

A synthesis of DFO contributions to freshwater fish habitat science since the 1950s

Jessica J. Taylor, Trina Rytwinski, Adrienne Smith, Morgan L. Piczak, Sara K. Garden, Robert J. Lennox, Cody J. Dey, Amanda K. Winegardner, Karin Ponader, Glenn Benoy, David G. Sheppard, and Steven J. Cooke

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by

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Abstract

Taylor, J. J., Rytwinski, T., Smith, A., Piczak, M. L., Garden, S. K., Lennox, R. J., Dey, C. J., Winegardner, A. K., Ponader, K., Benoy, G., Sheppard, D. G. and Cooke, S. J. 2022. A synthesis of DFO contributions to freshwater fish habitat science since the 1950s. Can. Tech. Rep. Fish. Aquat. Sci. 3484: ix + 37 p.

Fisheries and Oceans Canada (DFO) has a long history of generating scientific evidence related to freshwater fish habitat. In this report we provide the results of a bibliometric and scientometric analysis of 1739 articles produced by DFO since the 1950s in the area of freshwater fish habitat science. Species-habitat associations and environmental relations were among the most studied topics, and fish species in the family of Salmonidae (i.e. salmonids) were the most studied species in this dataset. Over time, most research topics showed an acceleration in research output (particularly evident for research on species-habitat associations, multiple stressors, and environmental conditions) which is perhaps due to increasing needs for scientific evidence to support legislative and regulatory decisions associated with freshwater fisheries and fish habitat management.

The majority of the studies (73%) identified here were led by a DFO author and 41% of papers had one or more non-DFO authors, however analysis showed a rather low level of collaboration with authors representing an Indigenous organization, with most such examples in the last decade. These findings will be useful to DFO as it considers how to best support and enable freshwater fish habitat science within its organization and in collaboration with external partners.

Résumé

Taylor, J. J., Rytwinski, T., Smith, A., Piczak, M. L., Garden, S. K., Lennox, R. J., Dey, C. J., Winegardner, A. K., Ponader, K., Benoy, G., Sheppard, D. G. and Cooke, S. J. 2022. A synthesis of DFO contributions to freshwater fish habitat science since the 1950s. Can. Tech. Rep. Fish. Aquat. Sci. 3484: ix + 37 p.

Pêches et Océans Canada (MPO) a une longue histoire de production de données scientifiques liées à l'habitat du poisson d'eau douce. Dans ce rapport, nous présentons les résultats d'une analyse bibliométrique et scientométrique de 1739 articles produits par le MPO depuis les années 1950 dans le domaine de la science de l'habitat du poisson d'eau douce. Les liens entre les espèces et les habitats et les relations environnementales figurent parmi les sujets les plus étudiés, et les espèces de poissons de la famille des *Salmonidae* (c.-à-d. les salmonidés) ont été les espèces les plus étudiées dans cet ensemble de données. Au fil du temps, la plupart des sujets de recherche ont montré une accélération des résultats (particulièrement évidente pour les recherches sur les liens entre les espèces et les habitats, les facteurs de stress multiples et les conditions environnementales) qui est peut-être due à des besoins croissants de données scientifiques à l'appui des décisions législatives et réglementaires associées à la gestion des pêches en eau douce et de l'habitat du poisson.

La majorité des études (73 %) répertoriées ici étaient dirigées par un auteur du MPO et 41 % des documents avaient un ou plusieurs auteurs n'appartenant pas au MPO, toutefois l'analyse a montré un niveau plutôt faible de collaboration avec les auteurs représentant une organisation autochtone, la plupart de ces collaborations ayant eu lieu au cours de la dernière décennie. Ces conclusions seront utiles au MPO tandis que le Ministère recherche la meilleure façon d'appuyer et de faciliter la science de l'habitat du poisson d'eau douce au sein de son organisation et en collaboration avec des partenaires externes.

1.0 Introduction

Canada has a rich history in fisheries and aquatic sciences (Dymond 1964; Castañeda et al. 2020). Although some of this can be credited to the academic community and provincial/territorial governments, Fisheries and Oceans Canada (DFO; and its previous entities or components such as the Fisheries Research Board of Canada) has long been engaged in generating science to support their mandate (Dymon 1964). One area of particular strength in Canada is in the realm of freshwater fish habitat science (Goodchild 2004). Today, DFO has research scientists and other scientific capacity dedicated to freshwater fish habitat science in the Ecosystems and Ocean Science Sector (EOSS) that support DFO's Fish and Fish Habitat Protection Program (FFHPP) and other internal clients (i.e., users of scientific information including the Species at Risk Program or Fisheries Management) involved in the management of freshwater fish and fish habitat. DFO's EOSS provides freshwater habitat science advice (amongst other topics) to FFHPP on objectives related to the implementation of the *Fisheries Act (FA)*, the *Species at Risk Act (SARA)* and the *Aquatic Invasive Species Regulations (AISR)*, as well as to support DFO's role under the *Impact Assessment Act (IAA)*.

Over the past decade there have been developments in bibliometric (analysis of books, articles, and other publications) and scientometric (analysis of scientific research) tools that enable analysis of research trends in the literature (e.g. Choudhri et al. 2015; Hossain et al. 2020). While distinct metrics by definition, in the production and analysis of academic literature in particular, these two types of analysis inherently overlap (Mejia et al. 2021). Indeed, such tools have been applied to characterizing trends in global fisheries science (Jarić et al. 2012), marine fisheries research (Aksnes and Browman 2016), and lakes and reservoir research (Ho and Goethals 2020). They have also been used to assess regional trends including the contributions of scientists based in India to aquaculture research (Kumaresan et al. 2014) and fisheries science (Vinitha et al. 2018), to explore species- or taxon-specific research realms (e.g. common carp research; Kumaresan et al. 2018; sturgeon research; Jarić and Gessner 2012), and to understand collaboration patterns within the fisheries science community (Syed et al. 2019).

It is important for DFO to understand its contributions to the freshwater habitat science literature including trends in research efforts, where these contributions have been published, and patterns in collaborations (internally and externally). This report was developed for use by DFO to communicate research activities and to help plan for future freshwater habitat science research activities that will provide the evidence decision-makers need. Here we provide the results of a bibliometric and scientometric analysis with a focus on identifying DFO contributions to freshwater fish habitat science since the 1950s.

2.0 Methods

2.1 LITERATURE SEARCHES AND INCLUSION CRITERIA

Searches (including search string scoping) to retrieve literature related to freshwater fish habitat science were conducted using Web of Science and DFO's internal library portal by DFO staff including a librarian and members of the Ecosystems and Oceans Science Sector. Efforts were made to find both primary (e.g., publications from peer-reviewed scientific journals) and secondary (e.g., report series published by DFO, such as Canadian Manuscript Reports of Fisheries and Aquatic Sciences) publications. The searches for primary publications included literature from 1955 to August 2019 and for secondary publications from 1950 to August 2019. See Appendix 1 for the detailed search strategy.

Search results were screened by DFO staff (members of the Environment and Biodiversity Science Branch) for eligibility. All articles had to meet the following criteria to be included in this review:

- Within the subject scope of the project (i.e., freshwater fish habitat)
- Authored, or including significant contributions, by at least one employee of DFO.
- Published or co-published by DFO or one of its components, or treated as such in the catalogue record.

Bibliographic data for the included articles were provided to the Canadian Centre for Evidence-Based Conservation at Carleton University for all subsequent data extraction and analysis.

2.2 DATA EXTRACTION

During data extraction, further screening of the publications retrieved resulted in 33 additional items being excluded: 4 duplicates from within the database, 11 written in French, 2 that lacked a freshwater component, 9 that did not have a DFO author, and 7 for which the full text was unobtainable either through interlibrary loans or directly from the DFO library). While initially included in the searching and article screening, publications written in French only were excluded from data extraction and further analysis due to resource constraints.

A total of 1739 publications underwent meta-data extraction. Data were extracted from the full-text document for each publication using a review-specific data extraction form that included the data fields provided in Appendix 2. In developing the data extraction form, the following key variables of interest were identified through discussions with DFO staff: (1) bibliographic information, (2) author details (e.g., author names, affiliations, total number of non-DFO/DFO authors, sector(s) of non-DFO authors, DFO regions(s) where DFO authors are based), (3) research and study location information [e.g., research type, site location (UTMs), DFO region(s) that is the focus of the research, environment,

primary research focus, study duration, taxa], and (4) funding sources (internal and external, as reported in the publication)). Note that data extraction was conducted prior to the official launch of the Ontario and Prairie Region and Arctic Region in 2020, and therefore Central and Arctic Region is used throughout to represent these regions.

Author affiliation was extracted in the order it was reported in the publication, and the author's employment sector was coded, assuming the author's primary affiliation was the first listed. An exception to this occurred for authors listing DFO as one of multiple affiliations: in these cases, the DFO affiliation took precedence over the others and they were coded as DFO authors. For authors representing Indigenous organizations, the sector was coded based on their primary affiliation, but any Indigenous affiliation was considered when analyzing Indigenous collaboration with DFO authors. Data related to accessibility (i.e. open access) and number of citations (reported by Google Scholar) were collected for all primary publications within the span of 2 days in November 2020 to ensure they were comparable. These values therefore represent only the moment they were collected (November 2020), despite what they may have been at the time the article was originally published. Although primary publications were retrieved from Web of Science, Google Scholar citation numbers were included in this analysis as they are more comprehensive and include citations by publications beyond those indexed in Web of Science (i.e. books, theses, reports) (University Library 2021).

Definitions and examples of categorical extractions are explained in detail within the database (a case-based matrix) in Appendix 2. Note, multiple rows were extracted for a given publication when there were multiple: (1) authors, (2) study sites, and/or (3) taxa. To ensure that information for coding was being extracted in a consistent and repeatable manner, two review team members (TR and JJT) piloted the extraction form by coding information from 10 of the same publications at the beginning of the process. Any disagreements were discussed, and additional, more detailed guidance was added to the extraction codebook to improve clarity. Any new review team member involved in data extraction underwent this same consistency check process of extracting data from the same subset of 10 publications. Here too, any disagreements were discussed and modifications to the extraction codebook were made to improve clarity if needed. Coding then proceeded independently by each review team member. In addition, at the conclusion of meta-data coding, authors JJT and AS reviewed all coding decisions for consistency.

2.3 ANALYSIS

A searchable database of publications (hereafter referred to as studies) was developed to describe the quantity and key characteristics of the DFO freshwater habitat literature, based on the data extraction described above. This database is available from the authors upon request. Descriptive statistics and plots (e.g. histograms, box plots) were used to describe patterns in the available literature.

Key knowledge clusters (areas of the DFO freshwater habitat literature that are well-represented) and knowledge gaps (areas that are under-represented in this literature base) were identified using structured heat maps. All analyses were conducted in R 4.0.3 (R Development Core Team 2017) using the tidyverse (Wickham et al. 2019), igraph (Csardi and Nepusz 2006), and ggraph (Pedersen 2020) packages.

When reporting the number of individual studies (out of 1739 studies) for a given analysis we use the term ‘studies’. However, in some descriptions, we included multiple counts within a given study (e.g. a given study could include multiple locations or focus on multiple taxa). In such instances, counts will exceed the total number of studies included (i.e. > 1739 studies). We still refer to these as ‘studies’ when speaking generally about descriptions (e.g. “Most studies were reporting evidence from Central and Arctic Region...”); however, to distinguish these counts from individual study counts, we use the term ‘cases’ when providing in-text descriptive statistics and in figure captions where applicable. Counts of cases are thus situationally defined, meaning the total number of cases is not similar for all descriptions.

3.0 Results

3.1 RESEARCH TOPICS

3.1.1 What is the distribution of research topics studied across DFO regions?

There were a substantial number of studies examining species-habitat associations, as well as environmental conditions, for both Central and Arctic and Pacific DFO regions (Figure 1). There were also a relatively high number of studies looking at multiple stressors and cumulative effects, flow regime changes and species distributions. Overall, there were fewer studies examining topics related to riparian zones and pollution. When the research focus was Canada-wide, there was relatively even distribution of research topics, with multiple stressors and cumulative effects and species-habitat associations being the most studied and riparian research the least studied.

