in both RES-DOCs and PR-DOCs but was consistently high in IFMPs.

The oceanographic theme that related to any discussion of environmental factors, but not necessarily in a climate-change context, arose in roughly half of the RES-DOCs (51%) and IFMPs (50%) and more so in PR-DOCs (78%).

The climate change theme, specifically related to long-term directed changes in climate, arose more than twice as frequently in PR-DOCs (29%) and IFMPs (27%) relative to RES-DOCs (11%). Among RES-DOCs, climate change arose in 81 documents (Supplementary Table S3[1]). It was most frequently associated with mammals, the Arctic, and large pelagic species (e.g., tunas) and least often with invertebrates, small pelagics (e.g., herrings), groundfish, and the Maritimes region. Climate change search terms were mentioned a maximum of nine times in a single RES-DOC on Atlantic salmon (*Salmo salar*) in the Maritimes but arose only once in 61% of documents (Supplementary Table S3[1]). In contrast with PR-DOCs and RES-DOCs, the frequency of climate change inclusion in IFMPs increased rapidly over time, particularly after 2010 (Fig. 2*b*). Secondary climate change themes, such as climate vulnerability and forecasting, arose relatively infrequently (<3% and <19%, respectively) but increasingly over time (since ~2015). Variability in theme occurrence was observed within the RES-DOCs (Supplementary Fig. S2[1]), with the Science Advisory Reports generally referencing the major themes more frequently than the RES-DOCs (see Supplementary Information for details).

Theme associations

Among the RES-DOCs, the co-occurrence analysis suggested that themes related to fishing, trophic dynamics, oceanographic, and the precautionary approach occurred together (Fig. 3*a*). Climate change and forecasting tended to co-occur, as did climate vulnerability and EAF. For IFMPs, most themes co-occurred, except for forecasting and climate vulnerability, which were not

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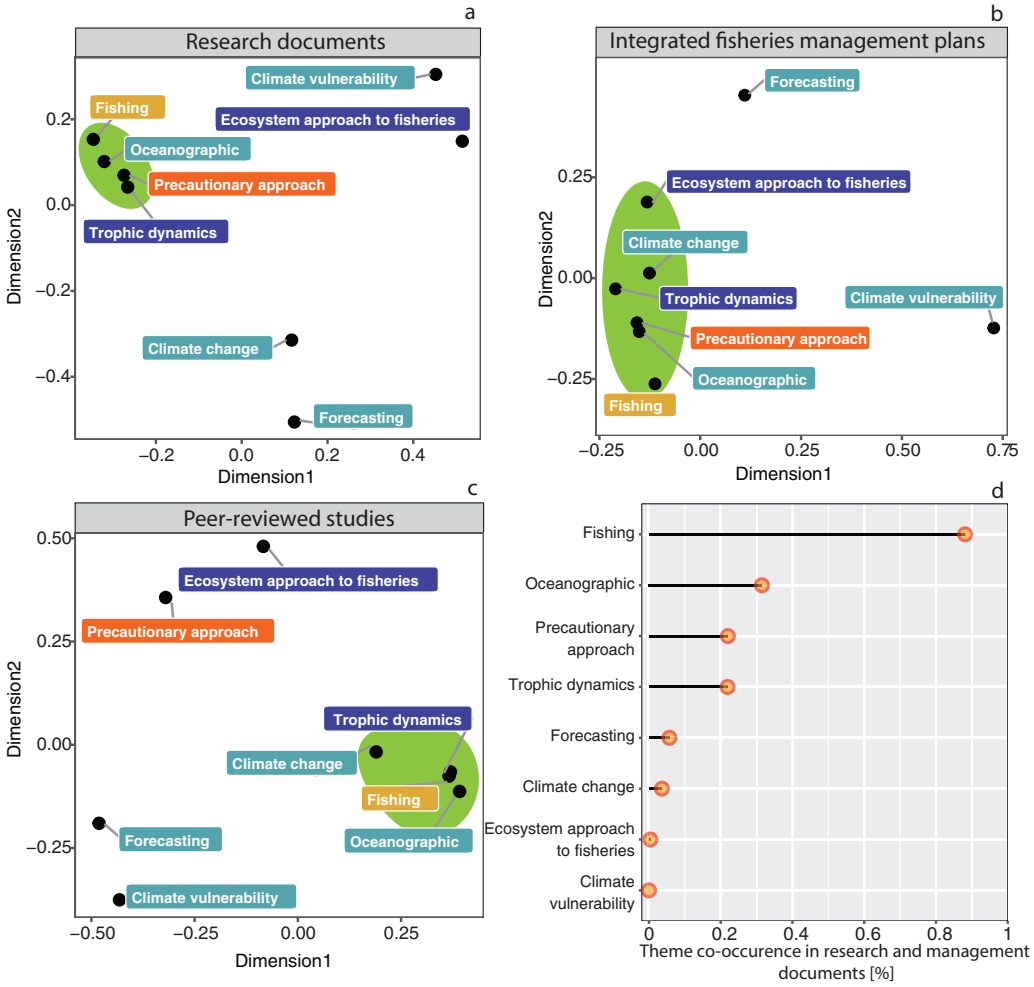
Fig. 3. Patterns of co-occurrence across themes. (*a*–*c*) Nonmetric multidimensional scaling results depicting the associations among the themes; themes that are grouped closer are more strongly associated. The colour labels depict the type of theme: light blue is climatological, dark blue is ecological, yellow is fishing, and red is precautionary. Green ellipses denote the core cluster of themes for each document type. (*d*) The probability that a theme occurs, or does not occur, together in both IFMPs and their matching RES-DOCs. Statistically significant co-occurrence differences are depicted as opaque orange symbols.



