Research priorities for the management of freshwater fish habitat in Canada

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Summary

Effective management of freshwater fish habitat is essential to supporting healthy aquatic ecosystems and sustainable fisheries. In Canada, recent changes to the *Fisheries Act* enhanced the protection of fish habitat, but application of those provisions relies on sound scientific evidence. We employed collaborative research prioritization methods to identify scientific research questions that, if addressed, would significantly advance the management of freshwater fish habitat in Canada. This list was generated by a diverse group of freshwater fish experts, including substantial contributions from practitioners who administer provisions of the *Fisheries Act*. The research questions generated in this study identify priority topics for future research, while highlighting issues that could be addressed with different funding models. As a result, this study should support evidence-based management of Canada's aquatic resources by identifying scientific knowledge gaps faced by practitioners, and suggesting mechanisms to address them. Given the important contribution of Canadian freshwater systems to global ecosystem values, and the similar scientific challenges facing fish habitat managers in other jurisdictions, this study is likely to have broad applicability.

Keywords: horizon scan, environmental management, aquatic ecosystem

Introduction

Freshwater ecosystems support a disproportionately high amount of biodiversity (Balian et al. 2008) and provide a broad suite of economic, environmental, cultural, and spiritual value to human populations (Millenium Ecosystem Assessment 2005). Among these benefits, freshwater fisheries support important commercial and recreational industries, and are a major contributor to food security for many human communities (Welcomme et al. 2010; Lynch et al. 2016). Healthy and productive freshwater fish populations are built on a foundation of high quality freshwater habitat that supports access to feeding and reproductive sites, shelter from predators and adverse environmental conditions, and connectivity between locations as required by fish life histories (Lapointe et al. 2014). The conservation and effective management of freshwater habitat is therefore key to supporting freshwater fisheries and protecting the diverse benefits that freshwater ecosystems provide.

Canada has one of the largest and most diverse portfolios of freshwater habitat in the world containing 26% of the Earth's surface fresh water and 60% of the Earth's fresh water lakes (Messager et al. 2016). Because of the high ecological value of freshwater ecosystems, and the vast assortment of freshwater systems in Canada, Canadian freshwater habitat management can have a strong impact on global ecosystem values and international conservation goals (Coristine et al. 2019). However, much of the freshwater habitat in Canada has been impacted by the direct and indirect consequences of human activities (e.g. Bradford and Irvine 2000; Chu et al. 2014; Maitland et al. 2016). For example, an estimated 98% of Canadian wetlands near urban centers have been lost or degraded (Federal Provincial and Territorial Governments of Canada 2010), and there are over 8400 dams contributing to habitat fragmentation in the province of Quebec alone (MELCC 2020). Correspondingly, freshwater fishes are one of the most imperiled species groups in Canada (Rainer et al. 2017).

Recognizing the important link between habitat and freshwater fisheries, many jurisdictions have legislative and regulatory frameworks to support the protection of freshwater fish habitat. In Canada, the Fish and Fish Habitat Protection Provisions of the *Fisheries Act* are one of the primary authorities used to manage the impacts of human activities on freshwater fish habitat. With findings that authorized impacts were not being sufficiently compensated to prevent the net loss of fish habitat (Quigley and Harper 2006; Quigley et al. 2006; Office of the Auditor General 2009; Favaro and Olszynski 2017) amendments were made to the *Fisheries Act,* 2019 that sought to modernize the Fish and Fish Habitat Protection Provisions. This included prohibitions against causing the death of fish or the harmful alteration, disruption or destruction of fish habitat, as well as the inclusion of a framework of considerations to guide decision making functions (DFO 2019). To implement evidence-based decision making in relation to these changes to the *Fisheries Act*, habitat managers require the availability of sound science related to the impacts of human activities on aquatic ecosystems and how these impacts could be managed.

Science, in the form of empirical and modelling studies, evidence syntheses, science advice, decision support tools, and data products, not only directly informs the day-to-day decisions of habitat practitioners, but also contributes to the development of effective legislation and policy and the *post-hoc* evaluation of policies and decisions. As such, scientific information and advice is an important component of freshwater fish habitat protection in Canada (e.g. Rice et al. 2015). Yet, despite broad awareness of the importance of science for the effective management of freshwater systems, identifying specific research that would best support resource managers remains a challenge. In part, this challenge stems from identifying the specific needs of practitioners, and framing them as testable scientific research questions (O'Connell and White 2017). In addition, prioritization of scientific research must balance the diverse informational needs of science users with the costs, challenges and timeliness of science delivery (Cvitanovic et al. 2013).

Fortunately, several global and regional initiatives are bringing together researchers, science users, and other stakeholders to prioritize scientific research via a formal iterative process that encourages collaboration and open discussion (e.g. Sutherland et al. 2009, 2013; Fleishman et al. 2011; Rudd et al. 2011). These 'collaborative research prioritization' approaches rely on an inclusive, transparent, and democratic framework for consensus building (Sutherland et al. 2011), and have been used to prioritize research in a variety of fields related to applied environmental management (reviewed in Dey et al. 2020).