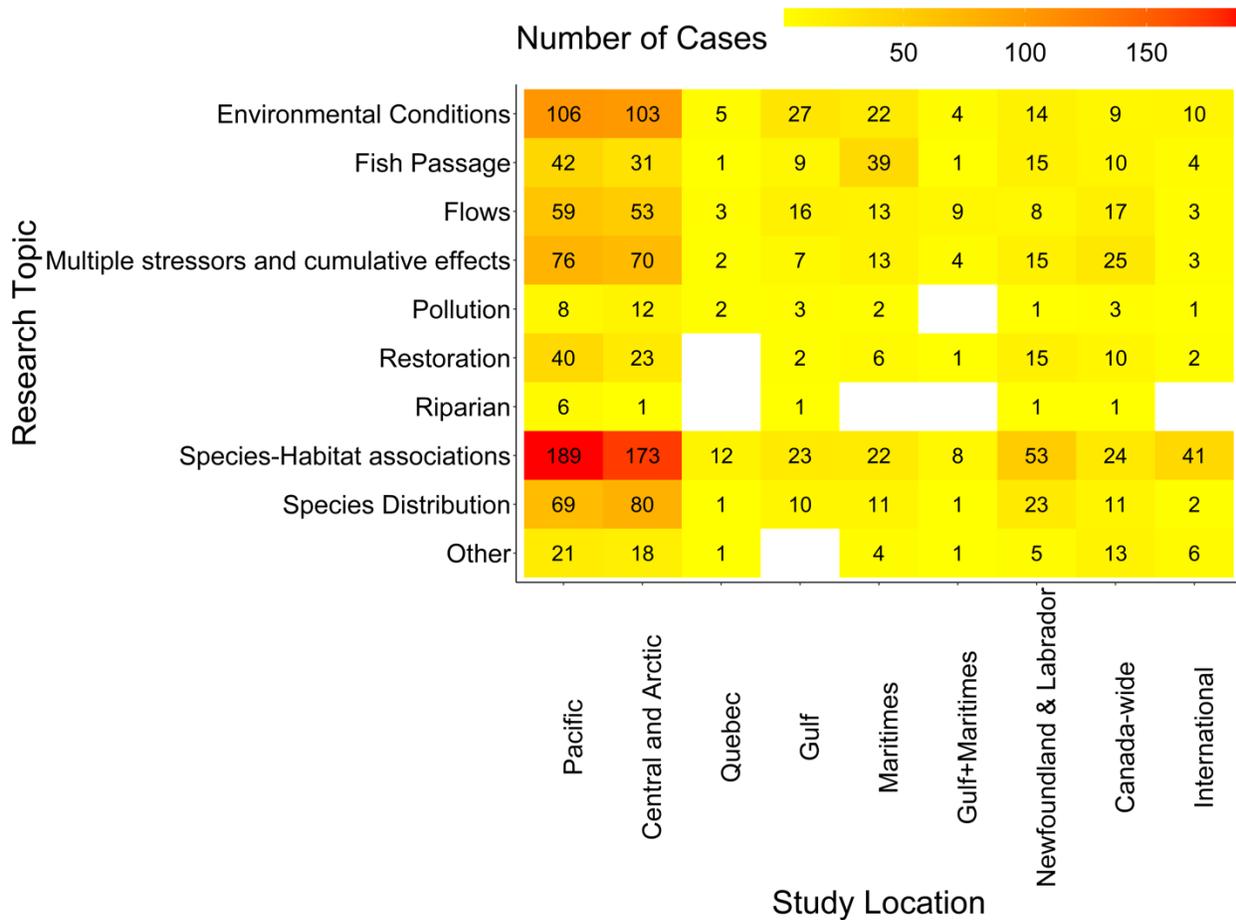


Figure 1. Frequency and distribution of research topics studied across DFO regions (study locations). Gulf+Maritimes represents individual studies that took place in both the Gulf and Maritimes DFO regions (e.g. contained field sites in both). Cases counted in Gulf+Maritimes are excluded from counts for the individual Gulf and Maritimes regions, but can be considered as taking place within those regions. ‘International’ studies are those that took place outside of Canada.

3.1.2 What is the distribution of research topics studied across environment types (e.g., lakes, streams, wetlands)?

Across various environment types, high numbers of studies focused on rivers, streams and whole lakes. The most commonly studied research topics within these systems (i.e. rivers, streams, and whole lakes) were species-habitat associations and environmental conditions (Figure 2). Rivers were the most studied (single) environment type across all research topics compared to other environment types, with species-habitat associations, flow regime changes, and fish passage being the dominant research topics. There were relatively fewer studies focusing on ponds, wetlands, and pelagic areas of lakes.

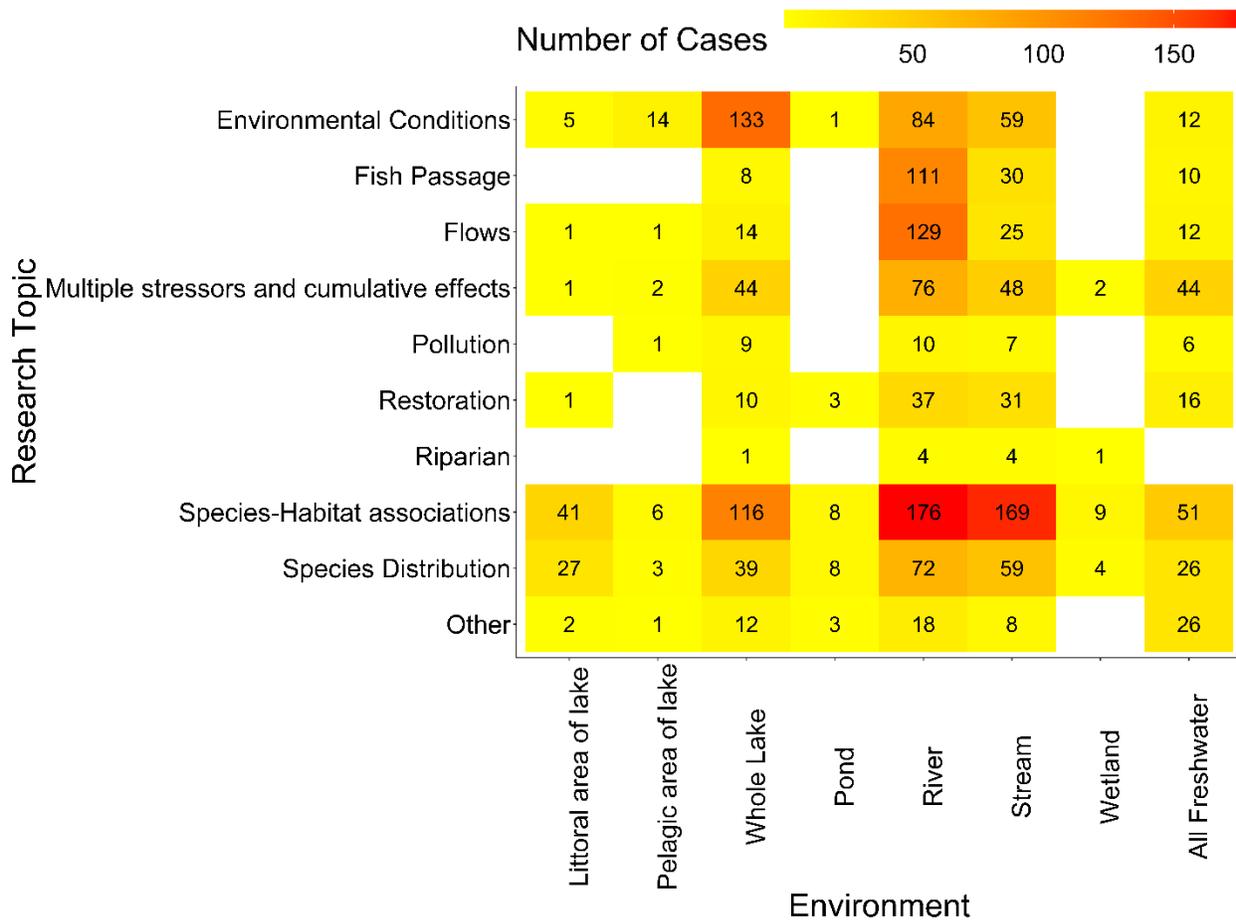


Figure 2. Frequency and distribution of research topics studied across aquatic environment types. ‘All freshwater’ are studies applicable to all freshwater environment types.

3.1.3 What is the distribution of research topics studied across document types?

Most research conducted across all DFO regions was published as either a primary (peer review) publication, a Canadian Manuscript Report of Fisheries and Aquatic Sciences (CMRFAS), or a Canadian Technical Report of Fisheries and Aquatic Sciences (CTRFAS) (Figure 3). Species-habitat association studies had the highest number of primary publications, followed by environmental conditions and flow regime changes. For CTRFAS, there were relatively high numbers of studies examining species-habitat associations, multiple stressors and cumulative effects, and environmental conditions.

Relatively few studies were published in other kinds of secondary publications, including Canadian Science Advisory Secretariat Science Advisory Report (CSASSAR), consultant reports, Canadian Data Report of Fisheries and Aquatic

Sciences (CDRFAS), or Canadian Science Advisory Secretariat Research Document (CSASRD). Many studies were published as other less common report types produced by DFO (DFO Other), which include progress reports, special publications, and working group reports.

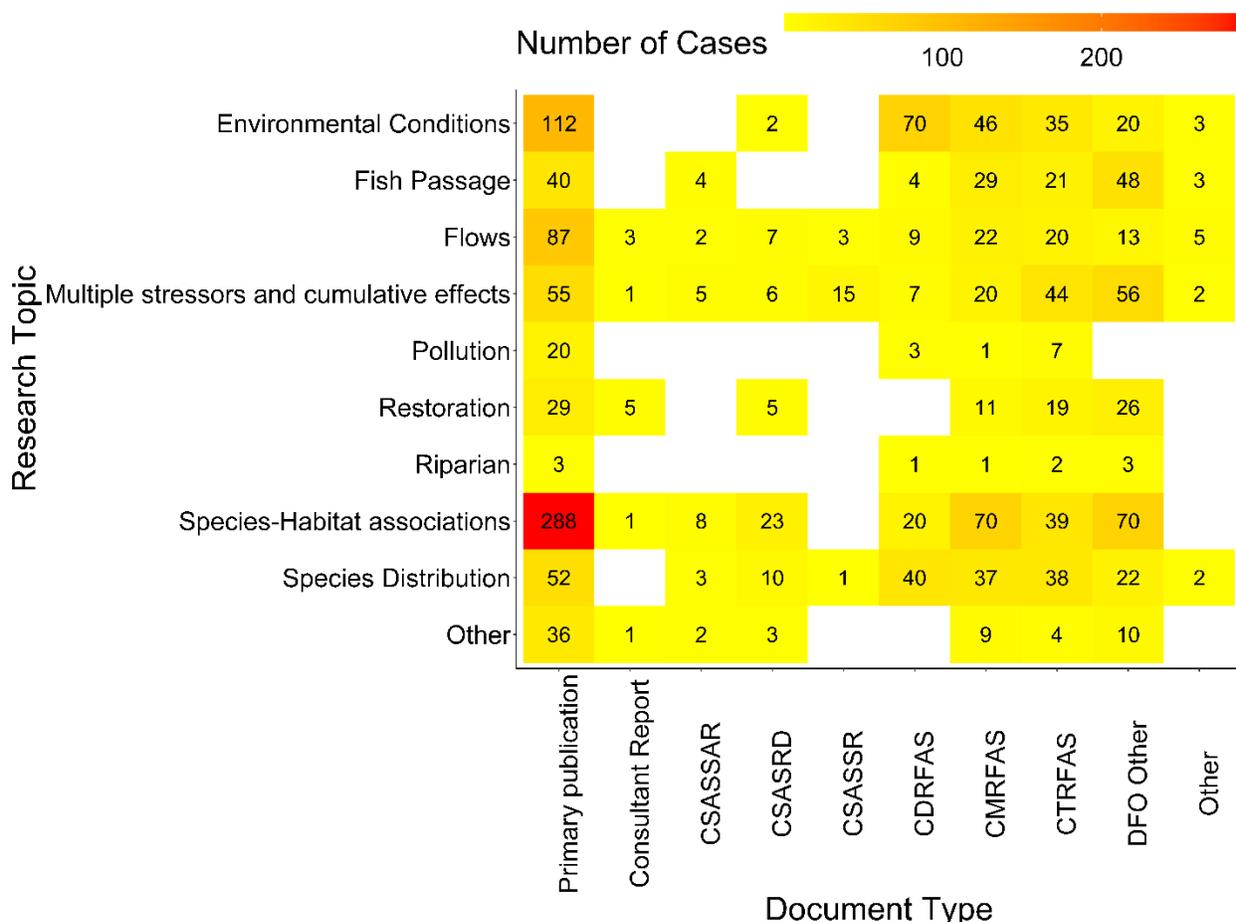


Figure 3. Frequency and distribution of research topics studied across document types for all DFO regions (study locations). CSASSAR = Canadian Science Advisory Secretariat Science Advisory Report; CSASRD = Canadian Science Advisory Secretariat Research Document; CSASSR = Canadian Science Advisory Secretariat Science Response; CDRFAS = Canadian Data Report of Fisheries and Aquatic Sciences; CMRFAS = Canadian Manuscript Report of Fisheries and Aquatic Sciences; CTRFAS = Canadian Technical Report of Fisheries and Aquatic Sciences; DFO Other = Other internal DFO reports; Other = Non-DFO Reports.

3.1.4 What is the frequency of research topics studied across decades?

Across all DFO regions, there has been a general increase in number of studies chronologically across decades from 1950 to 2010 (Figure 4). There was a peak in the number of studies examining environmental conditions in the 1970s. The number of studies examining species-habitat associations has drastically

increased since the 1950s and 1960s reaching 156 studies in the 2010 decade, triple the amount in any other research topic for that decade. The number of studies with a research focus related to riparian zones and pollution has remained relatively low over time. There were many studies conducted in the Pacific and Central and Arctic regions over time, with fewer studies across the remaining regions (Figure 5). Canada-wide, there was a small increase in study numbers with time. There were no studies in Quebec until the 1990s, and only relatively few studies after that, while studies in the Maritimes and Gulf have remained relatively constant through time. Similarly, within the Newfoundland and Labrador Region, study numbers have remained constant over time, albeit with a small increase in species-habitat association studies in the 1990s and 2000s.

