Canadian Science Publishing

PERSPECTIVE

The alarming state of freshwater biodiversity in Canada

Jessica E. Desforges, Julia Clarke, Evaline J. Harmsen, Alex M. Jardine, Jessica A. Robichaud, Serina Serré, Prosanta Chakrabarty, Joseph R. Bennett, Dalal E.L. Hanna, John P. Smol, Trina Rytwinski, Jessica J. Taylor, André L. Martel, Amanda K. Winegardner, Jerome Marty, Mark K. Taylor, Constance M. O'Connor, Stacey A. Robinson, Andrea J. Reid, Irena F. Creed, Irene Gregory-Eaves, Nicolas W.R. Lapointe, and Steven J. Cooke

Abstract: Little is known about the current state of freshwater biodiversity in Canada, one of the countries with the greatest amount of surface waters in the world. To address this knowledge gap, we compiled a list of all available assessments of conservation status for freshwater species (over 3000 taxa) and further evaluated the overall status of six distinct taxonomic groups, focusing on organisms reliant on fresh waters (i.e., aquatic plants, invertebrates (with a focus on freshwater mussels), fishes, herpetofauna (reptiles and amphibians), birds, and mammals). Overall, 11.7% of all freshwater species of plants and animals assessed were found to be "at risk" (i.e., listed as "Threatened", "Endangered", or "Extirpated") and 17.9% identified as "Special Concern". We found that 37.9% of species lacked sufficient data to enable their status to be assessed. Data gaps in Canada's assessment of its freshwater species were most prevalent in invertebrates (excluding freshwater mussels). Given the alarming state of freshwater biodiversity in Canada, we conclude by providing recommendations that focus on evaluating temporal trends and informing conservation actions.

Résumé : Les connaissances sur l'état actuel de la biodiversité des espèces d'eau douce au Canada, un des pays disposant de la plus grande quantité d'eau de surface au monde, sont limitées. Pour examiner cette lacune, nous avons compilé une liste de toutes les évaluations disponibles du statut de conservation d'espèces d'eau douce (plus de 3000 taxons) et évalué en outre le statut global de six groupes taxonomiques distincts, en mettant l'accent sur les organismes dépendant des eaux douces (c.-à-d., les plantes aquatiques, les invertébrés (plus particulièrement les mulettes), les poissons, l'herpétofaune (reptiles et amphibiens), les oiseaux et les mammifères). Globalement, 11,7 % de toutes les espèces d'eau douce de plantes et d'animaux évaluées sont « en péril » (c.-à-d., désignées « menacées », « en voie de disparition » ou « disparue au pays ») et 17,9 % ont un statut de conservation « préoccupant ». Nous constatons que les données disponibles sont insuffisantes pour permettre l'évaluation du

Received 30 March 2021. Accepted 10 June 2021.

J.E. Desforges, J. Clarke, E.J. Harmsen, J.A. Robichaud, S. Serré, J.R. Bennett, and S.J. Cooke. Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada.
A.M. Jardine. Department of Geography and Environmental Studies, Carleton University, 1125 Colonel By Dr., Ottawa, ON, K1S 5B6, Canada.
P. Chakrabarty. Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada; Museum of Natural Science, Department of Biological Sciences, Louisiana State University, 119 Foster Hall, Baton Rouge, LA 70803, USA; Beaty Centre for Species Discovery and Zoology, Research and Collections, Canadian Museum of Nature, 1740 Pink Road, Gatineau, QC J9J 3E7, Canada.
D.E.L. Hanna. Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada; Quebec Centre for Biodiversity Science, McGill University, 1205 Dr Penfield Ave., Montréal, QC H3A 1B1, Canada.
J.P. Smol. Paleoecological Environmental Assessment and Research Lab (PEARL), Department of Biology, Queen's University, Kingston, ON K7L 3N6, Canada.
T. Rytwinski and J.J. Taylor. Canadian Centre for Evidence-Based Conservation, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada.
A.L. Martel. Beaty Centre for Species Discovery and Zoology, Research and Collections, Canadian Museum of Nature, 1740 Pink Road, Gatineau, QC J9J 3E7, Canada.
A.K. Winegardner. Environment and Biodiversity Science Branch, Fisheries and Oceans Canada, 200 Kent St., Ottawa, ON K1A 0E6, Canada.
J. Marty. Institute of the Environment, University of Ottawa, 1 Stewart St., Ottawa, ON K1N 7M9, Canada.
M.K. Taylor. Parks Canada Agency, Banff National Park, 100 Hawk Ave., Banff, AB T1L 1K2, Canada.
C.M. O'Connor. Wildlife Conservation Society Canada, 344 Bloor St. West, Suite 204, Toronto, ON M5S 3A7, Canada.
S.A. Robinson. Ecotoxicology and Wildlife Health Division, Wildlife and Landscape Science Directorate, Science and Technology Branch, Environment and Climate Change Canada, Ottawa, ON K1S 5B6, Canada.
A.J. Reid. Centre for Indigenous Fisheries, Institute for the Oceans and Fisheries, The University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.
I.F. Creed. School of Environment & Sustainability, University of Saskatchewan, Saskatoon, SK S7N 5C8, Canada.
I. Gregory-Eaves. Department of Biology, McGill University, 1205 Dr Penfield Ave., Montréal, QC H3A 1B1, Canada.
N.W.R. Lapointe. Canadian Wildlife Federation, 350 Michael Cowpland Dr., Ottawa, ON K2M 2W1, Canada.
Corresponding author: Jessica E. Desforges (email: jdesforg@gmail.com).

statut de 37,9 % des espèces. Le groupe des invertébrés (à l'exception des mulettes) est celui pour lequel la prévalence des cas de manque de données pour l'évaluation d'espèces d'eau douce au Canada est la plus grande. Au vu de l'état alarmant de la biodiversité des espèces d'eau douce au Canada, nous concluons en formulant des recommandations qui mettent l'accent sur l'évaluation des tendances dans le temps et la production de données pour éclairer les mesures de conservation. [Traduit par la Rédaction]