In this study, we used collaborative research prioritization methods to co-produce (Cooke et al. 2020) a list of research questions that, if answered, would best support effective management of freshwater fish habitat in Canada. This list was generated by a diverse group of experts in Canadian fish habitat research, management, and policy. Included in this group was a large contingent from Fisheries and Oceans Canada's (DFO's) Fish and Fish Habitat Protection Program (FFHPP), who administer the Fish and Fish Habitat Protection Provisions of Canada's

Fisheries Act and several other relevant authorities related to Canadian freshwater fish habitat conservation and protection (e.g. *Species at Risk Act,* the *Aquatic Invasive Species Regulations,* aquaculture regulations, impact assessment legislation).

Candidate research questions were identified through an extensive literature search and a widely distributed expert survey. These questions were further refined and assessed through an online Delphi process (Mukherjee et al. 2015) to create the final list of priority research questions presented here. In addition to identifying questions that would best support habitat management, the project team also estimated the amount of scientific resources (i.e. human and financial resources, and time requirements) needed to answer each question, and the amount of scientific knowledge already available. These additional considerations were made to support researchers and science planners in selecting appropriate approaches to answering each question, and to help triage research questions when funding is limited.

Methods

Our study broadly follows collaborative research prioritization methods described elsewhere (e.g. Fleishman et al. 2011; Sutherland et al. 2011; Varma et al. 2015; Greggor et al. 2016) and reviewed by Dey et al. (2020). These methods are characterized by four main steps: *i)* solicitation of a large pool of candidate research topics, *ii)* processing and collating of candidate topics to prepare for prioritization, *iii)* democratic ranking or scoring of candidate research questions, and *iv)* dissemination of priority research questions in a list. Below, we briefly describe the method used for each of these steps in this study. For interested readers, complete methodological details can be found in Dey et al. (2021).

1. Building a pool of knowledge gaps

Knowledge gaps related to freshwater fish habitat science were gathered through a literature search and an expert survey. Documents likely to identify knowledge gaps related to Canadian freshwater fish habitat science were identified through searches of the Federal Science Library, and through recommendations by the project's steering committee. These documents were all published between 1986 (the date of publication of DFO's Policy for the Management of Fish Habitat;(DFO 1986)) and 2019, and included primary and grey literature publications (e.g. documents published by DFO's Canadian Science Advisory Secretariat). We reviewed full text versions of 262 documents, and 1045 knowledge gaps identified in the corpus were extracted to a database. Full details related to the literature review are available in Dey et al. (2021).

We also solicited scientific knowledge gaps from experts in research, policy, and management related to Canadian freshwater fish habitat using an online survey that was open from October 11th, 2019 to January 10th, 2020 (13 weeks). Invitations to complete the survey were distributed to DFO staff through departmental mailing lists, as well as to external experts identified by the project steering committee (including academics, non-governmental organizations, and staff of other government agencies) through email. One hundred and twelve respondents anonymously identified 858 scientific knowledge gaps they had encountered in their professional activities through open-ended questions (e.g. *"In your professional experience, what knowledge gaps are currently hindering the development of effective policies and management strategies for freshwater fish habitat in Canada?")* and in response to prompts related to broad areas of freshwater fish habitat science (e.g. "*Are you aware of any knowledge gaps related to stressors to fish habitat that should be priorities for future research to improve policy and management of freshwater fish habitat?"*). The survey design was reviewed and approved by the Lakehead University Research Ethics Board (permit #1467329). Together, 1903 knowledge gaps were identified through the literature review and expert survey (Figure 1).

2. Processing and Collating the Initial Pool of Knowledge Gaps

We refined the initial pool of knowledge gaps by combining conceptually similar knowledge gaps, and rephrasing knowledge gaps into research questions. To complete this procedure, we used a two-step approach that relied on computer-based natural language processing and expert judgement from human observers. First, we used the *quanteda* package (Benoit et al. 2018) in *R* (R Core Team 2019) to calculate pairwise similarity scores (ranging from 0 to 1) for all pairs of knowledge gaps using cosine text similarity (Gomma and Fahmy 2013). Next, we used walktrap clustering (Pons and Latapy 2006) implemented in the *igraph* package (Csardi and Nepusz 2006) to identify sets of similar knowledge gaps, and had an expert observer (CJD) decide whether those sets of knowledge gaps (or subsets thereof) were sufficiently similar to be combined. We conducted this process iteratively with new knowledge gaps (resulting from the combination of conceptually similar knowledge gaps) being fed back into the process. This process continued until there were 1000 knowledge gaps remaining in the pool.