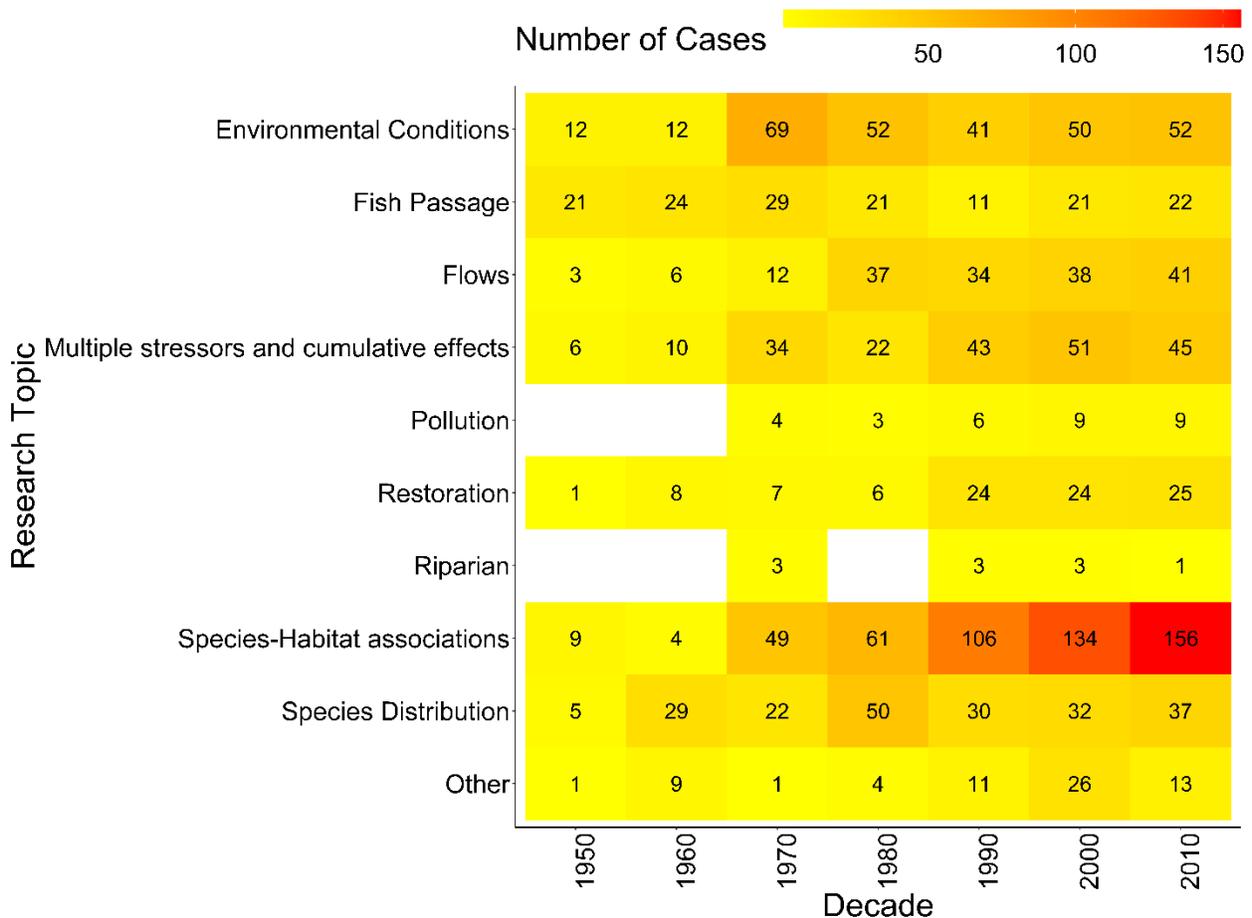


Figure 4. Frequency and distribution of research topics studied across decades for all DFO regions (study locations). Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade.

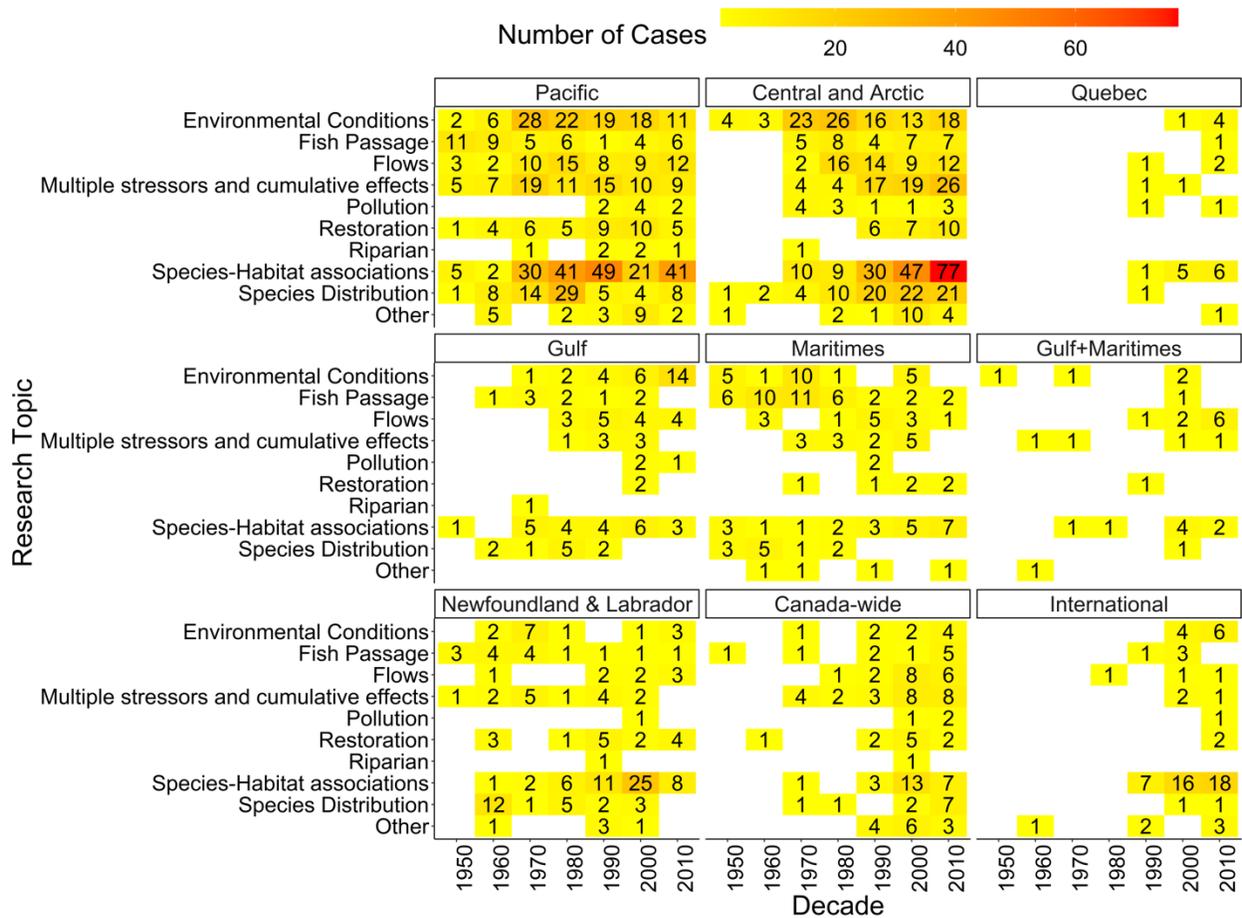


Figure 5. Frequency and distribution of research topics studied across decades for each DFO region (study location) separately. Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade. Gulf+Maritimes represents individual studies that took place in both the Gulf and Maritimes DFO regions (e.g., contained field sites in both). Cases counted in Gulf+Maritimes are excluded from counts for the individual Gulf and Maritimes regions, but can be considered as taking place within those regions. ‘International’ studies are those that took place outside of Canada.

3.2 TAXA

3.2.1 What is the frequency of taxa studied across decades?

Within the DFO freshwater habitat literature as a whole, fish have remained the dominant study taxa from the 1950s to 2010s studied across all DFO regions. The number of studies focusing on fish has increased over time, peaking in the 2010s with 277 cases (Figure 6). There were increases in the number of studies

examining invertebrates and general biota in the 1990s and 2000s, and plants in the 2000s. The number of studies focused on mammals, birds and other taxa (e.g. plankton) remained low throughout the entire study date range.

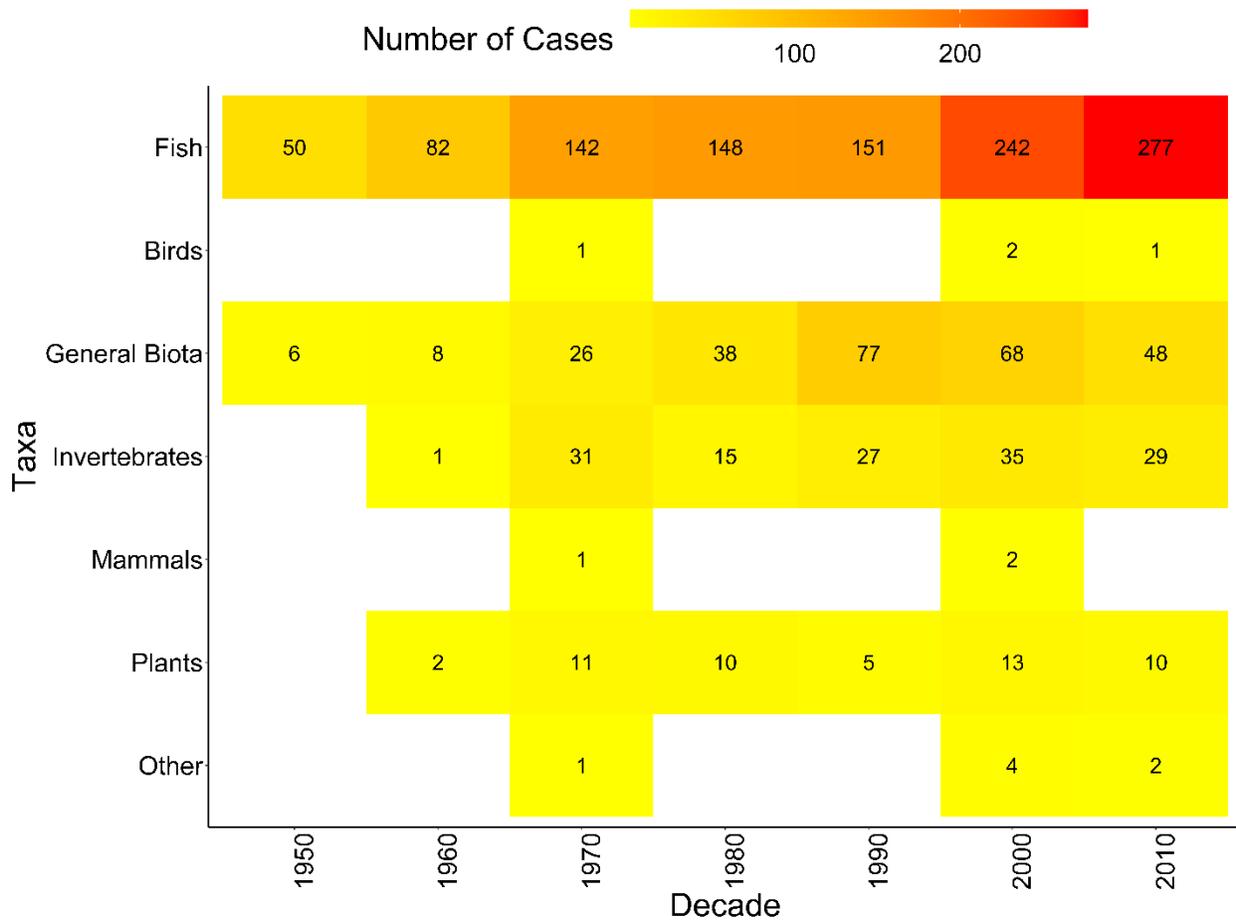


Figure 6. Frequency and distribution of taxa studied across decades for all DFO regions (study locations). Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade.

Within each DFO region, fish were the dominant study taxa, with the largest numbers conducted in the Pacific and Central and Arctic regions, and these numbers increased over time in these regions (Figure 7). The number of fish focused studies conducted in other DFO regions has remained relatively consistent, except for small increases in the 2000s for the Gulf and Newfoundland and Labrador regions, and Canada-wide and Internationally in the last two decades. Studies on general biota and invertebrates were also common in the Pacific and Central and Arctic regions, peaking in the 1990s and 2000s.