associated with any themes (Fig. 3*b*). The theme associations among PR-DOCs were similar to RES-DOCs, except that climate change tended to occur with the other themes instead of the precautionary approach (Fig. 3*c*).

For most themes, a RES-DOC occurrence did not increase its frequency of occurrence in the corresponding IFMP (Fig. 3*d*). Fishing, oceanography, the precautionary approach, and trophic dynamics were exceptions to this pattern. They were more likely to arise in IFMPs if they were also included in the corresponding RES-DOCs.

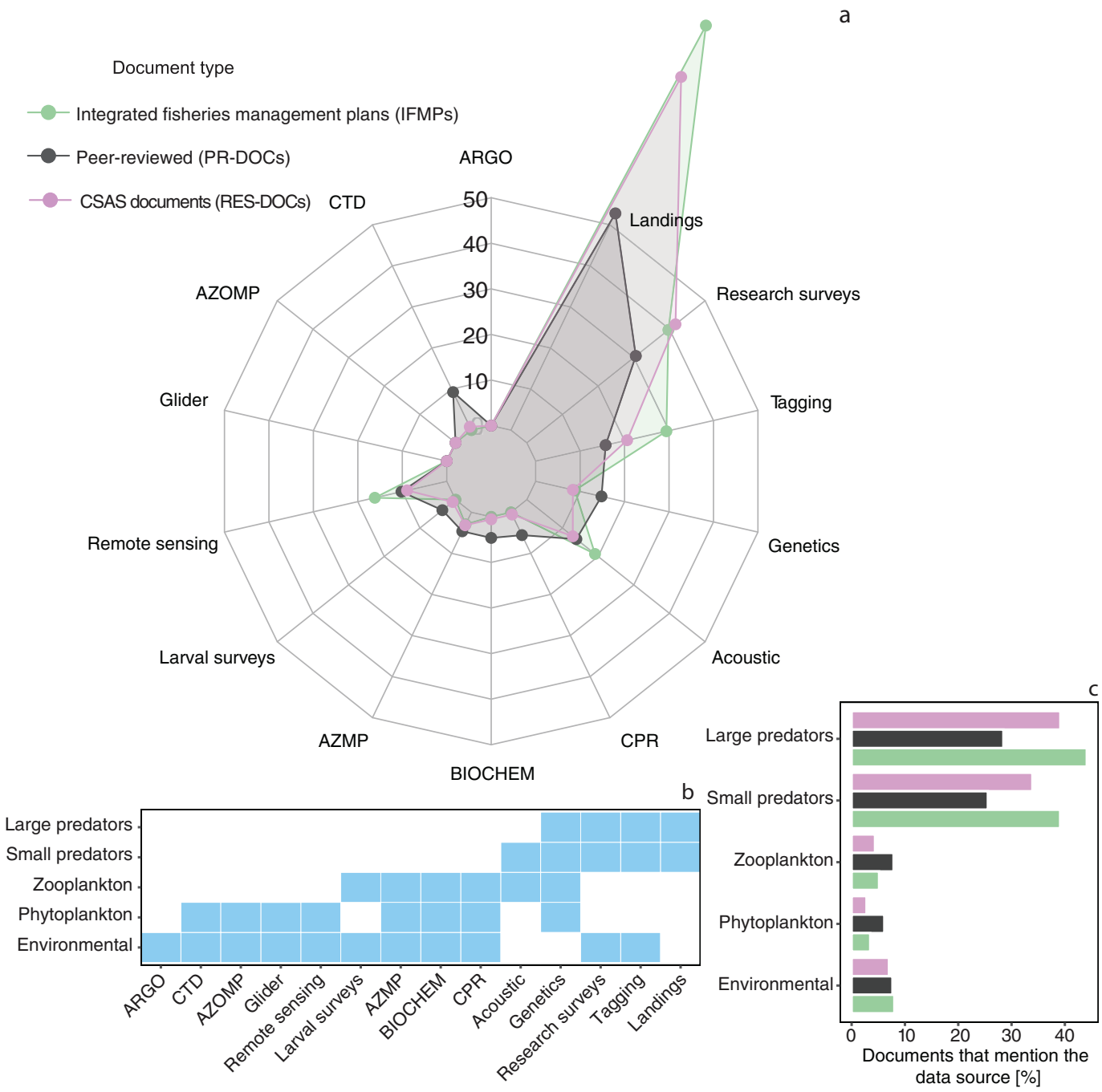
Use of ecosystem monitoring data

Fishery catch information was the most commonly included data source across all document types, being mentioned in 86% of RES-DOCs and 99% of IFMPs (Fig. 4). Research trawl surveys (~30%–45%) and tagging studies (~15%–30%) were mentioned moderately frequently across the documents. Acoustic (~10%–20%), remote sensing (~9%–20%), and genetics (~9%–20%) were mentioned with low frequency. The remaining data sources were cited in ~0%–10% of the documents. Considering the frequencies that the specific data observation types were mentioned in combination with the portion of the ecosystem that they sample enabled us to evaluate what component of the ecosystem could conceivably be assessed. For instance, data on trophic level four and higher are assessed from genetics, research surveys, tagging studies, and landings, and the average frequency of occurrence across these data sources gives us an estimate of the frequency of mention for upper-trophic-level components of the ecosystem (29%–44%). Using this