Next, we sorted the 1000 remaining knowledge gaps into groups based on keyword matching, and manually combined similar knowledge gaps within and across keyword groups. During this step, knowledge gaps that were unrelated to freshwater fish habitat (e.g. some were specific to marine environments), or deemed too broad (e.g., some survey responses were limited to entire research fields such as 'invasive species') were removed from the pool. Finally, the retained knowledge gaps were rephrased as research questions, and assigned to one of ten research theme areas. This process resulted in the creation of a pool of 334 research questions that collectively represented the range of knowledge gaps identified from the literature review and expert survey (see Rego et al. 2021a, 2021b for the complete list).

3. Identifying priority research questions

The 334 research questions served as a starting point for an online Delphi process aimed at identifying priority research questions. Delphi processes are characterized by iterative and anonymous participation by a group of experts that aim to arrive at a consensus (Mukherjee et al. 2015). Our Delphi process included three steps: 1) An initial scoring step, in which each participant scored a subset of the initial list of 334 research questions (mean of 7.8 responses per question, total of 60 individuals completed this step). These scores were used to narrow the scope of the remaining steps of the process by eliminating research questions that were deemed less important to fish habitat management in Canada. 2) A feedback step, in which the remaining 93 research questions were grouped into 10 themes and participants reviewed the initial scores given to each research question while being invited to provide written comments related to those scores. Participants were invited to comment both on the scores themselves (e.g., if they thought the group had rated a question as more or less important than it ought to be) or on the question text (e.g. if they thought the research question could be improved by small textual changes). Fifty four individuals completed this step. 3) A final scoring step, in which participants reviewed the comments of their peers and selected their final scores for the remaining research questions. Forty eight individuals completed this step.

During the initial and final scoring steps (1 and 3), participants were asked to score each question based on its importance to freshwater fish habitat management in Canada (six point Likert scale, ranging from 'very unimportant' to 'very important'), with the highest scores being reserved for questions that, if answered, would have transformative impacts on freshwater fish habitat management in Canada. In addition, participants scored questions based on the amount of scientific resources they thought would be required to answer the question (four point Likert scale, ranging from 'very low' to 'very high') and the extent of existing scientific knowledge related to the research question (four point Likert scale, ranging from 'very limited' to 'well known'). These additional metrics were included to help inform researchers, funders, and science planners of the likely costs and best approach to addressing each research question.

4. Data Availability

Data collected through this project are available in English and French in Rego et al. (2021). Additionally, an interactive web application (available in English and French) shows the 93 most important research questions identified through this project, and the final scoring data related to those questions.

Findings

Demographics of participants

Sixty-nine individuals participated in at least one stage of the process to identify priority research questions (Figure 2A), with 57% of these participants completing all three steps (initial scoring, feedback step, and final scoring). Participants were predominantly members of FFHPP (n = 24), researchers employed by DFO (n = 21), and researchers affiliated with Canadian universities or provincial agencies (n = 18). In addition, a group of external practitioners (n = 6), representing Canadian non-governmental organizations, conservation authorities, and other science-based federal departments contributed to the process. The majority of participants had more than 10 years of experience working on freshwater fish habitat issues (Figure 2B).

The top ten most important research questions for freshwater fish habitat management

We used the data collected during the final scoring step to assign ranks related to a question's perceived importance. First, we converted Likert scales to numeric values (very low = 0, very high = 5) and calculated mean importance scores based on the scores from researchers and practitioners separately. Then, we ranked questions based on equal weighting of the responses from researchers and practitioners, based on practitioner responses alone, and based on researcher responses alone (Table 1). Importance scores for all 93 priority research questions, and other data associated with this publication, can be downloaded from our interactive web application created using the *Shiny* package (Chang et al. 2020) in R (R Core Team 2019).

Table 1. The ten most important research questions for freshwater fish habitat management. Shown are the ranks of each question, with rank 1 indicating the most important question. Ranks are based on the responses of practitioner and researchers alone, or based on equal weighting of the responses of practitioners and researchers. In the case of a tie, similar ranks are shown for each question. Working definitions for ambiguous terms were provided to participants and are shown in the footer. An interactive table which includes all 93 priority research questions can be found at https://qecology-dfo.shinyapps.io/ShinyPrioritization.

	Equal weighting	Practitioners only	Researchers only
When do cumulative impacts on a system lead to tipping points (thresholds) in ecosystem health?	1	1	1
When, how, and over what scale, should management decisions consider cumulative effects?	2	2	1
How effective are common habitat restoration practices for achieving their intended outcomes?	3	4	3
What are the impacts of specific types of works, undertakings and activities on fish habitat?	4	3	9
How effective are different habitat offsetting methods in achieving their intended outcomes?	5	7	5
Can we define thresholds for habitat modification below which the effects on fish productivity are minimal?	6	6	10
How do the cumulative effects of catchment modification impact habitat quality?	7	9	13
How effective are common avoidance and mitigation measures used in freshwater habitat management?	8	14	8
What are the best metrics for quantifying the impact of stressors on fish habitat?	9	13	10
What are the impacts of different types of land use change on freshwater habitat?	10	8	16

Working definitions for ambiguous terms found in the 93 research questions

Productivity – the rate of generation of biomass in an ecosystem, typically in reference to the generation of fish biomass.