1.0. Introduction

Despite occupying less than 1% of the Earth's surface, the freshwater biome is home to 12% of all described species, including as much as one third of all vertebrates (Dudgeon et al. 2006; Garcia-Moreno et al. 2014; Strayer and Dudgeon 2010). Freshwater plants and animals help maintain countless essential functions from production services (e.g., primary production and nutrient cycling; Lake et al. 2000) to providing many provisioning, regulating, and cultural ecosystem services (Postel and Carpenter 1997; Dudgeon 2010; Hanna et al. 2018). Increasing anthropogenic pressures and disturbance on the global water cycle (e.g., damming, increased use of fresh waters for agriculture, aquatic invasive species) have resulted in fresh waters becoming the most threatened biome on the planet, with inland water systems particularly at risk (Garcia-Moreno et al. 2014; Creed et al. 2017). According to the Living Planet Index for 2020, monitored populations of freshwater vertebrates are currently experiencing the largest biodiversity decline (84% decline since 1970) relative to species that occupy terrestrial or marine environments, though we also acknowledge potential differences in defining fresh water (WWF 2020). In fact, the freshwater biodiversity crisis (see Abell 2002; Harrison et al. 2018; Reid et al. 2019; Albert et al. 2021) is so dire that it has inspired the development of an emergency action plan (see Tickner et al. 2020) intended to try to reverse these declines. Others have identified key areas to focus efforts on restoring freshwater biodiversity, such as developing plans to avoid extinctions regardless of incomplete knowledge or outlining management strategies to reduce the impact of climate change on freshwater ecosystems (Strayer and Dudgeon 2010). Nonetheless, it is essential to understand the state of freshwater biodiversity across a broad range of scales, including at the national scale, which tends to be the level at which many freshwater biodiversity initiatives (ranging from policies, to monitoring to recovery planning and management) occur.

Canada contains 20% of the world's fresh water, including 7% of the Earth's free-flowing renewable freshwater resource, as well as nearly 25% of all wetlands (Rainer et al. 2017; Government of Canada 2018). With approximately 891 163 km^2 of fresh water, including over 2 million lakes and 8500 rivers (Monk and Baird 2014), Canada stewards a unique and important component of the world's biodiversity. This includes many well-known temperate species such as river otters (*Lontra canadensis*) and beavers (*Castor canadensis*), as well as Canadian endemics including the copper redhorse (*Moxostoma hubbsi*), coldwater pondsnail (*Stagnicola woodruffi*), Banff Springs snail (*Physella johnsoni*), Hungerford's crawling water beetle (*Brychius hungerfordi*), and the Lake Erie watersnake (*Nerodia sipedon insularum*) (Enns et al. 2020). Despite the abundance of freshwater biota in Canada, little is known about the state of freshwater biodiversity aside from taxon-specific and often regional (and project-specific) assessments. While reports on the conservation status of certain species in Canada exist and produce highly valuable information (e.g., Canadian Endangered Species Conservation Council (CESCC) Wild Species reports, Committee on the Status of Endangered Wildlife in Canada (COSEWIC) annual reports), a more complete picture of the status of Canada's freshwater biodiversity in its entirety is not yet available (Pérez-Jvostov et al. 2020). For example, the WWF Canada Watershed reports focus on indicator species (e.g., fish and macroinvertebrates) with the goal of assessing ecosystem health, but not total biodiversity (WWF-Canada 2020). Similarly, a review of biodiversity in the lakes and rivers (wetlands were excluded) of Canada by Monk and Baird (2014; wetlands were excluded) used proxies of biodiversity status (e.g., habitat quality and quantity) rather than assessing the actual state of biodiversity. Further, Tognelli et al. (2017) reported on the state of freshwater biodiversity in Canada; however, not all freshwater-reliant species (e.g., birds, mammals, herpetofauna) were included and conservation status was not provided for all species. Additionally, other studies have focused on the status of individual freshwater taxonomic groups (e.g., Williams et al. 1993; Brown and Hecnar 2007; Collier et al. 2016).

Considering the rate of global biodiversity loss along with the urgent calls to implement action plans (WWF 2020; Tickner et al. 2020; Albert et al. 2021), we have a responsibility to gain a better understanding of the current state of Canada's freshwater biodiversity. This study seeks to address this knowledge gap by building towards a Canada-wide freshwater biodiversity assessment. This nation-wide assessment synthesizes the latest available information pertaining to the conservation status of Canada's freshwater species, providing researchers and practitioners with a description of freshwater biodiversity in Canada today, and highlighting data deficiencies where further research is needed.

2.0. Methods

The following sections summarize the methodology used to complete this assessment, broken down by the major steps, including creation of a species list, collection of conservation status, and data analysis. We then described freshwater dependency and how conservation status terms were selected. A full comprehensive breakdown of how data were collected and selected in this study is provided in Sections 2.1 and 2.2; data are available as supplemental material (Supplementary data S1[1] contains species list and conservation status for 3130 taxa).

2.1. Species list creation

A list of freshwater-dependent species in Canada was compiled from existing data sources to serve as a baseline to quantify the proportion of conservation status assessments completed among taxa. Species data were collected for the following macroscopic taxonomic groups: plants, invertebrates, fishes, herpetofauna (amphibians and reptiles), birds, and mammals. For each taxonomic group, freshwater species were identified and included if (1) the species accomplished all or part of its lifecycle in, or on, inland waters (spanning from fresh to supersaline) or (2) the species showed dependency inland water habitats for food or habitat. For example, Culicidae (mosquitoes), which require inland waters for the deposition of egg rafts and early life stages were deemed a freshwater species and included in this study (Smith et al. 1994). Although we acknowledge that species residing in supersaline inland water bodies may experience different challenges compared to those living in fresh water, we opted to include them in this analysis for logistical reasons. Species that were historically present in Canada, but that have since become extinct or extirpated, were also included.