approach, it was clear that data sources that evaluate mid- and upper-trophic-level components of the ecosystem (e.g., that directly relate to most fisheries) were, on average, mentioned much more frequently (26%–44%) than those pertaining to plankton, larvae, and the physical and (or) chemical environment (Fig. 4*c*). Data sources that assess primary production dynamics were mentioned, on average, in 3% of RES-DOCs, 4% of IFMPs, and 6% of PR-DOCs. Those that evaluate zooplankton and (or) larvae were mentioned in 4% of RES-DOCs, 5% of IFMPs, and 8% of PR-DOCs. Data types that can assess environmental conditions were mentioned in 7% of RES-DOCs, 8% of IFMPs, and 7% of PR-DOCs.

Discussion

This analysis suggests that of the primary themes considered, climate change and the EAF are currently infrequently considered in Canada's fisheries' science and management. Climate change was explicitly discussed, with increasing frequency over time, in almost a third (29%) of PR-DOCs, suggesting that it is a

Fig. 4. Occurrence of major DFO data sources across documents. (*a*) The average frequency (%) of occurrence of the major DFO data types for each document type; axes begin at the center of the plot and extend outward. Colours denote the document types: RES-DOCs are purple, IFMPs are green, and PR-DOCs are black. (*b*) Blue shading depicts the taxonomic scope of the major DFO data types. Environmental includes observations of physical, chemical, and atmospheric characteristics. (*c*) The proportion of documents that reference different ecosystem data types. Colours depict the document types, as in panel (*a*).