Habitat quality – a measures of the intactness, health and productive potential of a habitat, independent of the quantity (i.e. area / volume) of habitat.

Works, undertakings, and activities – projects in or near water that may affect fish or fish habitat

Offsetting – measures used to counterbalance the residual impacts of works, undertakings or activities, for example by the creation of new habitat, or the restoration and enhancement of existing habitat

Standards and Codes of Practice – procedures for avoiding the death of fish or the harmful alteration, disruption or destruction of fish habitat during common works, undertakings and activities

Overall, practitioners and researchers showed broad agreement on the importance of research questions, with a strong correlation between the ranks assigned by each group of respondents (Spearman rank correlation, Rho = 0.66, 95% CI = (0.53, 0.79), n = 93). Both groups of respondents considered the question *"When do cumulative impacts on a system lead to tipping points (thresholds) in ecosystem health?"* as the most important research question, with research questions related to habitat management effectiveness and stressors to fish habitat also being scored high by both groups (Table 1).

What are the most important research questions in each research theme?

Prior to the feedback step (step 2) of the prioritization process, we grouped research questions into ten themes to improve the efficiency of discussion on similar research questions. Below, we describe the link between each of the ten research themes and the management of freshwater fish habitat in Canada, and present the three most important research questions for each research theme (based on equal weighting of practitioner and researcher responses) followed by its overall ranking in brackets. Numeric values following each question indicate the question's overall rank out of all 93 priority research questions (based on equal weighting between practitioner and researcher responses).

Multiple stressors and cumulative effects

A growing body of literature suggests that ecosystems may not show linear responses to combinations of stressors, with many natural systems being impacted by multiple anthropogenic stressors acting over different temporal and spatial scales, on different species, or through different mechanisms (Côté et al. 2016; Hodgson and Halpern 2019). Moreover, the way in which stressors interact can influence the effectiveness of management measures (Brown et al. 2013). In response, Canada's *Fisheries Act* now requires considerations of "the cumulative effects of the carrying on of the work, undertaking or activity … in combination with other works, undertakings or activities that have been or are being carried out, on fish and fish habitat" (section 34.1 (1) (d)) during various decision-making processes. Research on multiple stressors and cumulative effects aims to reduce uncertainty around ecosystem responses, and to provide tools for decision-making in the face of limited data related to multiple stressors. The highest ranked research questions in this theme include:

- When do cumulative impacts on a system lead to tipping points (thresholds) in ecosystem health? (1)
- When, how, and over what scale, should management decisions consider cumulative effects? (2)
- How do the cumulative effects of catchment modification impact habitat quality? (7)

Habitat management effectiveness

Understanding if fish habitat management actions produce their intended outcomes is important for the protection and conservation of fish habitat. Despite concerns that many previous fish habitat compensation or offsetting projects have resulted in net losses of fish habitat (Quigley and Harper 2006; Favaro and Olszynski 2017), there are surprisingly few evaluations of the effectiveness of management measures such as mitigation, restoration, or offsetting (Theis et al. 2020). Research in this theme could help practitioners understand the uncertainty associated with the expected and intended outcomes of different management actions, thereby supporting the achievement of habitat management goals. Highly ranked research questions in this theme include:

- How effective are common habitat restoration practices for achieving their intended outcomes? (3)
- How effective are different habitat offsetting methods in achieving their intended outcomes? (5)
- How effective are common avoidance and mitigation measures used in freshwater habitat management? (8)

Stressors to fish habitat

Understanding the impacts of human activities and natural stressors on freshwater fish habitat is key to managing those impacts and protecting ecosystem health. Research in this domain provides evidence to habitat managers about the specific consequences of human activities on fish and fish habitat (e.g. Gray et al. 2012; Cox et al. 2018), including their likelihood of causing the death of fish by means other than fishing (e.g. prohibited under *Fisheries Act* subsection 34.4 (1)) and the harmful alteration, disruption or destruction of fish habitat (e.g. prohibited under *Fisheries Act* subsection 35(1)). This information can then be incorporated into management decisions designed to manage risk associated with certain types of projects, and to help set criteria for monitoring programs designed to evaluate the impact of projects on fish and fish habitat. Highly ranked questions in this theme include:

- What are the impacts of specific types of works, undertakings and activities on fish habitat? (4)
- What are the best metrics for quantifying the impact of stressors on fish habitat? (9)
- What are the impacts of different types of land use change on freshwater habitat? (10)