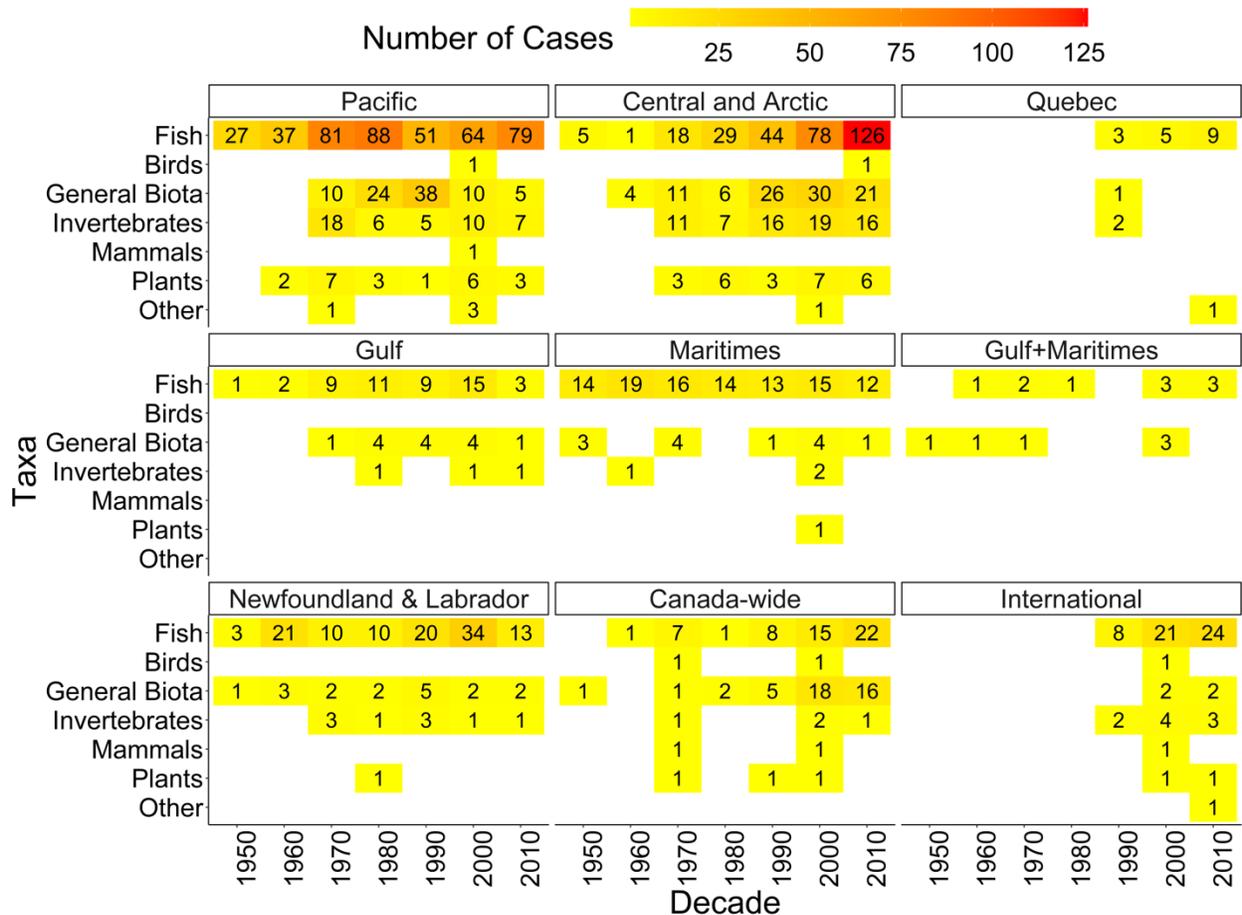


Figure 7. Frequency and distribution of taxa studied across decades for each DFO region (study location) separately. Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade. Gulf+Maritimes represents individual studies that took place in both the Gulf and Maritimes DFO regions (e.g. contained field sites in both). Cases counted in Gulf+Maritimes are excluded from counts for the individual Gulf and Maritimes regions, but can be considered as taking place within those regions. ‘International’ studies are those that took place outside of Canada.

3.2.2 What is the distribution of research topics studied across fish families?

Most research conducted across all DFO regions focused on salmonids, either alone (64% of cases) or together with other fish families (13%) (Figure 8). Studies including salmonids focused on a variety of research topics, most commonly species-habitat associations, species distributions, fish passage, and multiple stressors and cumulative effects. There were relatively few studies on all other fish families (each with $\leq 5\%$ of cases) which were most often in relation to species-habitat associations.

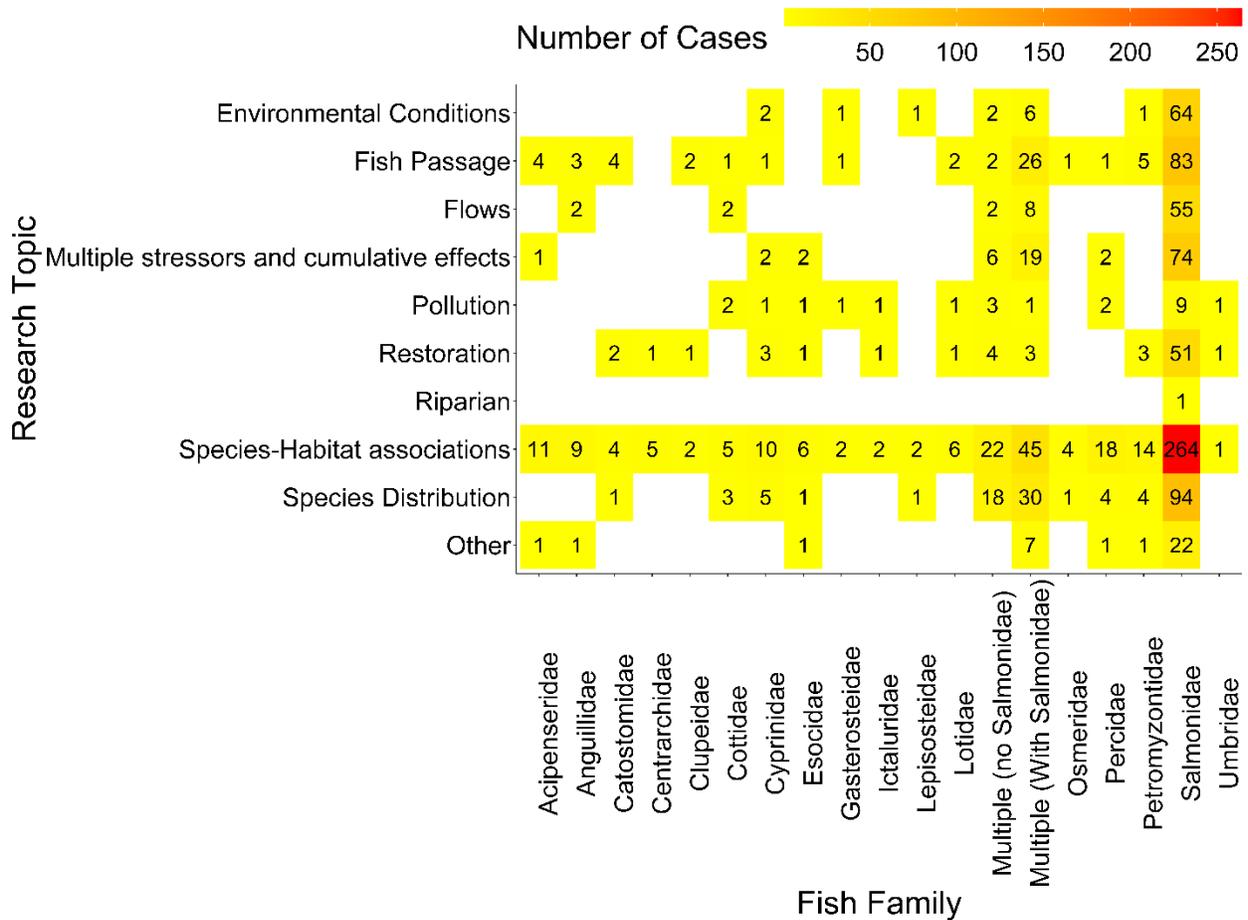


Figure 8. Frequency and distribution of research topics studied across fish families for all DFO regions (study locations). Studies that investigated species from >1 fish family were grouped together (=Multiple) and identified as either including species from the Salmonidae family (=With Salmonidae) or not (=no Salmonidae).

Salmonids were the most frequently studied taxa within each specific DFO region as well (Figure 9). Central and Arctic Region investigated the greatest diversity of fish families, across a variety of research foci. All other regions studied relatively few fish families on a limited number of research topics.

published in the last two decades (Figure 10). The number of studies available in open access was notably higher than those published behind a paywall in the 1980s (studies taking place in Pacific, Central and Arctic, Maritimes, and Gulf regions) and 1990s (studies taking place in Pacific, Central and Arctic, and Gulf regions, Canada-wide and internationally) (Figure 11). The higher proportion of studies in open access continued in the Pacific Region through the 2000s but decreased drastically in the 2010s. Only primary literature was included in this analysis as most of the secondary literature included in our review is freely available online.

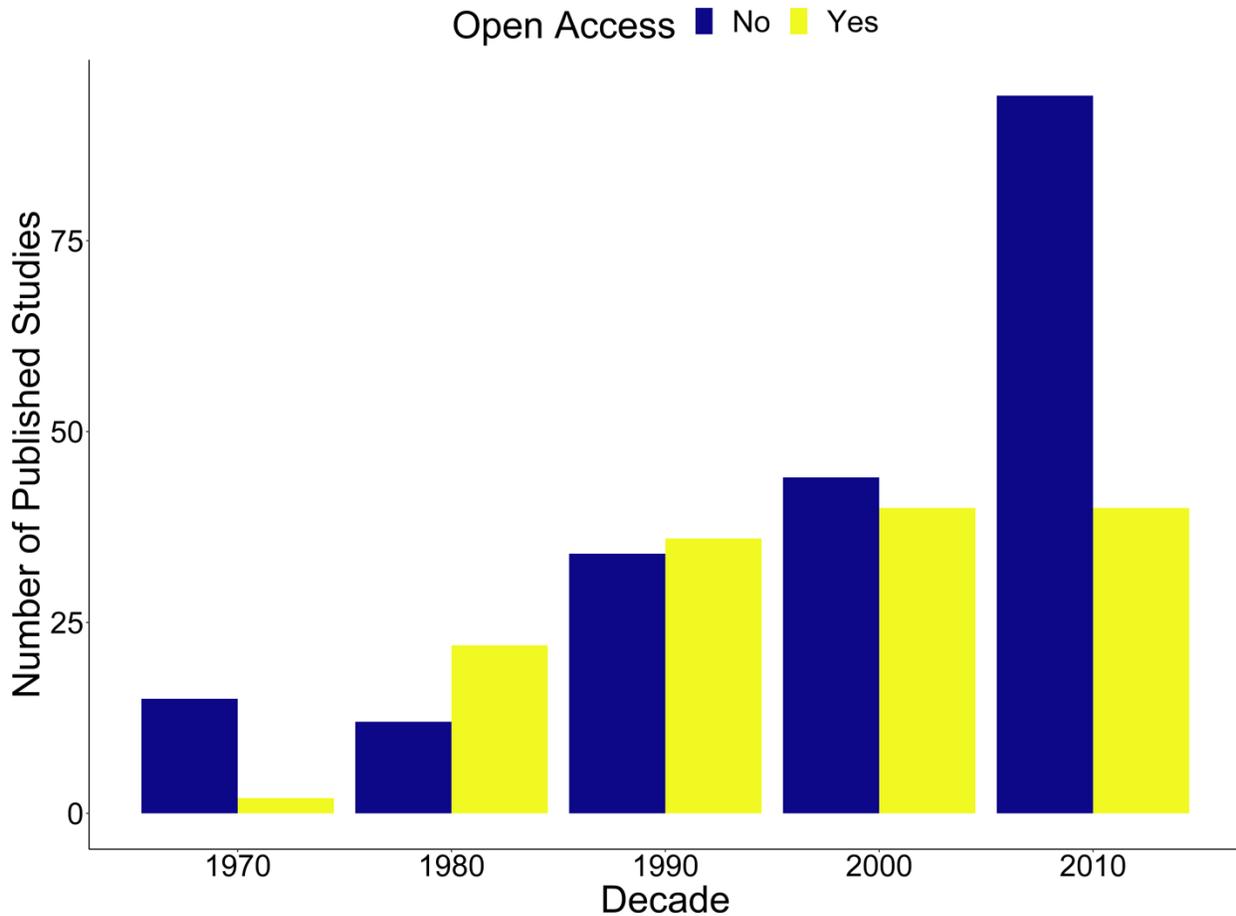


Figure 10. The number of open access versus closed access primary publications for all DFO regions (study locations) over time. Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade.