We excluded freshwater-dependent species that were considered non-native to Canada's fresh waters, since the main focus here is to address the state of freshwater biodiversity and to outline areas for improvement. While we acknowledge the importance of assessing the population trends and abundance of non-native species for management and monitoring purposes, management efforts

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2021-0073.

Table 1. Basis for the translation of CESCC status categories into COSEWIC status categories.

COSEWIC ranking term	Corresponding CESCC ranking	Justification
Extinct	Extinct	All definitions declare that there is no reasonable doubt the species still exists
Extirpated	Presumed Extirpated	All definitions state that the species has not been located in Canada but may exist elsewhere
Endangered	Critically Imperiled or Imperiled	All are defined as having a very high or imminent risk of extirpation
Threatened	Vulnerable	All are defined in terms of being likely, or at a high risk, of becoming endangered or extirpated
Special Concern	Apparently Secure	All are defined as species that may become threatened or endangered but are presently not currently at an immediate risk
Data Deficient	Unrankable	All definitions highlight a lack of available information to make an assessment
Not at Risk	Secure	All definitions mention being assessed to have no risk of extirpation or not qualifying for any at-risk categories (“Extirpated”, “Endangered”, “Threatened”)

tailored towards the conservation of native species are vastly different.

The species lists for plants, invertebrates, fishes, amphibians, reptiles, and mammals were created using data from COSEWIC, the International Union for Conservation of Nature (IUCN) Red List, and the CESCC 2015 Wildlife Species Report. Species lists were further augmented with data from FishBase (Froese and Pauly 2019) for fishes, the Canadian Herpetological Society for herpetofauna, and the Canadian Wildlife Federation (CWF) for mammals and plants (Canadian Wildlife Federation (CWF) 2020). We identified a total of 3130 freshwater-dependent species in Canada, though we acknowledge that this process may have underestimated species richness.

A number of taxonomic groups were omitted from this study, due largely to a lack of available data. For example, there is a lack of assessment data in particular for microbial biota, zooplankton, copepods, and other microinvertebrates. Of the few species for which data were available, a large portion are considered “unrankable” or “data-deficient” (Rozon et al. 2016). For example, when we examined a COSEWIC report on the status of freshwater ostracods in Canada, 81.5% of the freshwater species within the families Candonidae and Cyprididae were found to be “unrankable” (COSEWIC and COSEPAC 2012). Any taxonomic group that lacked enough data to make any accurate status assessments (including freshwater fungi, lichens, porifera, etc.) were also omitted from this study.

2.2. Conservation data collection

Following the creation of the species list, we obtained conservation status data for each species of the aforementioned six major taxonomic groups. COSEWIC was the primary source used for conservation status data rather than global assessments, because those assessments are specific to Canadian populations of species. We note that in some cases (e.g., species at the northern range edges), COSEWIC assesses species whose populations are globally secure as being at risk in Canada. Although the relative priority of conserving such species is debated (e.g., Raymond et al. 2018), there can be sound reasons for conserving them, including responsibility of a jurisdiction for its own biodiversity, as well as potential importance of northern populations for allowing range shifts as climate changes. In addition, when such species are protected under SARA, they have the same legal protection as species whose populations are globally imperilled. When species were not assessed by COSEWIC, CESCC data were used to determine their status. CESCC data were used to identify and assess species in an attempt to assist in guiding COSEWIC assessment priorities (CESCC 2016) while monitoring population trends at five-year intervals. It is important to note that although COSEWIC and CESCC provides conservation status for Canadian species, they are not legal listings under the Species At Risk Act (SARA) and are not given any specific rights or legal protection. CESCC rounded national ranks were used to provide additional information about species status and to complement information retrieved from COSEWIC.

COSEWIC conservation assessments statuses were categorized as follows: “Data Deficient”, “Not at Risk”, “Special Concern”, “Threatened”, “Endangered”, “Extirpated”, and “Extinct”. For species that had a COSEWIC assessment, that assessment was used as their primary conservation status. For those species that did not have a COSEWIC assessment, but had a conservation assessment from CESCC, the CESCC assessment term was matched to the COSEWIC listing based on the definitions and justifications provided in Table 1. This consolidation ensured that species were given an appropriate overall conservation status when data came from CESCC and did not directly match the COSEWIC status terms. Species without an assessment by either COSEWIC or CESCC were listed as “Not Available”. For the purpose of this study, we considered species “at risk” to include those assessed as “Threatened”, “Endangered”, “Extirpated”, and “Extinct”. The category of “Special Concern” was not included since COSEWIC specifically states that although these species may be vulnerable in the near future, they are not currently at risk. Species designated as “Special Concern” also do not receive legal habitat protection under SARA. COSEWIC assessments were given priority over CESCC due to the thoroughness of the former assessment process.

2.3. Analysis

The data were summarized visually to depict the conservation statuses for each family of species in each taxonomic group (comparative bar graphs created in R version 3.6.1; R Core Team 2016; using ggplot2; Wickham 2016; and the viridis package; Garnier 2018). A proportional bar graph and a chord diagram (circlize; Gu et al. 2014) were also generated to depict the overall differences in conservation status between broad taxonomic groups. Comprehensive lists with all Canadian freshwater species names and statuses were also created (Supplementary data[1]).