factor of importance to fisheries, and in one-quarter of IFMPs, suggesting that DFO managers also see it to be an important driver of population dynamics and fisheries productivity. However, climate change was incorporated in only 11% of RES-DOCs. Most (61%) of these instances contained only a single reference to it, suggesting that it is not routinely considered in the scientific basis that primarily informs the advisory process. Furthermore, on closer inspection, it was found that most of the references to climate change in the RES-DOCs expressed that there was a lack of understanding of how climate change would impact the dynamics of a given stock or process. For example, the Science Advisory Report for American plaice (*Hippoglossoides platessoides*) in the Gulf of St. Lawrence for 2011 stated that "The impact of global warming is yet unknown on the biology of American Plaice (DFO 2011)". Many other mentions acknowledged the threat of climate change but did not incorporate it into the stock assessment or science advice. For example, the Science Advisory Report for northern shrimp (*Pandalus borealis*) in Newfoundland in 2013

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stated, "Effects of climate change on shrimp resources should be considered when making management decisions. However, the meeting agreed that there is a need to conduct more research to determine whether environmental variables could be used in conjunction with recruitment signals to produce resource status predictions." (DFO 2013). Statements of this nature are useful in identifying knowledge gaps but also emphasize that reference to climate change does not necessarily imply that it is incorporated into the relevant science advice or management action.

The frequency with which climate change and EAF occurred has increased over time in IFMPs but not in the RES-DOCs (Fig. 2*b*). The co-occurrence analyses indicated that fishing, oceanography, and trophic dynamics were "core" themes across all document types, but climate change and EAF were not (Figs. 3*a*–3*c*). However, climate change was a core theme in peer-reviewed studies and IFMPs. EAF was a core theme in IFMPs but not in RES-DOCs or PR-DOCs. There was a low degree of co-occurrence of the climate change theme in the RES-DOCs and their corresponding IFMPs. Cumulatively, these results suggest that climate change and EAF are current priorities and are being discussed at the fisheries management stage (IFMPs) but less so within the science process (RES-DOCs).

This low representation of climate change and EAF in RES-DOCs contrasts sharply with the precautionary approach theme, which arose in 56% of IFMPs and 38% of RES-DOCs, and was discussed more frequently over time in both document types (Fig. 2). The increasing frequency of reference to the precautionary approach in RES-DOCs roughly coincided with the 2006 release of a framework for its incorporation into management (DFO 2006) and the subsequent 2009 precautionary approach policy (DFO 2021*a*). This may suggest that priorities could be more effectively incorporated into science and management when there are explicit guidelines for doing so. However, as climate change and ecosystem factors will introduce additional sources of uncertainty to fisheries assessments, neglecting to consider these factors in the science that informs management decisions could also erode the efficacy of the entire precautionary approach decision-making framework (DFO 2006). Furthermore, whereas the framework for the precautionary approach is relatively concise (DFO 2006) and integrates easily into existing fisheries management approaches, climate change and EAF are more complex challenges that lack standardized solutions (Garcia et al. 2003; Busch et al. 2016; FAO 2018; Koen-Alonso et al. 2019; Boyce et al. 2021). The optimal management approach can depend on the species, location, available data, and resources. Despite this, providing explicit guidelines for incorporating climate change or EAF into fisheries is tractable, and there are several tools for doing so (e.g., Pinsky and Mantua 2014; Busch et al. 2016; Ojea et al. 2017; Holsman et al. 2019; Boyce et al. 2021). For example, climate vulnerability assessments (Homrum et al. 2013; Greenan et al. 2019) and climate and ecological forecasting (Wang et al. 2018; Lotze et al. 2019) are approaches that can quantitatively incorporate different aspects of differential responses of species to climate change at the shorter-term scales (e.g., seasonal) required by management. Management strategy evaluations can find candidate management strategies that are potentially robust to different future climate scenarios, population and ecosystem dynamics, and other uncertainties. Dynamic management can set harvest rates based on dynamic forecasts or respond in real time to changing conditions (Dunn et al. 2016). Ecosystem models can incorporate multiple species interactions and environmental effects to understand better the impact of exploitation on exploited species' dynamics. Such models are being successfully used by NOAA and include temperature-dependent weight-at-age functions and temperature-specific predation interactions (Holsman et al. 2017). Ideally, these approaches would be used in conjunction with other climate adaptation approaches and integrated into relevant science advice. For example, the Alaska Eastern Bering Sea Integrated Ecosystem assessment program uses food web and multispecies assessment models, climate forecasts and projections developed by regional ocean modelling systems, and scientific surveys to inform the North Pacific Fisheries Management Council (NOAA 2021).