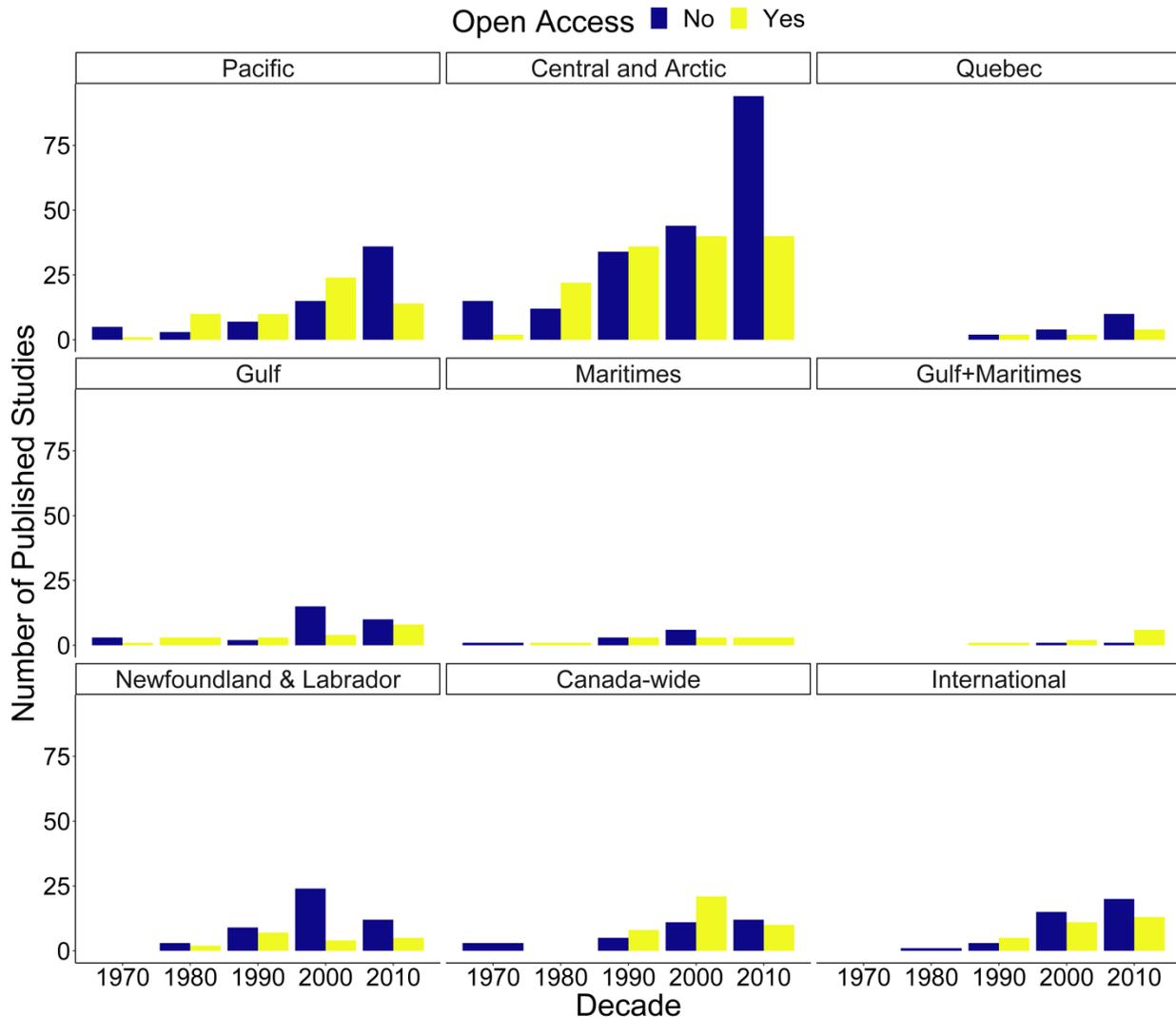


Figure 11. The number of open access versus closed access primary publications within a given DFO region per decade. Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade. ‘International’ studies are those that took place outside of Canada.

3.3.2 What is the median number of citations for primary literature across DFO regions?

Overall, the number of citations reported by Google Scholar for primary publications across all regions ranged from 0 to 1479, with a median value of 27. Primary literature conducted Canada-wide and in the Gulf Region had the highest median number of citations, followed by International and Pacific regions (Figure 13). Most primary literature sources were cited ≤ 200 times; however, some Canada-wide studies were heavily cited (i.e., 4 primary publications with >500 citations).

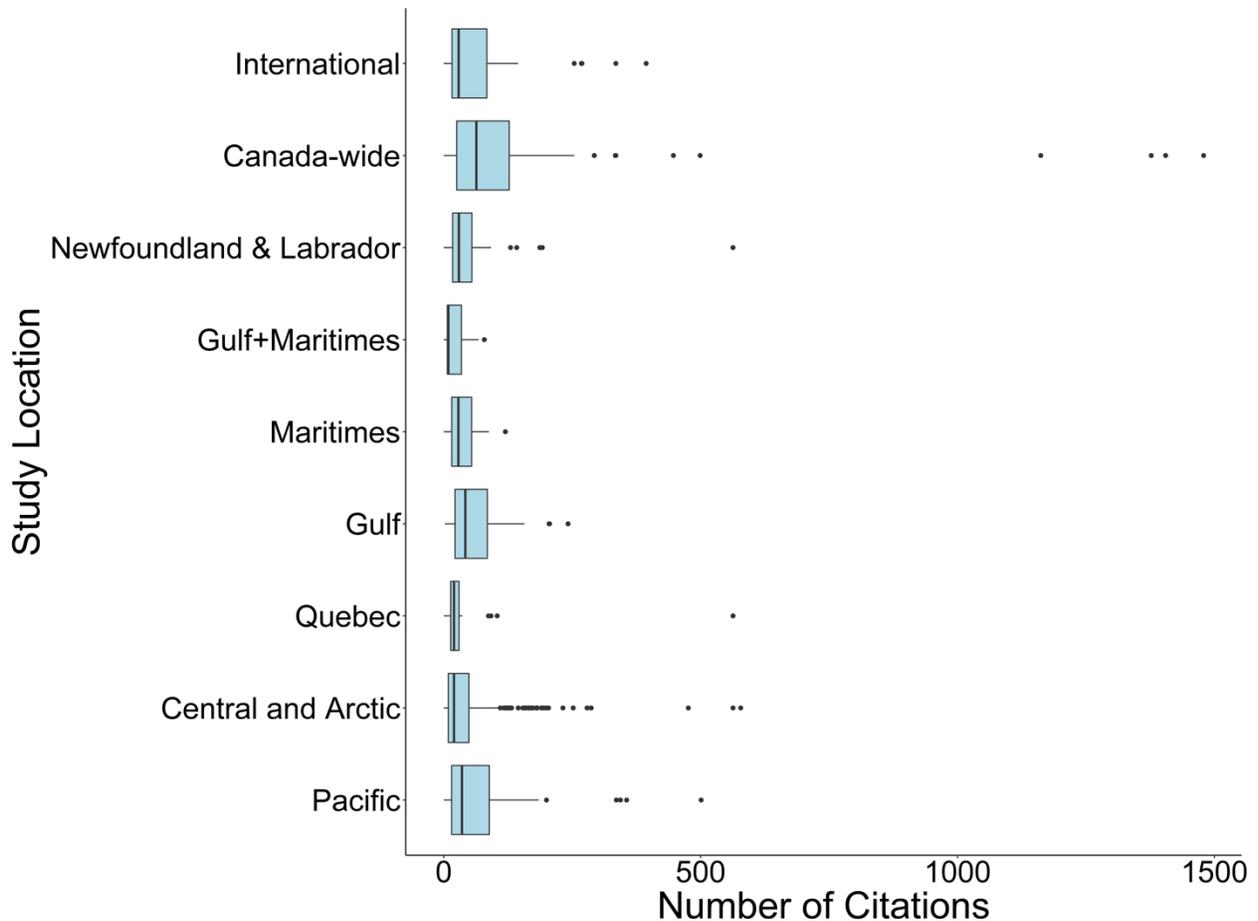


Figure 12. Box-plot of the number of citations (Google Scholar) for primary publications across DFO regions (study locations). The boxes represent the 25th and 75th percentiles, and the vertical line in each box indicates the median. The whiskers (i.e. horizontal lines) signify maximum and minimum values, and circles indicate outliers. Gulf+Maritimes represents individual studies that took place in both the Gulf and Maritimes DFO Regions (e.g. contained field sites in both). Cases counted in Gulf+Maritimes are excluded from counts for the individual Gulf and Maritimes regions, but can be considered as taking place within those regions. ‘International’ studies are those that took place outside of Canada.

Considering the age of the publication may confound citation numbers (with older papers having more time to accumulate citations), this may only be the case in the 1970s (Figure 13). The median citation number is generally similar for the 1980s, 1990s, and 2000s with some clear outliers in the 2000s (three highly cited papers). While publications from the 2010s do have the lowest median citation number, not all lower cited papers are from recent years.

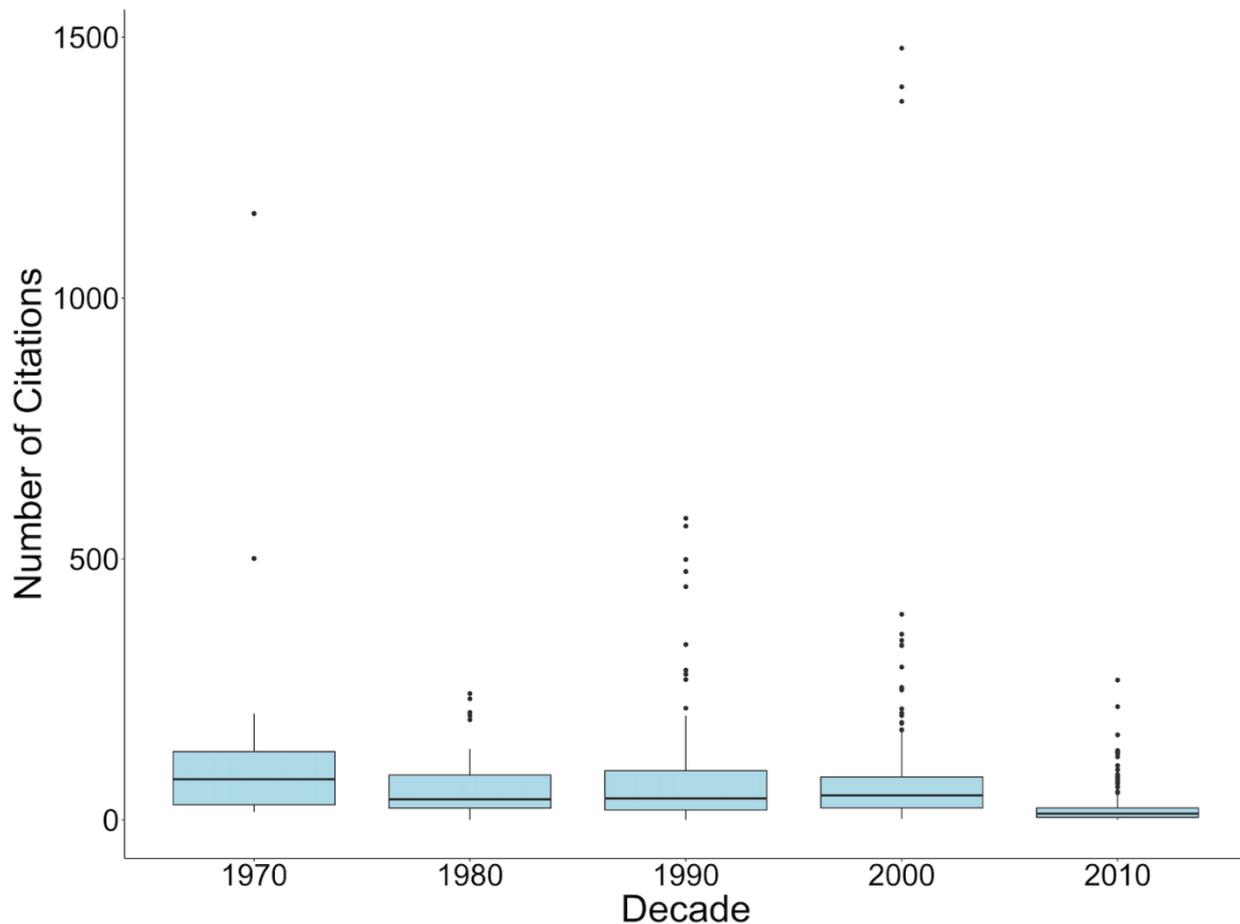


Figure 13. Box-plot of the median number of citations (Google Scholar) for primary publications across decades. The boxes represent the 25th and 75th percentiles, and the horizontal line in each box indicates the median. The whiskers (i.e. vertical lines) signify maximum and minimum values, and circles indicate outliers.

3.4 AUTHORS

3.4.1 What proportion of the evidence base was led by a DFO author?

1278 out of a total of 1739 studies were led by a DFO author (73%). Note that 124 of these 1278 were attributed to DFO without a specific author indicated, which is standard practice for official departmental science advice such as is produced in the Canadian Science Advisory Secretariat Science Advisory Reports (CSASSAR). Of the 717 primary publications, 329 were led by a DFO author (46%), whereas 926 out of the 996 secondary publications (e.g. CTRFAS, CSASSAR) were led by DFO (93%).

Focusing on changes over time, the proportion of primary publications led by a DFO author (versus non-DFO author-led) has generally declined from the 1970s to 2010s (85% compared to 35% DFO author-led papers; Figure 14). A similar decreasing trend over time can be seen in the proportion of DFO author-led reports internal to DFO (i.e., 100% DFO author-led reports in the 1950s and 1960s compared to 88% in the 2010s), although this proportional change was not as large as with primary literature.