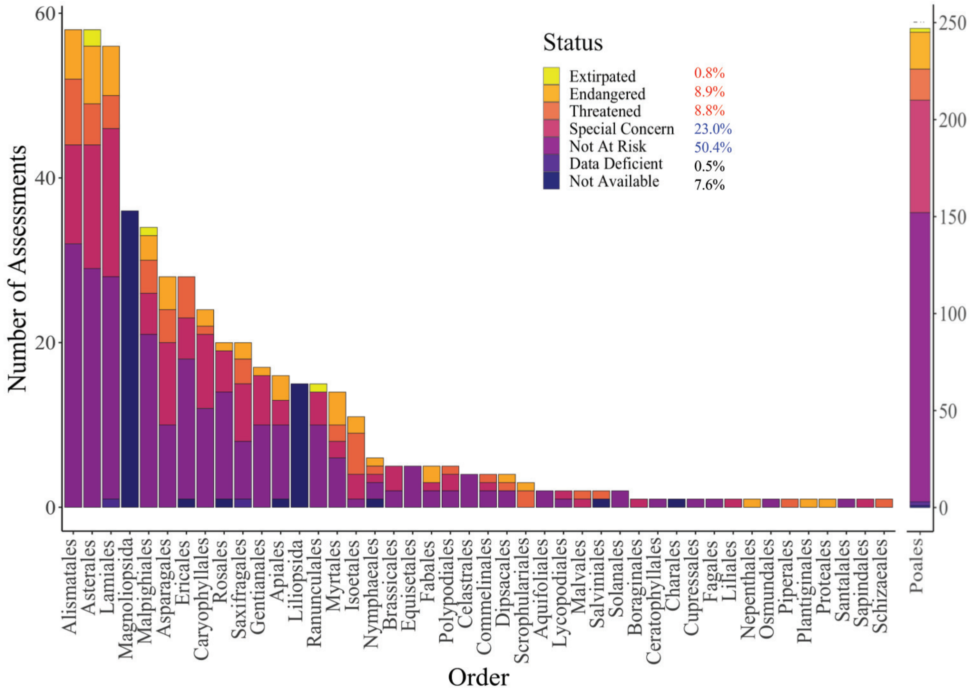
3.0. Taxonomic results and discussion

Each of the six major taxonomic groups (plants, invertebrates, fish, herpetofauna, birds, and mammals) were assessed individually and then in comparison to the other major taxonomic groups.

3.1. Freshwater plants

According to our plant species list, Canada has 762 native freshwater plant species (Fig. 1; based on data from COSEWIC, CESCC, and IUCN). Of these plant species, six (0.8%) are listed as “Extirpated”, which included plants in the orders Asterales, Poales, Malpighiales, and Ranunculales. Another 68 species (8.9%) were considered “Endangered”, 67 species (8.8%) as “Threatened”, and 175 species (23%) as “Special Concern”. Interestingly, 58 species (7.6%) of all identified plant species were deemed “Not Available”, since they lack a conservation assessment in Canada. Therefore,

Fig. 1. Number of assessments by order of freshwater-dependent plant species in Canada. Data are further subdivided by assessment status, from "Not Available" to "Extirpated" according to the most recent COSEWIC–CESCC assessment (Table 1), with the percentage of each assessment included next to the status category. [Colour online.]



the number of at-risk freshwater plant species reported in this study could be either over or underestimated. Additionally, four species (0.5%) were listed as "Data Deficient". The most frequent status of plant species listed in this study (384 species, 50%) have been assessed as "Not at Risk".

Species-level information for freshwater plants was synthesized by order. Of the 45 plant orders assessed, three orders (Liliopsida, Magnoliopsida, and Charales) did not have any assessment information available in Canada. Further, 17 orders had more than 50% of their species considered to be at risk and of those, ten orders had 100% of their species listed as at risk. Comparatively, another 17 orders had more than 50% of their species considered to be not at risk and of those, nine orders had 100% of their species categorized as not at risk. The remaining eight orders were divided evenly among conservation categories. The orders Poales (grasses, bromeliads, etc.), Alismatales (pondweed), and Asterales contained the most freshwater plant species in Canada (247 species of Poales and 58 species of both Alismatales and Asterales). The orders containing more freshwater plant species tended to have an even division of conservation rankings with about 50% of those species considered to be at risk and 50% considered not to be at risk. While those orders with very few species (less than five) were either 100% not at risk or 100% at risk.

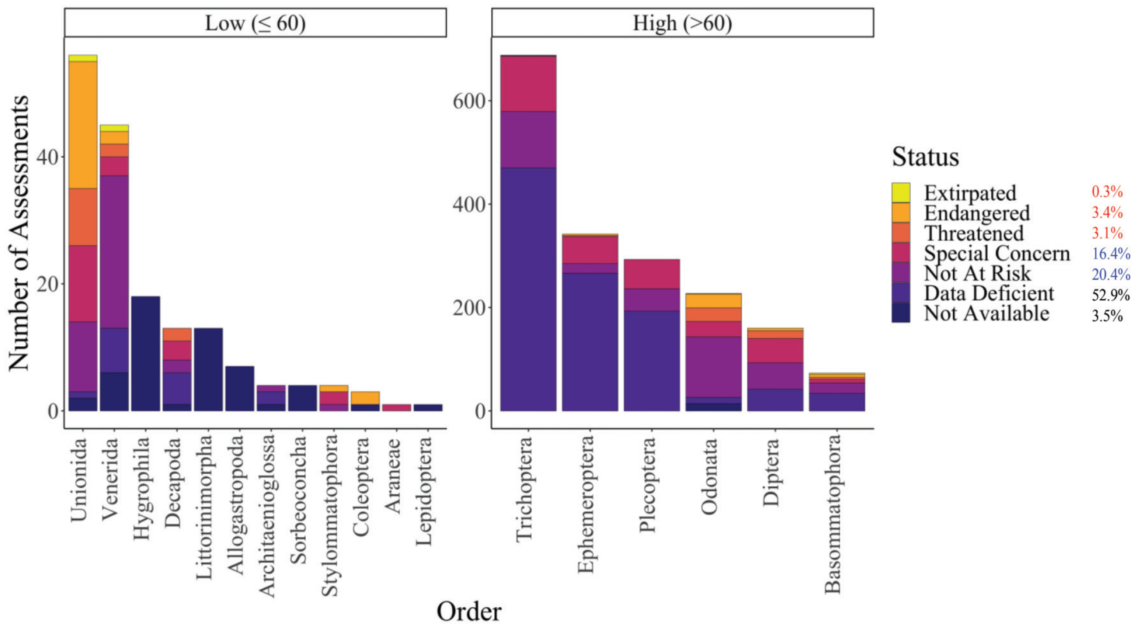
Notably, the Isoetales (quillworts) had one of the highest proportions of species that were at risk (in total 11 species, 91% at risk). Canada is home to multiple rare species of quillworts including *Isoetes prototypus*. This species is considered a regional endemic species and is only found in 12 lakes in Nova Scotia and New Brunswick, as well as one lake in Maine, USA (COSEWIC 2005). This species has been listed as "Threatened" as it faces threats brought on by human recreational activities such as boating, fishing, and swimming (COSEWIC 2005). Additionally, another rare quillwort endemic to Canada is the recently described *Isoetes laurentiana*, located only in the fluvial freshwater portion of the St. Lawrence River (Brunton et al. 2019). These endemic species point to the need to conserve some of the truly unique freshwater habitats in Canada, along with the conservation of the species that inhabit them. Freshwater plants are key to maintaining aquatic biodiversity as they provide shelter, food, and act as a stabilizing force in maintaining water quality in aquatic ecosystems (Chambers et al. 2007). Considering the fundamental role of freshwater plants in aquatic ecosystems (Scheffer et al. 1993), decreases in populations will have detrimental impacts on other freshwater organisms. Freshwater plants in Canada face threats such as habitat degradation, pollution, flooding and drainage, as well as recreational activities such as the use of boats (Jain 1990; Pérez-Jvostov et al. 2020). The direct application of aquatic herbicides to control invasive macrophytes also poses a risk to threatened native plant species (Sesin et al. 2018). Our results show that there is a significant portion (30%, 36 assessments) of plant species that remain at risk and these percentages are highly comparable to other groups considered.