Habitat, population dynamics, and community structure

The quality and quantity of aquatic habitat has important impacts on fish productivity, population dynamics, and the structure and function of aquatic communities. Understanding the specific mechanisms by which habitat components affect the vital rates of fish populations is important for determining the likely response of those populations to changes in habitat (Hayes et al. 2009). In addition, understanding the links between species interactions (e.g. predator-prey dynamics, competition) and habitat will inform assessments of the sensitivity or resilience of aquatic ecosystems (Downing and Leibold 2010). Highly ranked questions in this theme include:

- Can we define thresholds for habitat modification below which the effects on fish productivity are minimal? (6)
- What are the mechanisms by which habitat changes impact fish populations? (15)
- How does the quantity and quality of habitat relate to fish productivity? (28)

Habitat monitoring

Data from habitat monitoring programs is crucial for understanding the health of ecosystems, the impacts of human activities, the effectiveness of management actions, and the performance of policies and regulations. Scientific research can support the design of habitat monitoring programs that make efficient use of limited resources, while providing essential information for decision-making and evaluation (Nichols and Williams 2006; McDonald-Madden et al. 2010). In addition, scientific research can develop new technologies that improve the collection and management of habitat data. Highly ranked questions in this theme include:

- What monitoring methods are effective for very large projects? (20)
- How long should monitoring programs be conducted to ensure that projects met their intended outcomes? (22)
- How can we standardize monitoring to better understand the performance of different management measures? (26)

Flow, fish passage and habitat connectivity

Flow is considered a master variable driving the structure and function of fluvial ecosystems, and altering the natural flow regime can have a range of effects on ecosystem processes and habitat needs of biota (Poff 2018). The alteration of flow regimes, connectivity among aquatic habitats, and the ability of fish to pass anthropogenic and natural obstructions in waterways is a consequence of many human activities within watersheds (Nilsson et al. 2005; Liermann et al. 2012). When habitat connectivity is disrupted, aquatic species and their resources cannot move among habitats, which can alter nutrient and energy cycles, block access to feeding or reproductive sites, or prevent gene flow required for adaptation. Conversely, restoring connectivity can be associated with trade-offs between management objectives (e.g., native species restoration versus non-native species control; McLaughlin et al. 2013). Scientific information can contribute to advice on the effects of flow management on aquatic ecosystems, how barriers impact fish and fish habitats, and how both structural and functional connectivity can be maintained between habitats in the face of human disturbances. Highly ranked questions in this theme include:

- How does hydrological connectivity impact the quality of freshwater habitats? (19)
- How do flow regimes impact freshwater habitat? (23)
- How can flow management be designed with whole aquatic ecosystems in mind? (33)

Habitat classification

The characterization and classification of aquatic habitat provides a basis for the protection of sensitive, highly productive, rare or unique habitats through the designation of ecologically significant areas (*Fisheries Act* section 34.4(2)(g) and 35(2)(g)). In addition, research on habitat classification supports decision-making surrounding habitat offsetting programs (e.g. in understanding when compensations are equivalent), and the spatial aspects of habitat stressors. Scientific research related to the variation in physical and biological habitat components, or in structure and function of ecosystems, can help to define habitat patches and inform area based management decisions (Minns and Wichert 2005). Highly ranked questions in this theme include:

- What are the best metrics for quantifying habitat quality? (11)
- What are the priority habitat types for restoration and offsetting? (16)
- What are the desired attributes of new protected areas? (50)

Climate impacts on habitat

Climate change is influencing the quality, quantity and distribution of freshwater habitat in Canada by altering precipitation patterns, changing seasonal phenology, shifting thermal profiles in aquatic systems, and facilitating range shifts for native and invasive species (Poesch et al. 2016; Myers et al. 2017). These changes are likely to impact the success of habitat management measures, interpretation of habitat monitoring data, and contribute towards cumulative effects in many aquatic systems. Highly ranked questions in this theme include:

- How will climate change impact water temperature, water supply, and water quality in Canadian freshwater systems? (14)
- How should climate change be considered during offsetting and restoration projects? (32)
- How will climate change impact productivity of freshwater fish habitats? (34)

Habitat use

Understanding how fishes use aquatic habitat is key to understanding which species may be exposed to risk from various stressors, when they may be exposed (e.g. for migratory species), and the mechanisms that mediate how habitat changes impact populations and communities (Minns 2001). Information on occupancy and abundance of different fish species in different habitat types can help inform practitioners as to how changes in specific habitat components will impact fish populations, and whether harms are specific to certain life-stages (e.g. if only young or old fish will be impacted). Highly ranked questions in this theme include:

- What are the habitat requirements for different life stages of freshwater species? (13)
- What is the availability, distribution, and quality of habitat for a given species? (29)
- What are the features of good and sub-optimal spawning habitats for freshwater fishes? (39)

Other habitat issues

The remaining research questions did not fit into one of the nine research themes above, and were grouped into a final ‘other’ category. Many of these questions focused on issues surrounding the transfer of scientific knowledge into guidelines and decision-support tools for practitioners. Highly ranked questions in this theme include:

- What are appropriate targets or benchmarks that can be used to guide habitat management? (27)
- What types of management tools need be developed to integrate scientific information with policies? (31)
- How can the results of focused scientific studies be scaled-up to inform decision making at larger scales? (35)

The costs and context for priority research questions

In addition to data on the perceived importance of each research question, we also collected expert opinion on the amount of scientific resources required to answer each research question (i.e. the financial, human resources, and time costs), and on the amount of scientific information that is already available for each research question. Most previous collaborative research prioritization studies have not considered these important elements of context (but see Cvitanovic et al. 2013; McWhinnie et al. 2017), which may have hindered progress on addressing previously identified research priorities (Rees et al. 2016; Jucker et al. 2018; Dey et al. 2020) .

We found that there was a moderate positive correlation between the amount of scientific resources required to answer a question and the question's importance to freshwater fish habitat management in Canada (Figure 3; Spearman rank correlation, Rho = 0.34, 95% CI = (0.16, 0.52)). Questions that were considered to be very important to freshwater fish habitat management were generally thought to require more scientific resources. This pattern could be due to an underlying relationship with the scope of the question since broadly formulated questions are likely to be more important to management and more costly to answer. Additionally, we found a weak negative correlation between the amount of existing knowledge related to a question and a question's importance (Rho = -0.22, 95% CI = (-0.43, -0.02)), suggesting that the most important research questions have a smaller background of existing knowledge. Taken together, these results suggest a challenge to answering the most important research questions, in that these questions tend to be relatively costly and have limited existing knowledge on which to draw. Yet, despite these general trends, there was considerable variance in resource requirements and the amount of existing knowledge across the range of importance scores. As a result, it should be possible to identify questions that meet desired combinations of various criteria (e.g. high importance, high existing knowledge, low cost) and could serve as low-hanging fruit for future research.

Approaches for addressing priority research questions

If the authors of collaborative research prioritization studies are to convince scientific funders to support research on the identified priorities, it would be beneficial to identify what approaches would most effectively distribute limited research funds while also addressing the identified priorities. Below, we use data on the importance, resource requirements (costs), and amount of existing knowledge, to suggest different funding models that could address the identified priority questions. We categorized each research question as having a 'higher' or 'lower' score for importance, costs, and existing knowledge based on whether the mean score provided by participants for a given question was above or below the median score across all 93 priority research questions. Then, the project's steering committee identified potential mechanisms that could be used to support research on questions with different combinations of importance, costs and, existing knowledge (Table 2) .

For example, some research questions may be highly important to management and may already have a large body of relevant scientific knowledge. In such a case, funding that supports evidence syntheses, science advice products, or the development of decision-support tools (Smokorowski and Pratt 2007; Copp 2013), might support effective ecosystem management with relatively low costs to funders. Conversely important research questions that would require high amounts of scientific resources may be best addressed by the formation of research networks, with collaboration across different institutions and funding from multiple sources (e.g. Aquatic Habitat Canada, Canadian Freshwater Species at Risk Research Network). In Table 2, we also display some examples of questions that could be addressed through different funding approaches, but note that our interactive Web Application provides further tools for identifying research questions that meet different criteria.

Table 2. Suggested approaches for addressing priority research questions depending on their importance to freshwater fish habitat management, amount of existing knowledge, and scientific resource requirements (costs). N refers to the number of questions that fall into each of these categories, with higher/lower values for each metric being defined by scores above or below the median value for that metric. Empty cells indicate that any value for the specific metric would be consistent with the suggested approach.

Importance	Costs	Knowledge	Approaches	Examples	N
Higher		Higher	Evidence syntheses, science advice products and decision support tools	How can we standardize monitoring to better understand the performance of different management measures? What are the priority habitat types for restoration and offsetting?	17
Higher	Higher	Lower	Research networks and long term collaboration	What are the impacts of specific types of works, undertakings and activities on fish habitat? How do the cumulative effects of catchment modification impact habitat quality?	22
Higher	Lower	Lower	Targeted projects over shorter time lines	What, if any, are the residual habitat impacts from works, undertakings and activities that follow DFO's Standards and Codes of Practice? What is the likelihood of death of fish from different types of work, undertakings or activities in freshwater?	8
Lower			As value-added projects that piggy-back on higher priority research	What are the anthropogenic barriers to movement in freshwater systems for each species and life stage? How do fish communities and fish habitats naturally change over time?	46

Synthesis

Effective policy and management of freshwater fish habitat relies on a strong base of scientific evidence for sound decision-making. In this study, Canadian freshwater fish habitat experts collaborated to produce a list of research questions that, if answered, would improve freshwater fish habitat management in Canada. Research questions related to cumulative effects, to the impacts of single stressors on fish habitat, and to the effectiveness of habitat management were considered highly important to freshwater fish habitat management in Canada. Some of these priorities are likely related to changes included in the 2019 *Fisheries Act.* In these cases, the specific research questions identified herein should provide a clear path to produce the evidence required for sound decision-making under the new legislation. However, this study also highlights some long-standing research questions that require more attention. For example, the need for more evidence on the effectiveness of habitat restoration and offsetting measures was identified over 40 years ago (Horak and Olson 1980; Roni et al. 2008; Tischew et al. 2010), and while the impacts of individual stressors on aquatic ecosystems has received significant research efforts (e.g. DFO 2014; Hunsicker et al. 2016) there is still important knowledge gaps to address.