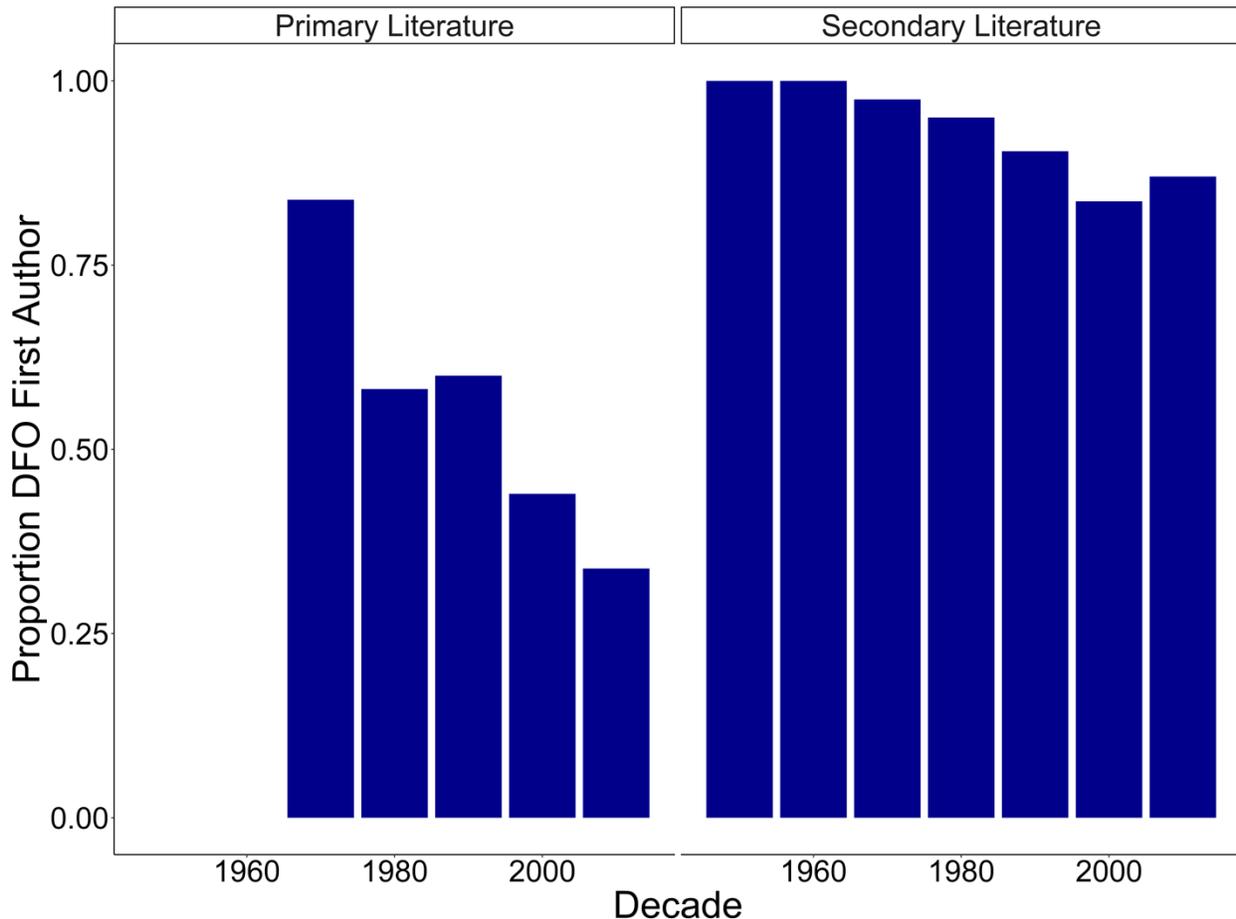


Figure 14. The proportion of DFO author led studies for each of primary literature and secondary literature (i.e. reports published by DFO) types separately (out of the total number of studies of each type) per decade. Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade.

3.4.2 What proportion of the evidence base involved a collaboration among DFO and non-DFO authors when publishing?

709 out of a total of 1739 studies involved a collaboration among DFO and one or more non-DFO authors (41%). Of the 717 primary publications, 547 studies

involved a collaboration among DFO and one or more non-DFO authors (76%), whereas 158 out of the 996 secondary publications (e.g. CTRFAS, CSASSAR), involved a collaboration among DFO and one or more non-DFO authors (16%). Note, 124 studies attributed to DFO without a specific author indicated were excluded from this analysis as authorship, and therefore collaboration, was unclear.

3.4.3 What is the proportion of studies involving a collaboration among DFO and non-DFO authors within a given DFO region across decades?

The proportion of studies involving a collaboration among DFO and non-DFO authors has generally increased over time in most study regions, with all but one region showing $\geq 70\%$ of studies involving a collaboration by the 2010s. The largest increases in the proportion of collaborations among DFO and non-DFO authors were evident in the Pacific and Quebec regions (increases of 51% and 33% from the 1990s to 2010s alone, respectively (Figure 15). The proportion of studies involving a collaboration among DFO and non-DFO authors has remained relatively high for international studies, and relatively low for studies in the Maritimes across all decades.

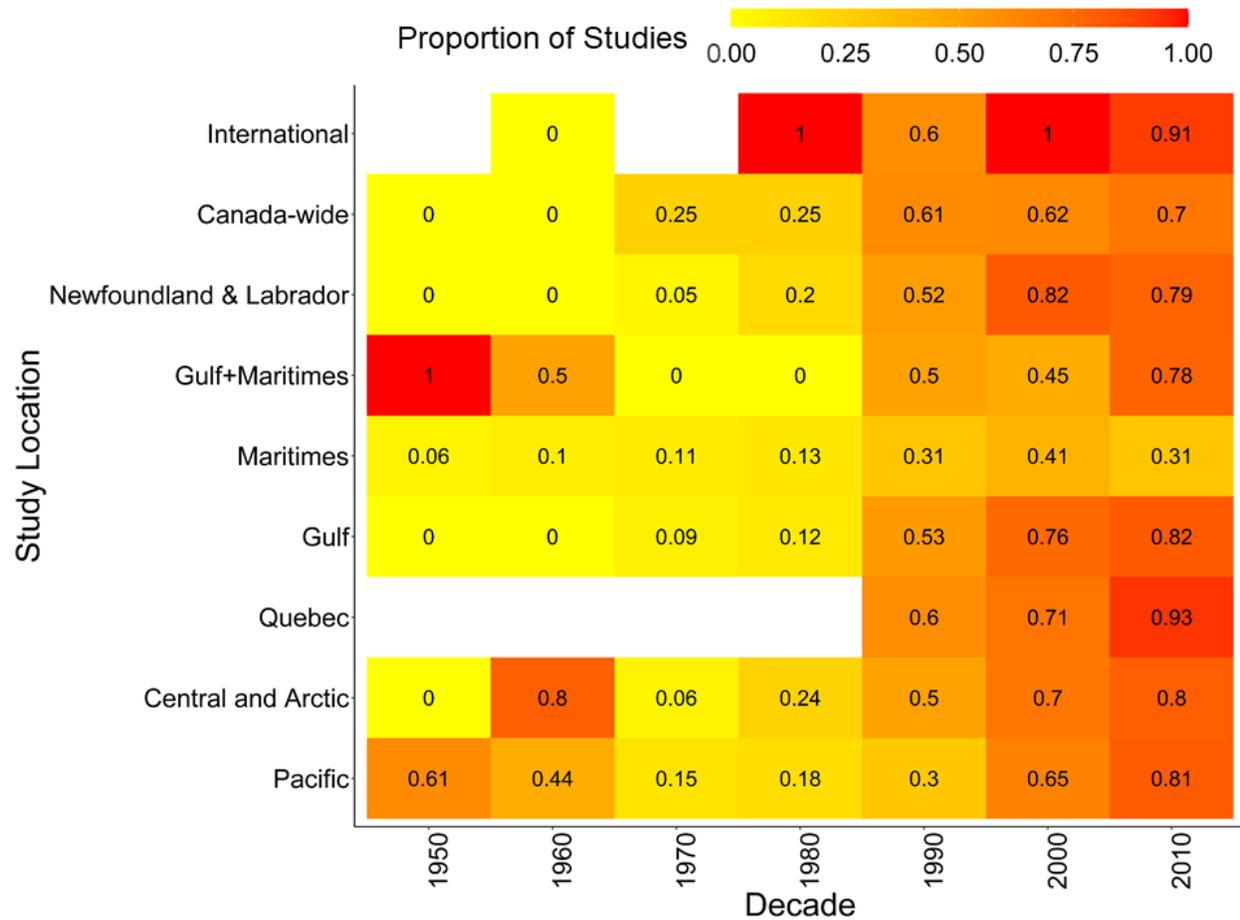


Figure 15. The proportion of studies involving a collaboration among DFO and non-DFO authors (out of the total number of studies) within a given DFO region (study location) across decades. Only articles up to August 2019 were included in this report, as such the data for the 2010s does not represent a complete decade. Gulf+Maritimes represents individual studies that took place in both the Gulf and Maritimes DFO Regions (e.g. contained field sites in both). Cases counted in Gulf+Maritimes are excluded from counts for the individual Gulf and Maritimes regions, but can be considered as taking place within those regions. 'International' studies are those that took place outside of Canada.

3.4.4 What is the frequency of collaborations among DFO and non-DFO authors in relation to the number of authors?

Most studies involved a single DFO author with no collaborations with non-DFO authors (n =376; Figure 16). There were also a relatively high number of studies with 2 or 3 DFO authors and no collaborations with non-DFO authors (n = 277 and n = 136, respectively), or a single DFO author and ≤ 3 non-DFO authors. There were relatively few studies that included both a high number of DFO and non-DFO authors (> 4 each).

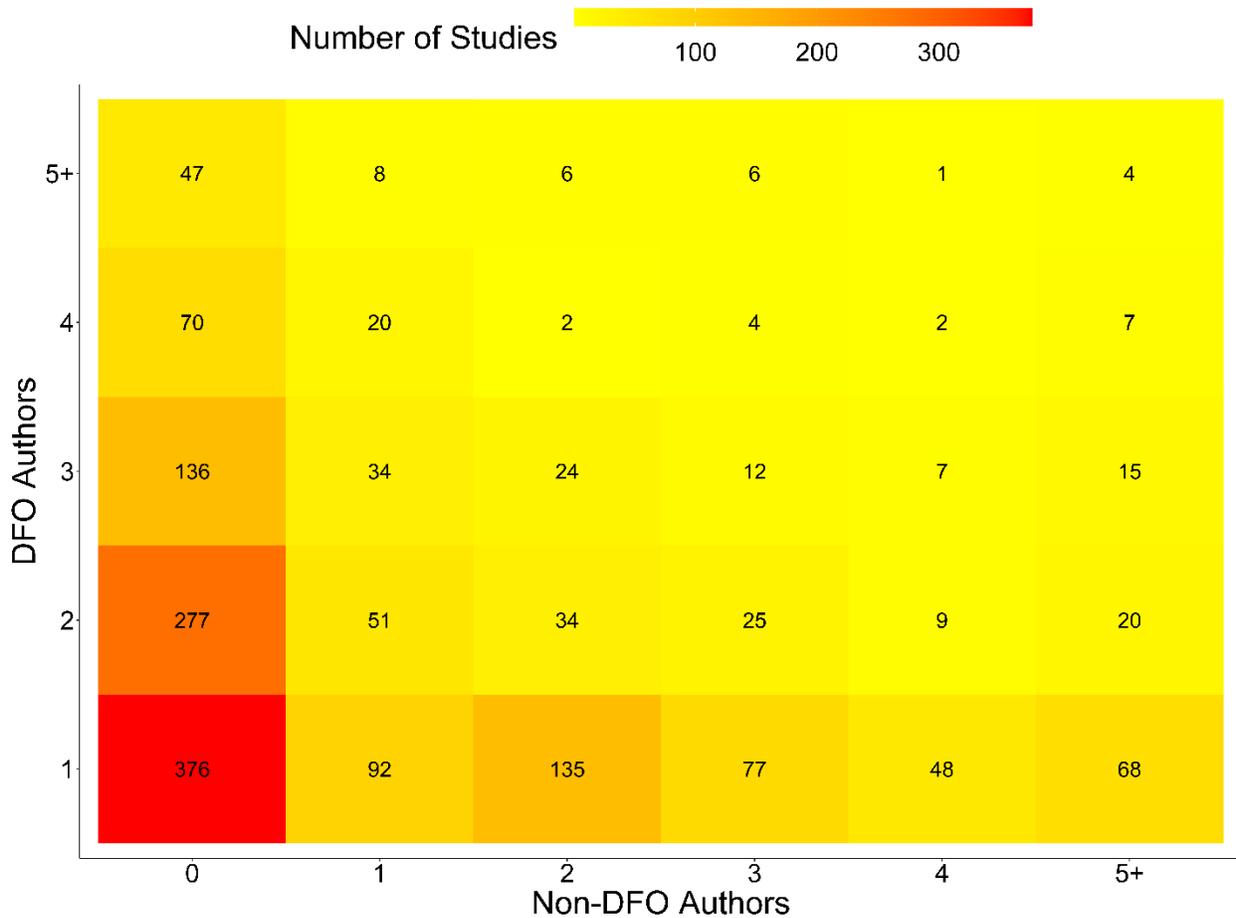


Figure 16. The number of studies for all DFO regions with collaborations among DFO and non-DFO authors in relation to the number of authors. 124 studies attributed to DFO with no specific authors listed are excluded from this figure as collaboration is unclear

3.4.5 How often do DFO authors publish studies conducted within their own DFO region?

DFO authors conducted research most often within their own DFO region [Newfoundland and Labrador: 77% (131/170 cases); Maritimes: 68% (117/171); Gulf: 69% (88/128); Quebec: 50% (9/18); Central and Arctic: 77% (501/650); Pacific: 90% (520/577); Figure 17]. Central and Arctic Region conducted most of the Canada-wide and international research (59% and 45% of the cases, respectively).