3.2. Freshwater invertebrates

A total of 1952 freshwater invertebrate species were identified in Canada using IUCN, COSEWIC, and CESCC (Fig. 2). Of the 1952 assessments for freshwater invertebrate species, 1032 species (53%) were considered "Data Deficient", while 68 species (3.5%) were classified as "Not Available" since they were not considered for conservation assessment by any source. Another 719 (37%) were not considered to be at risk (i.e., 398 "Not at Risk", 321 "Special Concern"). Based on the completed assessments to date, we know that at least 6.6% of all identified freshwater-dependent invertebrate species are considered to be have a classification of "Threatened" or more severe.

The most evident trend pertaining to the state of freshwater invertebrate biodiversity was the lack of available data, particularly for insects. For example, Trichoptera (caddisflies) represent a large proportion of freshwater insect diversity in Canada (35.3%) with 688 species listed, yet most of those listed have been classified as "Data Deficient" due to lack of available data (68%).

Fig. 2. Number of assessments by order of freshwater-dependent invertebrate species in Canada, split according to a low vs. high number of assessments. Data are further subdivided by assessment status, from "Not Available" to "Extirpated" according to the most recent COSEWIC–CESCC assessment (Table 1), with the percentage of each assessment included next to the status category. [Colour online.]



Some orders had a much greater proportion of assessed species such as Unionida (freshwater mussels) and Odonata (dragonflies). Over half of freshwater Odonates (64.8%) were not considered at risk, while 23.3% were considered to be at risk (of which approximately half of the at risk group are "Endangered"). For example, Unionida (freshwater mussels) only had one species listed as "Data Deficient" while the majority of other species (55%) in this order were considered to be at risk (and more than half of the at risk group are considered "Endangered"; Supplementary Fig. S12[1]). This coincides with global trends as freshwater mussels are among the most endangered groups of organisms on Earth (Williams et al. 1993; Ricciardi and Rasmussen 1999). One of the major threats and causes for declines in freshwater mussels is the inability to adapt to altered water conditions associated with impoundment (Vaughn and Taylor 1999). There is also evidence that suggests that the presence of invasive species (dressenid mussels in particular) threaten native counterparts (Baker and Levinton 2003). This decline is particularly concerning owing to the role of freshwater mussels in water filtration, sediment dynamics, and the overall hydraulic environment, such that their decline can have catastrophic effects on freshwater ecosystems (Strayer et al. 1994).

Based on our findings, severe knowledge gaps exist regarding the overall status of freshwater invertebrates in Canada. Mayflies are among the groups of invertebrates that are understudied (Ephemeroptera: 78% "Data Deficient"), five species of which are endemic to Canada (Enns et al. 2020). Mayflies are highly important in freshwater ecosystems not only as useful bioindicators, but also as climate regulators, water purifiers and pollinators (Leemans and De Groot 2003). Further, mayflies represent an important food source for freshwater fishes and aerial insectivore birds (Epanchin et al. 2010), serving as a link in the energy flow from primary production to secondary consumption, and across the aquatic–terrestrial interface (Jacobus et al. 2019).