Monitoring data spanning the ecosystem's breadth are required to ensure that fisheries management strategies are robust to climate and ecosystem variation and change. For example, climate-associated changes in zooplankton distribution are currently driving the spatial distribution of right whales (*Eubalaena glacialis*), an endangered species, with critical consequences for their management and recovery prospects (Plourde et al. 2019). Despite this, data sources that contain such ecosystem information were mentioned in only 3%–8% of RES-DOCs. DFO currently invests substantially in ecosystem monitoring, and there is a wealth of available data sources that, if treated appropriately, could enable a more direct consideration of climate change and ecosystem effects on fisheries.

Targeted funding to increase the inclusion of climate change (ACCASP) and ecosystem considerations (SPERA) into Canadian fisheries management has led to new knowledge and insights published in the peer-reviewed literature. Although some articles may have been inadvertently overlooked, DFO authors have published 185 studies related to fishery dynamics over the period of interest. Targeted funding to ACCASP led to 64 published studies and SPERA to 29. Despite this, our text analysis suggests that these studies' information are often not directly connected to fisheries management processes and subsequent decision-making. None of the SPERA funded studies and only 3% of ACCASP funded studies were mentioned across the RES-DOCs. It is possible that the knowledge from some of these studies is being communicated to fisheries researchers and decision-makers through alternative pathways, for instance, orally. However, combined with the finding that climate and EAF themes infrequently arose in management documents and that environmental and multitrophic data types needed to incorporate these themes were not widely used, it is more likely that knowledge from peer-reviewed studies is not commonly considered in management. A recent DFO review of ACCASP emphasized the development of tools through ACCASP, such as the Fish Stock Climate Vulnerability Assessment Tool (FSCVAT; DFO 2021*b*). However, while the FSCVAT would indeed be a valuable tool for fisheries, it is not publicly available and has not been used in any fisheries management setting thus far. Our study complements and builds on a recent DFO Canadian Science Advisory Secretariat report by Pepin et al. (2020) that reviewed the extent to which ecosystem considerations, broad-scale regional climate variability, and physical drivers that operate across multiple timescales were included in a sample of 178 DFO stock assessments. Although the study did not explicitly evaluate climate change, the precautionary approach, or EAF, it did provide a substantive and detailed investigation of how environmental and ecological information was included in DFO fisheries assessments. The study reported that when ecosystem, oceanographic, or climate variability information was included quantitatively in assessments, it also tended to be included in management recommendations. Together with our analysis, these results suggest that it may be necessary to include this information quantitatively. Pepin et al. (2020) also reported that only 21% of the assessments (38 of 178) incorporated ecological, oceanographic, or climate variability in a quantitative manner and that most (42%) accomplished this by estimating a time-varying parameter (e.g., mortality, productivity) within the population model. However, the estimation of time-varying parameters alone does not necessarily evaluate or capture the full spectrum of ecological or climate-driven changes on fisheries that are possible. As the parameters are often estimated as by-products of the models, they may capture variation in phenomena that are unrelated to climate or ecosystem effects. For these and other reasons, the approach has not been recommended as a sole solution for incorporating climate (Busch et al. 2016; FAO 2018) or ecological (Garcia et al. 2003; Koen-Alonso et al. 2019) information into fisheries management. However, it could contribute considerably towards a more