Similar methods have been previously used to identify topics of importance to Canadian resource management. Indeed, one of the first collaborative research prioritization studies published was the prioritization of research for Canadian conservation policy and management by Rudd et al. (2011). More recently, Pérez-Jvostov et al. (2020) conducted a horizon scanning exercise to explore emerging threats and opportunities for Canadian inland waters, and identified research and policy options for helping to address these issues. These publications identify some common research priorities to the current study, which we interpret as evidence for common challenges that cut across Canadian resource management issues. For example, Pérez-Jvostov et al. (2020) identified 'the dynamics of state changes caused by multiple stressors' as a priority issue, which is conceptually similar to the current study's finding that research on cumulative effects was considered highly important. Similarly, developing technologies to remotely monitor and assess freshwater habitat (identified as a priority in the current study), would also support an understanding of the expansion of land and water use in northern Canada, another emerging issue identified by Pérez-Jvostov et al. (2020). Recently, the Government of Canada began consultations on a new Canada Water Agency (Government of Canada 2020), which could provide national leadership in addressing these types of cross-cutting freshwater issues, including supporting or coordinating research on priorities that are common to different management concerns.

As part of the management-focused approach to research prioritization taken in our study, we involved a large group of freshwater fish habitat practitioners (managers and policy experts). Interestingly, our methods resulted in broad consensus among researchers and practitioners regarding the importance of individual research questions. Indeed, the research question that received the highest importance scores ("*When do cumulative impacts on a system lead to tipping points (thresholds) in ecosystem health?"*) was considered 'very important' by 100% of practitioners and 83% of researchers, suggesting consensus both among and within groups of participants. This finding is similar to results from the collaborative research prioritization of US resource management issues which also found that there was no clear divide in the research priorities of researchers and practitioners (Rudd and Fleishman 2014). Only seven research questions had a difference in importance score of more than 0.5 points (1/2 of a step on the Likert scale) between researchers and practitioners. Of the questions that researchers thought were more important than practitioners, two referred to the mechanism by which habitat changes impact freshwater ecosystems (*What are the mechanisms by which habitat changes impact fish populations? What are the mechanisms by which different stressors interact to influence fish or fish habitat?*) perhaps suggesting a divide in opinion on the importance of mechanistic (i.e. why certain patterns occur) versus phenomenological (i.e. what the patterns are) comprehension of habitat responses. Supporting this idea, several research questions with a phenomenological focus were among the questions scored more highly by practitioners (e.g. *What are the population dynamics of fishes in artificial habitats such as municipal drains and hydropower reservoirs?*).

In addition, some of the heterogeneity in responses among participants of both groups could have been due to differences in the importance of topics across different regions of Canada. Our study included research and practitioner participants from across Canada, and it is likely that the scores provided by participants differed according to the issues that are most prominent in their regions. For example, climate change impacts on freshwater habitat may have been scored as a more important topic for those with greater experience working in Canada’s north (where temperature increases have been more profound; Previdi et al. 2020), while multiple stressors may have been considered more important by those working in southern areas with a higher density of human activity, despite participants being instructed to consider the national importance of each issue.

The Canadian federal government is one of the primary jurisdictions involved in managing freshwater fish habitat in Canada, and one of the primary motivators for our study was the changes to Canada’s *Fisheries Act, 2019*. For this reason, we involved a large contingent of researchers and practitioners from DFO, who would be well positioned to identify research priorities related to this legislation. However, we acknowledge that other organizations, such as provincial, territorial and municipal governments, Indigenous peoples, and proponents of works, undertakings, and activities near water, also play an important role in protecting Canada’s aquatic resources (DFO 2019). Research priorities (and their relative importance) for freshwater fish habitat management identified by other organizations could differ from those outlined in the current study. However, we suggest that addressing the research priorities identified in the current study would benefit a range of organizations, because many jurisdictions are dealing with common threats (e.g. climate change, fragmentation, invasive species, etc; Dudgeon et al. 2006; Reid et al. 2019).