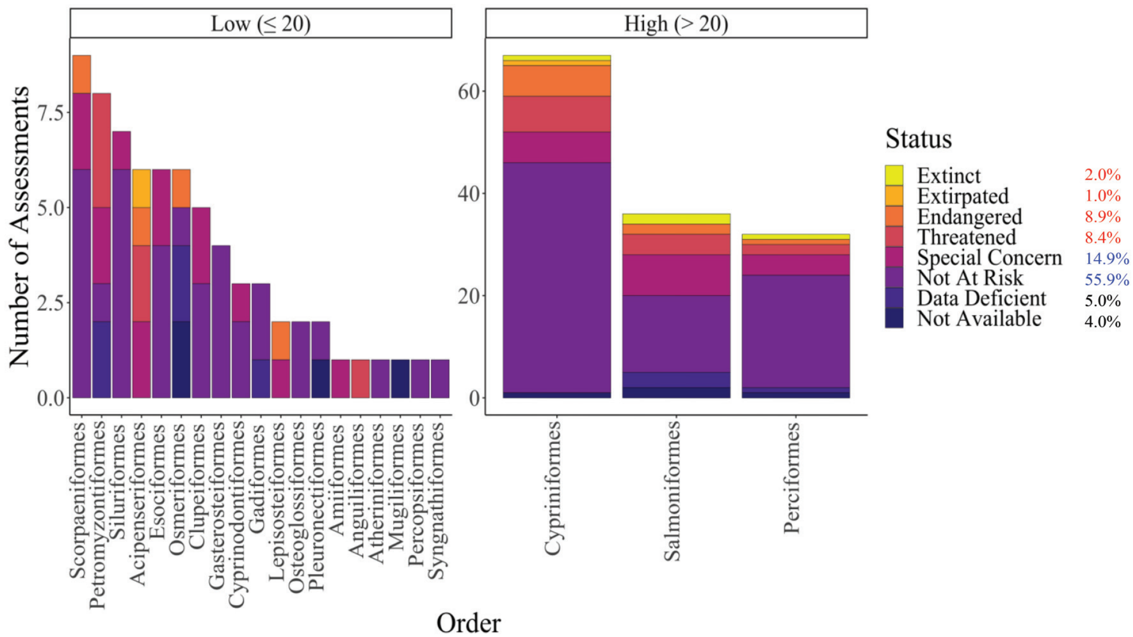
A disproportionately large number of assessments were observed in some orders (e.g., Trichoptera, Diptera), which suggests a bias in conservation status assessments for socioculturally important species. The bias towards species of human importance was most reflected in the orders Trichoptera (caddisflies, 688 total assessments) and Diptera (flies, 160). Caddisflies (Trichoptera) — which serve as important biological indicators of ecosystem health — were the most frequently assessed invertebrate group and are among the most common aquatic invertebrates in the world (Prommi 2018). Caddisflies are also known to be important to anglers who benefit from the predator–prey relationship between caddisflies and fish (Ames 2008). Considering that the recreational fishing industry brings in about $2.5 billion annually in Canada (Fisheries and Oceans Canada 2015), it is perhaps not surprising that there has been a higher prioritization for conservation assessment of trichopteran compared to other invertebrate species. Based on the frequency of assessment for these particular orders, invertebrates that are commonly found to be interwoven with important ecosystem services value may be identified as candidates for assessment before less common species.

There also appears to be assessment bias towards species that are presumed to be imperiled prior to assessment. This is particularly noticeable in the assessment data from COSEWIC, which our report found listed 62% of freshwater invertebrates as "Endangered", whereas CESCC only listed 3.2% as "Endangered". Notably, there are substantial differences in the number of species considered by COSEWIC and CESCC; however, it has been previously acknowledged that a bias may exist for assessing species that are presumed to be imperiled or endangered, or that have already been assessed multiple times (Favaro et al. 2014). While these species require more frequent assessments to prevent further decline, it is equally important to acknowledge that data deficient species could be declining at similar rates.

3.3. Freshwater fish

A total of 204 native freshwater-dependent fish species were evaluated for their conservation status in Canada (Fig. 3). Of these 204 assessments, nine (4.4%) were considered "Data Deficient", while eight (4%) had no data available at all. Another 146 species (73%; 117 "Not at Risk", 32 "Special Concern") were not considered to be at risk, though particular attention should be focused on the 32 species progressing towards more critical stages. Additionally, 19 (9.3%) were considered "Threatened", 13 (6.4%) as "Endangered", 2 (1%) as "Extirpated", and 4 (2%) as "Extinct". Overall, 38 (18.7%) of

Fig. 3. Number of assessments by order of freshwater-dependent fish species, split according to a low vs. high number of assessments. Data are further subdivided by assessment status, from "Not Available" to "Extinct" according to the most recent COSEWIC–CESCC assessment (Table 1), with the percentage of each assessment included next to the status category. [Colour online.]



identified freshwater-dependent fish species were considered to be at risk. It is also important to recognize that this analysis was conducted at a species-level to identify national trends; these results could be masking more severe declines in population sizes on smaller geographic scales. For example, many commercially harvested fish are managed at a stock level and numerous stocks of Pacific salmon have been assessed to be at risk (see COSEWIC status reports). The management and conservation of mixed stock fisheries and genetically or spatially isolated populations is complex and assessment can vastly differ across regional scales.

Some orders have been assessed more than others, specifically Cypriniformes (carps and loaches), Perciformes (the diverse perch-like fishes), and Salmoniformes (salmon, trout, whitefish, etc.) (Fig. 3). While this could be a reflection of higher species richness in these orders (see Samarasin et al. 2015), it could also demonstrate unequal attention attributed across groups and may represent a bias in the assessment process. For example, many species of Cypriniformes are common and highly abundant, facilitating the process of data collection in comparison to that of imperiled species. However, unlike Salmoniformes, Cypriniformes are not typically considered among the most economically or culturally important species, leading to many species being classified as "Not Available" despite the relative ease of data collection. In contrast, Salmoniformes are considered important cultural and socioeconomic native species, and have been well documented by COSEWIC in the past, making them ideal candidates for consistent assessments. The perception of value associated with particular species may skew the assessment processes.