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integrated approach (Minto and Worm 2012; Britten et al. 2017), such as those employed by the Alaska Eastern Bering Sea Integrated Ecosystem assessment program (NOAA 2021). Excluding time-varying instances from consideration, the study of Pepin et al. (2020) indicates that only 13% of stock assessments include climate or ecological information quantitatively. This lack of quantitative inclusion may explain why our analysis found a low co-occurrence of climate change and EAF themes in RES-DOCs and IFMPs (Fig. 3*d*). It may also explain why most (61%) of the 81 RES-DOCs that included climate change in our study contained only a single reference to it (Supplementary Table S3[1]). The low citation frequency of climate change terms suggests that it is most often mentioned in passing, rather than being rigorously evaluated or discussed. These findings are at odds with a recent report by DFO that 22% of fisheries stock assessments incorporate climate change considerations and that it was on track to reach a target of 100% by 2026 (DFO 2021*b*). Lastly, Pepin et al. (2020) reported higher incorporation of climate variability in salmon (Salmonidae) assessments from the Pacific, a region that we did not include.

Why are these priorities not incorporated more visibly in Canada's fisheries management? Is it possible that these priorities are incorporated into management, but our textual analyses fail to detect them reliably? We ran robustness analyses to ensure that this was not the case (see Supplementary Fig. S3[1]). One explanation may be that the complexity of the problem combined with uncertainty in choosing from the numerous possible approaches leads to "analysis paralysis", whereby overanalyzing a complex challenge can impede progress through fear of making an incorrect decision. In some situations, the necessary resources, including monitoring, technical, or human resources, could contribute. It is also plausible that the relevant questions needed to integrate these management priorities are not being included in the Terms of Reference (ToR) that guide the science (Supplementary Fig. S1[1]). Unless the ToRs request information related to climate change and ecosystem dynamics, these priorities could easily be absent from the assessments and thus the entire management process. A related possibility is that these priorities, particularly climate change, are being interpreted as strategic (e.g., long-term intentions), rather than tactical (e.g., shorter-term actions; 1–2 years) fisheries management objectives, and are thus excluded from the ToRs, which are primarily focused on immediate tactical needs. It may be that over the shorter tactical timeframes relevant to the ToR, fishing is understood to be the dominant driver of fisheries productivity, with climate change being viewed as a slower-moving, longer-term strategic concern. However, while climate change is a multidecadal process, its impacts on fisheries are also commonly and increasingly manifest over shorter (tactical) timeframes and are becoming increasingly important relative to the well-known impacts of fishing (Britten et al. 2017). Hence, an increasing number of fishery management regimes worldwide are now including climate change within their tactical management strategies. We thus suggest that climate change must be taken up in both the strategic and tactical stages to be fully integrated into management. For instance, whereas primary publications, including those funded through SPERA and ACCASP, are often more aligned with strategic objectives, they often contain highly relevant information to tactical management objectives and should thus be integrated with the management process. Finally, Canada's Fisheries Act does not include climate change among its list of factors to be considered in management decisions, nor does it require fishery management decisions to be made public or to be explained. We suggest that rectifying this during the 5-year review of the Act would increase transparency and accountability while facilitating climate change integration into fisheries management.

In conclusion, although the precautionary approach is increasingly considered in Canada's fisheries, it is not yet fully applied to all the major fish stocks it manages. In contrast, other key priorities, such as an ecosystem-approach to fisheries and climate change, are less frequently considered. These issues are of critical importance to the productivity of fisheries in Canada's Atlantic and Arctic regions, where climate change impacts are already visible and will accelerate into the foreseeable future (Loder and van der Baaren 2013; Loder et al. 2015; Saba et al. 2016; Bernier et al. 2018; Bryndum-Buchholz et al. 2020). Observed climate changes to date have been associated with changing species distribution (Pinsky et al. 2013) and large-scale ecosystem reconfigurations (Frank et al. 2007; Shackell et al. 2010) with implications for fisheries (Cheung et al. 2010). A framework for incorporating these themes into management advice and action would provide an important starting point to increase their uptake into Canadian fisheries management.

Contributors' statement

D.G.B, S.F., and K.S. initiated the study. D.G.B. and C.K. compiled the data. D.G.B. conducted the analyses. All authors discussed the results and edited the manuscript.

Data availability statement

The documents used in this study are publicly available through the Canadian Science Advisory Secretariat website: http://www.isdm-gdsi.gc.ca/csas-sccs/applications/Publications/search-recherche-eng.asp.

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