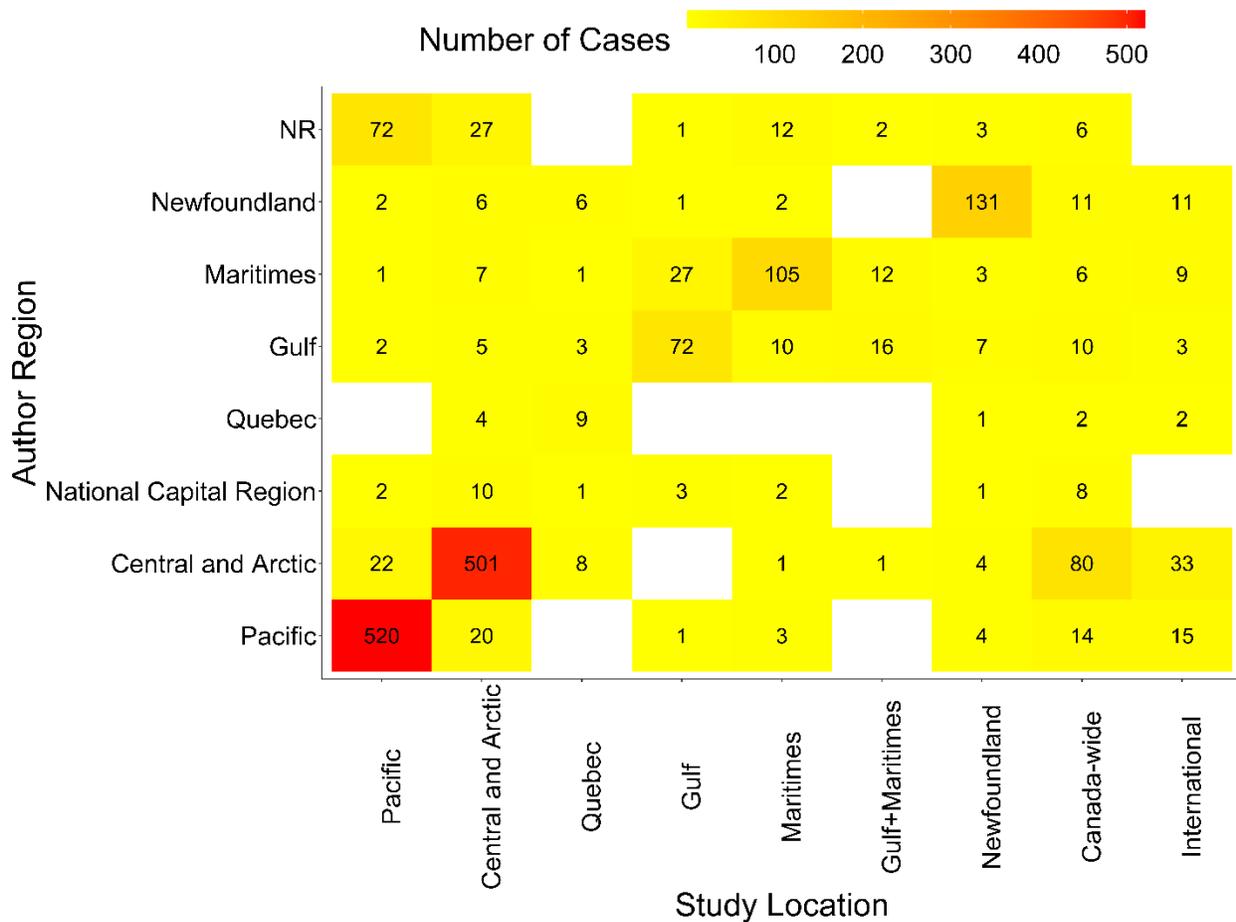


Figure 17. Frequency and distribution of the DFO regions where DFO authors are based across the DFO regions that is the focus of the research (study locations). DFO author region NR = studies attributed to DFO with no specific author listed. 'International' studies are those that took place outside of Canada.

3.4.6 How often do DFO authored publications report funding from external sources?

515 out of a total of 1739 studies (30%) reported funding from an external source (e.g. NSERC, Carleton University, BC Hydro). When considering reports written solely by DFO authors, only 100 out of 906 (11%) studies reported external funding, compared to 413 out of 709 studies (58%) when there were one or more non-DFO authors. Note, 124 studies attributed to DFO without a specific author indicated were excluded from this analysis as authorship was unclear.

3.4.7 How often do DFO authors collaborate with authors representing Indigenous organizations?

Only 14 of the 1739 DFO freshwater habitat studies (0.8%) involved a collaboration among one or more DFO authors and an author representing an Indigenous organization. In total, there were 27 individual authors within this database of literature that listed an Indigenous organization as one of their affiliations. DFO authors from only three regions have collaborated with one or more authors representing Indigenous organizations: Pacific (13 DFO authors), Central and Arctic (12), and Newfoundland and Labrador (3).

4.0 Discussion

The present report uses bibliometric and scientometric approaches to analyze DFO contributions to freshwater fish habitat science between 1950 and August 2019. Our analysis reveals trends that can be used to inform future DFO investments in freshwater habitat science, to better understand the fish habitat science research ecosystem, and to identify potential gaps in research. We preface our discussion by noting that our goal here is to not make any judgements on the trends revealed here. Rather, our goal is to simply summarize key trends and anchor them in the context of the literature.

We identified 1739 studies that fit our criteria. Species habitat association and environmental conditions were among the most studied topics although this varied somewhat among regions and environment types (e.g. rivers, lakes). Given the large number of freshwater fish in Canada and the need for species-specific data on habitat needs, this cluster of knowledge is not surprising. Regional clusters of research activity reflect regional issues (e.g. fish passage and fish flow research were more prevalent in regions with large numbers of hydropower development). Despite the large number of hydropower developments in Quebec (Smokorowski 2021), we identified relatively few studies conducted in the province, and none before 1990 (see Figure 5). We acknowledge this as a limitation of the review as articles provided only in French were excluded from this analysis.

The most common outlets for research were primary publications (i.e. peer reviewed journal articles and book chapters), and certain secondary literature series (specifically Canadian Manuscript Reports of Fisheries and Aquatic Sciences and Canadian Technical Reports of Fisheries and Aquatics Sciences). These secondary literature series are inherently open access (no subscription cost) and accessing individual documents in these series has become easier now that such reports are published freely online. Focusing solely on the primary literature publications in our dataset, there is evidence that they are increasingly being published in open access forums over time, which may reflect early impacts of DFO's National Policy for Scientific Publications, introduced in November 2016. However, there remains a larger number of studies behind a

paywall compared to openly accessible studies published in the last two decades. With respect to there being a lower proportion of open access papers in the 2010s than the 2000s, this may be an artifact of some older articles being released from paywalls as they age, which is a common practice for many scientific journals (Piwowar et al. 2018).

Over time, most research topics showed an acceleration in research output as assessed by the number of contributions. This was particularly evident for research on species-habitat associations, multiple stressors, and environmental conditions. Such patterns varied by region which may reflect differences in regional research priorities and research capacity over time. Although we do not explore the specific drivers of those patterns, some associations could be revealed by looking at historical events (e.g. construction of DFO research facilities, changes in DFO policy; often precipitated by external domestic or international influences). We also noted some taxonomic trends in research effort that also varied regionally. For example, research on species-habitat associations for salmonids in both the Pacific, and Central and Arctic regions featured prominently in the heat maps as major clusters of activity. Salmonids are of high value (e.g. cultural, socio-economic, ecological) and are regarded as being particularly sensitive to habitat alterations which may contribute to the large amount of focused research activity in our dataset. Indeed, a global bias in research focusing on salmonids has been previously noted (see Jarić et al. 2012).

Most of the studies (1278/1739) identified here were led by a DFO author (73%). The extent of external collaboration varied across regions but overall has increased dramatically since the 1950s (see Figure 15) and 41% of papers had one or more non-DFO authors. Applied environmental science is inherently complex and partnerships are increasingly recognized as important drivers of success in generating actionable knowledge (Cooke et al. 2020). It is therefore not surprising to see an increase in collaboration with non-DFO researchers. It is also worth noting that many DFO research scientists have adjunct appointments at universities, and there are also multiple co-located DFO facilities on university campuses to enable and encourage such collaboration (e.g. DFO Cooperative Fisheries Management Unit at Simon Fraser University; the DFO Freshwater Institute at the University of Manitoba). Collaborative teams have also been enabled via funding streams such as the NSERC Partnership grants (now called Alliance grants) that have supported initiatives such as NSERC HydroNet (see Smokorowski et al. 2011), leading to strong collaborations between DFO, academics, and other partners.

515 out of a total of 1739 studies (30%) reported funding from an external source (e.g. NSERC, a university, BC Hydro, Genome Canada). Considering only those studies authored solely by DFO staff (i.e. those with zero non-DFO authors), only 11% of studies reported funding from an external source. When studies were conducted collaboratively between DFO and non-DFO authors, external funding was reported for 58% of the studies, indicating additional financial support is

often provided by non-DFO authors. DFO research scientists with adjunct status at academic institutions can seek NSERC Discovery Grant funds, however this is relatively uncommon, as most NSERC funding is accessed through academic partnerships where a full-time academic is the lead applicant.

Notwithstanding the trend towards more collaboration and partnership funding over time, most studies had a single DFO author with no external collaborators (n = 376). There were also a relatively high number of studies with 2 or 3 DFO authors and no external collaborators (n = 277 and n = 136, respectively). Overall, there were relatively few studies that included both a high number of DFO and non-DFO authors, with most being from the last decade.

We observed a generally low level of collaboration with authors representing Indigenous organizations, with most examples in the last decade. Relationships between the Crown and Indigenous communities and governments reflects a complex history so this is not surprising. Nonetheless, we note that this may be an underestimation of collaboration as this statistic is based solely on authors reporting an Indigenous affiliation and authors were not contacted to ask about whether they identify as Indigenous (but, for example, may have reported only a government or academic affiliation). As Canada continues on its path to reconciliation (Wong et al. 2020) and we adopt a more inclusive approach to fisheries science that better values Indigenous knowledge (Reid et al. 2021), more work must be done to co-develop studies and engage with Indigenous groups if we hope to see more examples of such collaboration in the future. Indeed, there are ongoing efforts by DFO to understand the bridging of Western scientific and Indigenous knowledge in the realm of freshwater fisheries science in Canada (Alexander et al. 2021).

Given differences in research topics (some of which may inherently require more collaboration), individual approaches to research (e.g. some researchers are inherently more collaborative than others; Nguyen et al. 2019), institutional changes (e.g. in leadership culture, in funding) and other factors, a varying level of collaboration can be expected. It is also challenging to interpret without understanding individual context, which is beyond the scope of this study. Future efforts to consider how collaborations function on a regional or topical basis may be informative. It is increasingly recognized that some individuals have certain characteristics that may be desirable for enabling collaborative research, and this may be enabled by, for example, more efforts to co-locate DFO science staff with academics (or vice versa).

5.0 Conclusion

Canada has a global reputation for its role in conducting freshwater fish habitat science. In our review of the state of DFO-authored freshwater fish habitat science, it became apparent that there has been a large amount of science done in that space. In the context of DFO, such research is done to support the mandate of DFO and its related legal responsibilities. Historically, such work was

almost exclusively the remit of DFO scientists, while today it is more common for it to be done in a collaborative manner with external partners. This paradigm is common and found more broadly in applied conservation research where partnerships and collaboration are recognized as recipes for success (Cooke et al. 2020).

The heatmaps generated in this report will be useful for identifying both knowledge clusters and knowledge gaps on different taxa, species groups, regions and/or topics. Consistent with global research trends, fish species in the family Salmonidae were the most studied species in the context of freshwater fish habitat science conducted by DFO.

Given the importance of the scientific record (i.e. publications) for establishing the evidence base upon which decisions are made, and of ensuring research outputs can be accessed by scientists and knowledge users outside of DFO (e.g. habitat managers), opportunities to more fully embrace open access publishing should be considered. Indeed, this would be consistent with the Canadian government's own open science initiatives and policies (see Roche et al. 2020).

These findings will be of use to DFO as it considers how to best support and enable freshwater fish habitat science within its organization and in collaboration with external partners. Much has changed in the world of freshwater habitat science since the 1950s as evidenced by our review, including declines in the number of studies led by DFO-affiliated authors. This decline may be the result of funding committed to long-term monitoring and fundamental research within DFO. However, this review has demonstrated a significant contribution from DFO-affiliated authors to peer-reviewed literature which supports the development of a robust evidence base needed to inform freshwater management and decision-making. There are further opportunities to refine and even redefine how science is conducted to ensure that the evidence base supporting fish habitat management in Canada is holistic (regionally, topically, taxonomically), carried out in a way that fosters collaboration and engagement with Indigenous communities, stakeholders, and rightsholders, and leverages opportunities for funding (e.g. NSERC, academic partnerships), and that produces findings which are shared in an open manner. Nonetheless, DFO should continue to feature prominently and take a leadership role in coordinating, guiding, and conducting freshwater fish habitat science.