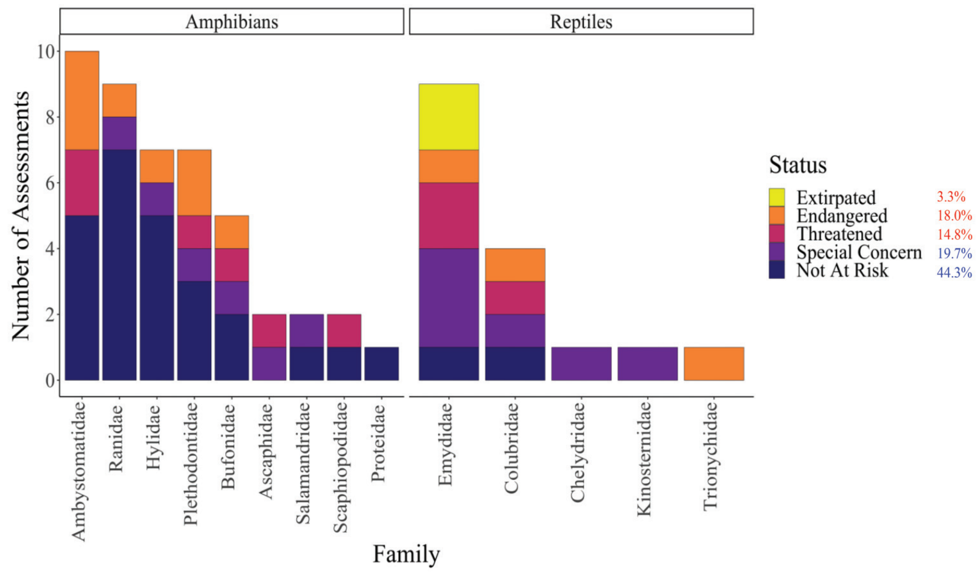
Orders containing economically valuable migratory species, such as Salmoniformes and Acipenseriformes, also display higher numbers of assessments, many of which are considered at risk (22.2% and 66.6%, respectively). Globally, migratory fish have declined by an estimated 76% on average since 1970 (Deinet et al. 2020). We did not specifically conduct a temporal analysis, but our analysis suggested that migratory species may encounter more threats than orders containing nonmigratory species. This seems to have been acknowledged by COSEWIC assessment committees, as these orders have been thoroughly assessed and prioritized for substantial monitoring and conservation efforts (Deinet et al. 2020). Likewise, Acipenseriformes is composed of several iconic species (e.g., Atlantic sturgeon, *Acipenser oxyrinchus*; and American paddlefish, *Polyodon spathula*) that are known to have suffered from human development and exploitation (e.g., Auer 2013). Low catch rates were reported by fishers and have led to close monitoring and management of their populations (Scott and Crossman 1973; Pikitch et al. 2005). Similar to others, we observed a general trend that suggests that large, charismatic, and well-known species are more likely to be considered for assessment than other less iconic species (supported by Olden et al. 2007; Walsh et al. 2013). The decline of recreationally, culturally, and socioeconomically important or iconic native species seems to influence assessments of freshwater-dependent fishes in Canada. Evaluating the state of freshwater-dependent fish biodiversity in Canada relies on developing a transparent, nonbiased system that ensures equal assessment of all endemic species.

In the past, freshwater fish have often been overlooked by policymakers and the general public (WWF 2021). Although there is evidence that points towards higher numbers of assessments in socioeconomically or culturally valuable freshwater fishes (e.g., Donaldson et al. 2017), a recent report by WWF (2021) states that freshwater fish remain largely undervalued on a global scale. The proportion of fish species classified as "Extinct" in Canada is over four times higher (1.96% of 204 identified species) than that observed worldwide by WWF (0.44% of 18 075 identified species), though we also acknowledge that there could be differences in methodological processes involved in generating these results. Considering the magnitude of biodiversity loss observed not only across the globe but also within Canada, it is essential to implement management practices such as those outlined in the Emergency Recovery Plan for freshwater biodiversity (Tickner et al. 2020).

3.4. Freshwater herpetofauna

A total of 61 species of freshwater-dependent Canadian amphibians and reptile species were evaluated for their conservation status in Canada (Fig. 4). This consisted of 16 reptiles (four snakes and

Fig. 4. Number of assessments by order of freshwater-dependent amphibian and reptile species in Canada. Data are further subdivided by assessment status, from "Not Available" to "Extirpated" according to the most recent COSEWIC–CESCC assessment (Table 1), with the percentage of each assessment included next to the status category. [Colour online.]



12 turtles) and 45 amphibians (25 frogs and 20 salamanders); 64% (27 "Not at Risk", 12 "Special Concern") were not considered to be at risk. Overall, 36% of freshwater herpetofauna were deemed to be at risk (nine "Threatened", 11 "Endangered", and two "Extirpated"), with a relatively high proportion of assessments ranking as "Endangered" compared with other taxa.

Of the four freshwater snakes found in Canada, two were found to be not currently at risk — the northern watersnake (*Nerodia sipedon sipedon*) and the Lake Erie watersnake (*Nerodia sipedon insularum)*. The remaining species are considered at risk: the eastern ribbonsnake (*Thamnophis saurita*) listed as "Threatened"; and the queensnake (*Regina septemvittata*) listed as "Endangered".