Similarly, we suggest that many of the research questions identified as priorities in the current study will also be highly relevant to aquatic habitat management in other countries (especially other temperate countries), because habitat practitioners rely on a global body of scientific evidence. As such, scientific gaps hindering management of Canada's freshwater fish habitat are also likely to hinder the application of programs such as the United States' Essential Fish Habitat Program (under the *Sustainable Fisheries Act*) or the European Union's Water Framework Directive. Additionally, given the important role of Canadian freshwater habitat management in meeting global biodiversity goals (Coristine et al. 2019) it is likely that the important research questions identified herein may have importance well beyond the initial scope of our project.

Author contributions

The idea for this study was formulated by Marten Koops, Jon Midwood, and Amanda Winegardner. Work planning and logistical support for the project was provided by a steering committee consisting of Cody Dey, Marten Koops, Jon Midwood, Amanda Winegardner, Alex de Paiva, Lisa Robichaud, Karin Ponader, Katherine McKercher, Michael Bradford, Keith Clarke, and Neil Mochnacz. Data collection and analysis was primarily conducted by Cody Dey and Adam Rego, with support from those listed above. Other co-authors participated in the research prioritization process. All authors contributed to writing and revising the manuscript.

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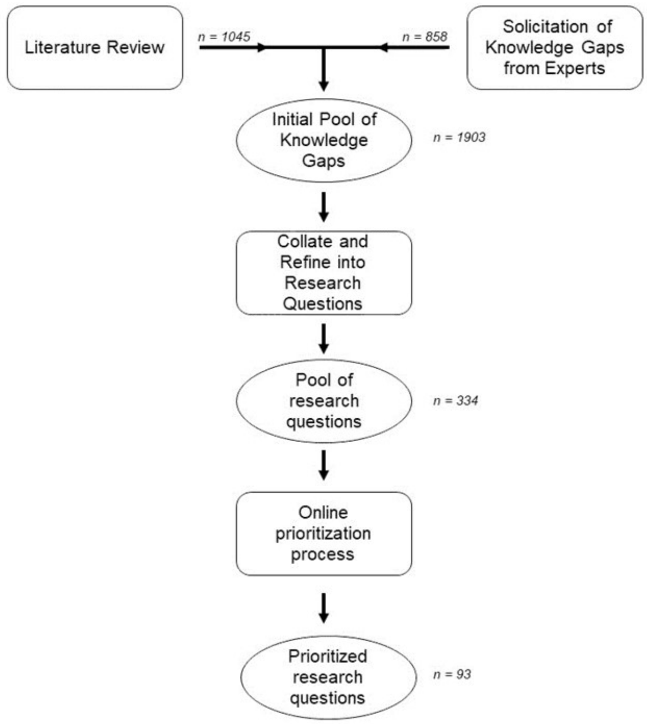

Figure 1. Outline of the project workflow. Numeric values in grey indicate the number of knowledge gaps or research questions considered in each step of the process.

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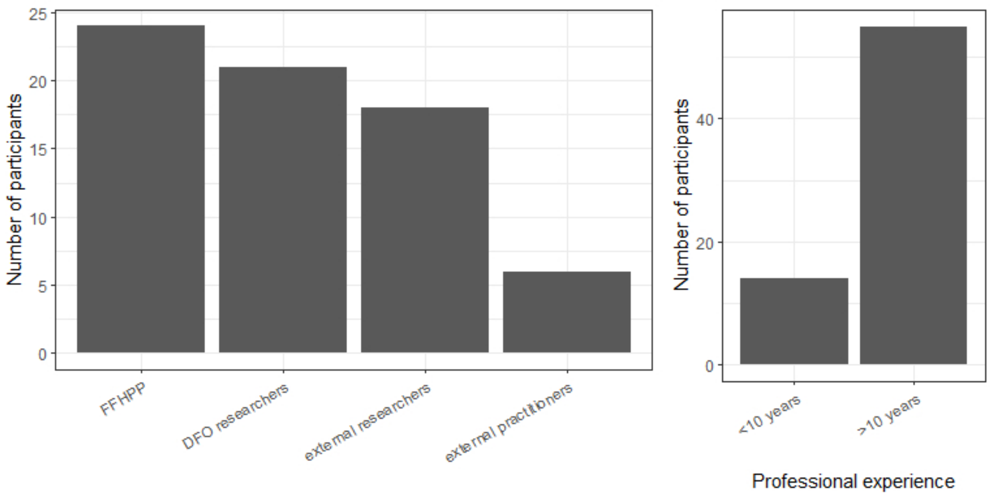

Figure 2. Professional affiliations (left) and professional experience in the field of freshwater fish habitat, for the participants involved in prioritization of freshwater fish habitat research questions (n = 69). FFHPP indicates the Fish and Fish Habitat Protection Program, while DFO indicates Fisheries and Oceans Canada.

Figure 3. The relationship between the amount of scientific resources required (i.e. the costs, left panel), the amount of existing scientific knowledge (right panel), and the importance to freshwater fish habitat management in Canada, for each of 93 priority research questions. For each question we plotted the mean score based on equal weighting of the responses from researchers and practitioners.