Author Contributions

The initial idea for this study was developed by AW, KP and GB. Literature search was performed by DS, with initial review and validation of results by AW. Document review and data compilation was conducted by JT, TR, AS, MP, and SG. Data analysis and figure construction was performed by JT, TR, and RL. Manuscript writing was conducted by JT, TR, and SC, with support from AS, MP, CD, AW, KP, GB and DS.

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Appendix

APPENDIX 1. SEARCH STRATEGY

Primary Literature

Journal articles were retrieved using Web of Science (Science Citation Index Expanded, 1955-present). Due to the wide variety of terms that are potentially relevant to the subject, the approach taken was to retrieve a broad set of search results which would then be reviewed individually to select the articles that fall within the scope of interest. The majority of the retrieval and selection was performed between June and September 2018, but further searching was conducted periodically, ending in August 2019.

The results were primarily retrieved using a search string with three components: the name of the department ('Fisheries & Oceans Canada') in the Organization Enhanced index (since renamed the Affiliation index), to retrieve articles by authors affiliated with DFO and its predecessor organizations; a set of topical terms denoting freshwater environments; and a further set of topical terms related to habitat and associated subjects.

The final search string was as follows:

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OG=(Fisheries & Oceans Canada) AND TS=((freshwater* OR "fresh water" OR lake* OR lacustr* OR river* OR fluvial OR creek* OR stream* OR brook* OR pond* OR watershed*) AND (water* OR habitat* OR hydrolog* OR environment* OR ecosystem* OR productivity OR limnolog* OR "fish ladder*" OR fishway* OR culvert* OR "spawning area*" OR "spawning ground*" OR passage OR obstruction* OR diversion* OR barrier* OR impound* OR hydroelectric OR hydropower OR restoration OR improvement* OR turb*))
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Supplementary searches by author name were performed for DFO-affiliated authors of three or more relevant articles. The additional results retrieved by these searches were reviewed and selected according to relevance.

Web of Science was also used to perform supplementary searches in journals having a limited subject focus closely related to freshwater habitat. Results were retrieved using a combination of 'Fisheries & Oceans Canada' (in the Affiliation index) and each journal's name (in the Publication Name index, since renamed the Publication Titles index). Any relevant articles that had not already been discovered using the other search methods described above were selected. The journals searched in this way were as follows:

- Aquatic Conservation: Marine and Freshwater Ecosystems
- Australian Journal of Marine and Freshwater Research

- Ecology of Freshwater Fish
- Freshwater Biology
- Freshwater Science
- Journal of Freshwater Ecology
- Journal of Great Lakes Research
- Lake and Reservoir Management
- Marine and Freshwater Behaviour and Physiology
- Marine and Freshwater Research
- New Zealand Journal of Marine and Freshwater Research
- Regulated Rivers: Research & Management
- River Research and Applications

It is likely that there were additional relevant journal articles indexed in Web of Science that are not included in the final result set. The primary source of uncertainty was the wide variety of terms that are potentially relevant to this subject. In the process of developing the search string, some additional terms were considered for inclusion, but not included if they were found to significantly increase the number of irrelevant results. The inclusion of more topical terms in the search string may have resulted in a slightly larger final result set, but would have substantially increased the time involved in the review. Performing individual author searches for every DFO-affiliated researcher found to have authored a relevant article could also retrieve additional results. Again, the decision not to do this was due to the amount of time it would have added to the search process.

While DFO's subscription to Web of Science covered indexed content from 1955 on at the time the searches were performed, no articles published prior to 1974 were located during this search. Older records typically contain less descriptive metadata, and therefore there is less possibility of retrieving them using topical search terms. Locating earlier work in this area would involve further research using other sources, such as printed bibliographies.

Secondary Literature

Reports and other kinds of secondary documents were retrieved from the catalogue of the Federal Science Libraries Network using the Summon discovery tool embedded in DFO's internal library portal. Here again, the approach taken was to retrieve a broad set of potentially relevant search results, and review them manually to locate the documents that fall within the particular scope of the present project. A search string was developed gradually using an iterative process of addition/subtraction of terms and review of results.

In order to retrieve documents produced and/or issued by DFO and its subsidiaries, the names of these entities were queried in both the Publisher and AuthorCombined fields. Names of major departmental entities (such as research institutes) were included in the search string, as were previous names of the department (back to 1950). The addition of French-language equivalents of these names was tested in the main phase of the search process, and those that were found to retrieve additional documents were included in the search string.

The term 'freshwater' was the sole topical term included in the search, with the goal of retrieving all reports covering freshwater subjects. The DFO Library has a long-standing practice of using FAO's Aquatic Science and Fisheries Thesaurus for subject cataloguing, including its three 'environmental regime' categories, of which 'freshwater' is one. (This term appears as two words ['fresh water'] in a number of catalogue records, but Summon automatically retrieves this form as well.) Including this term was deemed to be the most reliable way of retrieving all potentially relevant results. The term was entered as a general keyword in the search string so that it would be found not only in the subject descriptor fields, but in any field (e.g. title, abstract, table of contents, etc.).

As initial results were reviewed, some substantial groups of out-of-scope documents were noticed in the result set. In order to exclude these, a number of additional terms were added to the search string using the Boolean operator NOT, as general keywords as well as in the TitleCombined and PublicationSeriesTitle fields. These were only added if the risk of excluding relevant results was deemed to be minimal.

The final search string was as follows:

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((((Publisher:("fisheries & oceans" OR "peches et oceans" OR "Ministère des Pêches et des Océans" OR DFO OR MPO OR "fisheries & marine service" OR "Service des peches et de la mer" OR "fisheries & the environment" OR "peches & environnement" OR "fisheries & forestry" OR "dept. of fisheries" OR "department of fisheries" OR "ministere des pecheries" OR "fisheries branch" OR "marine & fisheries" OR "Fisheries Research Board of Canada" OR "biological board of canada" OR "canadian science advisory secretariat" OR "Secrétariat canadien de consultation scientifique" OR "Canadian Stock Assessment Secretariat" OR CSAS OR SCCS OR CAFSAC OR "Canadian Atlantic Fisheries Scientific Advisory Committee" OR CSCPCA OR "Comite scientifique consultatif des peches canadiennes" OR "Bedford Institute of Oceanography" OR "Great Lakes Laboratory for Fisheries and Aquatic Sciences" OR "Great Lakes Biolimnology Laboratory" OR "Great Lakes Fisheries Research Branch" OR "Bayfield Institute" OR "Canada Centre for Inland Waters" OR CCIW OR "freshwater institute" OR "Institut des eaux douces" OR "andrews biological station" OR "Atlantic Biological Station" OR "Centre des pêches du Golfe" OR "Arctic Biological Station" OR "Institute of Ocean Sciences" OR "Pacific Biological Station" OR
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"Maurice Lamontagne Institute" OR "Institut Maurice-Lamontagne" OR "Northwest Atlantic Fisheries Centre" OR "Sea Lamprey Control Centre")) OR (AuthorCombined:("fisheries & oceans" OR "Ministère des Pêches et des Océans" OR DFO OR MPO OR "fisheries & marine service" OR "Service des peches et de la mer" OR "fisheries & the environment" OR "peches & environnement" OR "fisheries & forestry" OR "dept. of fisheries" OR "department of fisheries" OR "ministere des pecheries" OR "fisheries branch" OR "marine & fisheries" OR "Fisheries Research Board of Canada" OR "biological board of canada" OR "canadian science advisory secretariat" OR "Secrétariat canadien de consultation scientifique" OR "Canadian Stock Assessment Secretariat" OR CSAS OR SCCS OR CAFSAC OR "Canadian Atlantic Fisheries Scientific Advisory Committee" OR CSCPCA OR "Comite scientifique consultatif des peches canadiennes" OR "Bedford Institute of Oceanography" OR "Great Lakes Laboratory for Fisheries and Aquatic Sciences" OR "Great Lakes Biolimnology Laboratory" OR "Great Lakes Fisheries Research Branch" OR "Bayfield Institute" OR "Canada Centre for Inland Waters" OR CCIW OR "freshwater institute" OR "Institut des eaux douces" OR "andrews biological station" OR "Atlantic Biological Station" OR "Centre des pêches du Golfe" OR "Arctic Biological Station" OR "Institute of Ocean Sciences" OR "Pacific Biological Station" OR "Maurice Lamontagne Institute" OR "Institut Maurice-Lamontagne" OR "Northwest Atlantic Fisheries Centre" OR "Sea Lamprey Control Centre")) AND (freshwater NOT (Ireland OR Scotland OR "FISS report")) NOT ((TitleCombined:("annual report" OR proceedings OR "compte rendu" OR "fisheries management plan" OR "project funding agreement" OR "fisheries agreement" OR "allocation agreement" OR "working agreement" OR "recovery potential assessment" OR "Evaluation du potentiel de retablissement" OR "Recovery strategy" OR "Programme de retablissement" OR "contribution agreement" OR commercial OR exports OR invasive OR aquaculture OR virus OR market OR angler OR sport OR "fog signals")) OR (PublicationSeriesTitle:(Manitoba OR Alberta OR Ontario OR "Nova Scotia" OR Washington OR translation)))

The results were limited to the library catalogue, and to items published in 1950 and later. They were then sorted by date and reviewed. During the review, documents that matched all of the following criteria were selected:

- Within the subject scope of the project
- Authored, or including significant contributions, by employees of DFO.
- Published or co-published by DFO or one of its components, or treated as such in the catalogue record.

Documents consisting of meeting or workshop proceedings, as well as documents primarily focused on designation of protected areas or on species at risk issues (e.g., recovery potential assessments), were considered to be out of

scope. French-language reports were included, but only when a full English version was not available.

Where available, a digitized copy of each item was briefly consulted during review to confirm one or more of the criteria. Otherwise, the decision to include or exclude an item was made based on its catalogue record.

Although we are confident that a large majority of in-scope publications have been retrieved, there were a number of sources of uncertainty. Firstly, in-scope publications may have been missed during the process of manually reviewing more than 9000 search results, due to human error and/or misjudgment of relevance. When there was doubt as to whether or not a search result fell within the review criteria, it was included, since a further review and validation of the result set was conducted by departmental staff with subject expertise. Secondly, the main review of search results was conducted in the summer of 2018. The search was subsequently repeated (up to the end of August 2019) to locate any documents newly published in the time since the main review phase. If the review of results had been repeated in full, it would likely have yielded further relevant documents, as cataloguing of older publications and maintenance of catalogue records continued during the intervening time. Thirdly, it is likely that there are further names and variant names of DFO-associated entities that, had they been included in the search string, would have retrieved additional relevant results. A combination of factors – variation over time in cataloguing practices, the presence of typographical errors, and numerous name changes at both departmental and sub-departmental levels – makes it virtually impossible to be certain that all variants have been captured by a given set of search terms.

APPENDIX 2. EXTRACTED DATA FIELDS

Data Fields	Description
Citation	Formatted according to Instructions to Authors for the <i>Canadian Journal of Fisheries and Aquatic Sciences</i>
Title	As Written
Journal Title	As Written
Year	As Written
Volume	As Written
Issue	As Written
Pages	As Written
Document Type	Type of article (e.g., Primary publication, Thesis, Canadian Technical Report of Fisheries and Aquatic Sciences, Canadian Science Advisory Secretariat Research Document)
Open Access	Was literature behind a paywall at the time this review was conducted
Number of Citations	From Google Scholar
First Author Name	List first author for each row
Authors	List author name - Last Name, First and Middle Initial (e.g. Taylor, J.J.).
Author Affiliation	Institution/Organization (e.g., DFO, Carleton University, Canadian Wildlife Federation, BC Hydro).
Total number of authors	Number
Number of non-DFO authors	Number
Number of DFO authors	Number
First author DFO	Did the first author work for DFO at time of article publication
Sector(s) of Non-DFO authors	Sector (e.g., academia, industry, NGO)
Country of Non-DFO authors	Country
DFO Region(s) where DFO author(s) are based	The DFO Region(s) where DFO authors are based (e.g., Pacific, Newfoundland and Labrador)
Research Type	Type of article (e.g., primary, data set, commentary)
Study Type	How and where was the study conducted (e.g., field study, lab experiment, modelling)
Study Class	Only applies to field and lab studies (e.g., manipulative, non-manipulative)
Site Location	UTM location of site where research occurred
Site Name	Description used for research sites if applicable
Province/Territory	Where research sites were located or review was focused.

Lab or facility	Name of lab or facility where study occurred
DFO Facility	Name of DFO facility if applicable (e.g., Cultus Lake Salmon Research Lab, Miramichi River Science Field Station)
DFO Region(s) that is the Focus of the Research Environment	The DFO Region(s) where work occurred (e.g., Pacific, Newfoundland and Labrador) The focal location of the research (e.g., wetland, stream, littoral area of lake)
Research focus	The focus of the research being done (e.g., fish passage, species distribution). One research focus was attributed to the entire publication based on its core theme.
Study Duration	Time from research start to finish
Study Interrupted	Were there interruptions in the research at the YEAR level (not month)
Taxa	Focal taxa (e.g., fish, mammals, birds)
Focal Fish Family	Indicate at family level only for fish
Internal Funding Source	Funding provided by DFO as listed (e.g., Fraser River Action Plan, Strategic Science Fund)
External Funding Source	Funding provided by non-DFO sources as listed (e.g., NSERC, BC Hydro)
Comments	Comments related to funding source