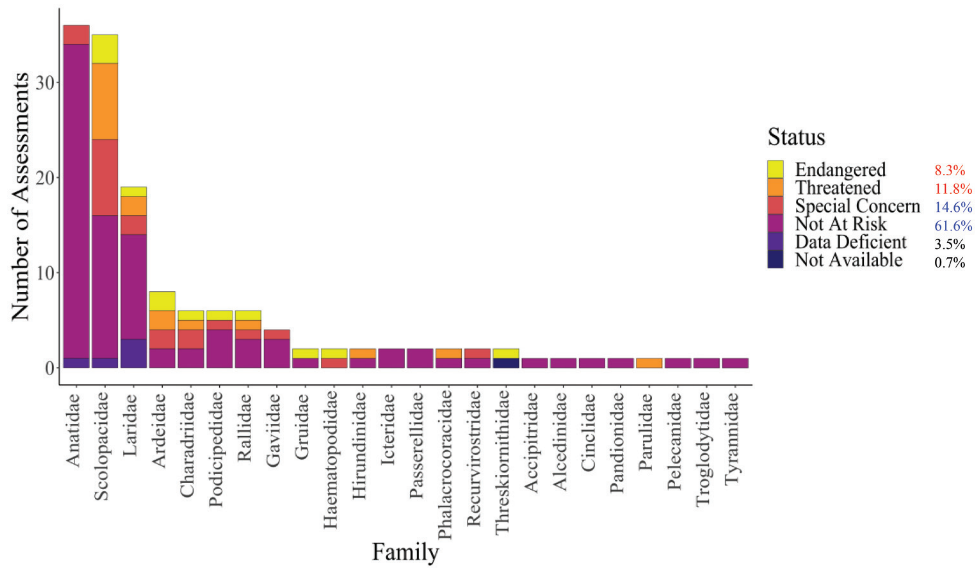
A total of 12 turtle species in Canada are freshwater-dependent, all of which have been assessed for a conservation status. The western painted turtle (*Chrysemys picta bellii*) is the only freshwater turtle species that was "Not at Risk". Within the turtle group, 42% (five species) were listed as "Special Concern": the snapping turtle (*Chelydra serpentina*); the midland painted turtle (*Chrysemys picta marginata*); the eastern painted turtle (*Chrysemys picta picta*); the northern map turtle (*Graptemy geographica*); and the eastern musk turtle (*Sternotherus odoratus*). Several (17%) were listed as "Threatened": the Blanding's turtle *(Emydoidea blandingii*) and the wood turtle *(Glyptemys insculpta*). Some ranked as "Endangered" (17%, two species): the spiny softshell turtle (*Apalone spinifera*) and the spotted turtle (*Clemmys guttata*). Finally, the Pacific pond turtle (*Actinemys marmorata*) and the eastern box turtle (*Terrapene carolina*) are listed as "Extirpated" in Canada (17%).

Likely due to their sensitivity to anthropogenic threats and their relatively lower diversity, freshwater reptiles have been assessed more thoroughly relative to other freshwater-dependent species in this study. All native freshwater reptile species have a conservation assessment, with 50% considered to be at risk, making them a highly threatened taxonomic group (Fig. 4). Freshwater snakes and turtles face threats such as habitat degradation, destruction, and fragmentation, as well as pollution, disease, road mortality, human recreation, poaching, and climate change (Brown and Hecnar 2007; Lesbarrères et al. 2014). In Canada, most freshwater reptiles and amphibians are at the northern edge of their range, wherein suitable habitat is limited because of the cooler climate (Lesbarrères et al. 2014). This is particularly concerning for freshwater amphibians whose required vegetation, wetland types, and thermal regimes are limited (Lesbarrères et al. 2014). Notably, amphibians are globally one of the most threatened vertebrate groups (Wake and Vredenburg 2008; Stanford et al. 2019).

We identified 25 species of freshwater-dependent frogs in Canada. Anurans are the least threatened herpetological group in Canada, with 60% (15 species) assessed as "Not at Risk". The remaining species assessments were ranked as follows: 16% (four species) as "Special Concern"; 12% (three species) as "Threatened"; and 12% (three species) as "Endangered". Species listed as "Special Concern" include the Great Plains toad (*Anaxyrus cognatus*), the coastal tailed frog (*Ascaphus truei*), the western chorus frog (*Pseudacris triseriata*), and the red-legged frog (*Rana aurora*). The western toad (*Anaxyrus boreas*), the Rocky Mountain tailed frog (*Ascaphus montanus*), and the Great Basin spadefoot (*Spea intermontana*) are all listed as "Threatened". Finally, Blanchard's cricket frog (*Acris blanchardi*), Fowler's toad (*Anaxyrus fowleri*), the Oregon spotted frog (*Rana pretiosa*) are listed as "Endangered".

Twenty salamander species in Canada are freshwater-dependent, which represents about 5% of the global species of salamanders, a highly endangered group (Milanovich et al. 2010). Of these assessments, 50% (ten species) are listed as "Not at Risk"; 10% (two species) as "Special Concern"; 15% (three species) as "Threatened"; and 25% (five species) as "Endangered". Our data suggest that salamanders have been relatively well-studied, and there is sufficient assessment data depicting changes in growth, decline, and threats to different populations. What is unclear is the differentiation between species and subspecies observed in Canada, with some subspecies being given their own COSEWIC rankings while simultaneously not being considered an individual species in CESCC rankings or by species lists given by groups such as the Canadian Herpetological Society. Such is true for the unisexual mole salamander subspecies (*Ambystoma laterale* – (2) *jeffersonianum*); this specific subspecies of salamander has been assessed and listed as "Not at Risk" by COSEWIC but is not listed as a species in CESCC data or under the Canadian Herpetological Society. Because of the lack of information surrounding subspecies of salamanders specifically, we chose to not include subspecies in this report, focusing on species and their overall conservation assessments. We did include subspecies for other groups that have more universally accepted

Fig. 5. Number of assessments by order of freshwater-dependent bird species in Canada. Data are further subdivided by assessment status, from "Not Available" to "Endangered" according to the most recent COSEWIC–CESCC assessment (Table 1), with the percentage of each assessment included next to the status category. [Colour online.]



taxonomic statuses and conservation assessments. However, it is important to note that this discrepancy is detrimental for species that have subspecies populations at higher risk levels and is something that should be considered and amended in national reports in the future to ensure vulnerable and unique populations are not overlooked.

A major reason for amphibian declines worldwide is chytrid fungus (*Batrachochytrium dendrobatidis*). This disease is thought to have been identified in North America in 1961 (Weldon et al. 2004), perhaps giving time for populations to develop some form of resistance. In tropical areas, amphibians have been exposed more recently, which could account for more severe declines observed in these areas (Ouellet 2005). This would likely explain why amphibian populations in Canada, although threatened, are less drastically threatened by extinction as tropical species overall. Nonetheless, the status of the freshwater herpetofauna of Canada is critically important to monitor, considering that 50% of freshwater reptiles and 31% of freshwater amphibians are currently at risk. The abundance of the herpetofauna data is likely due to the frequent study of both groups in response to habitat and land development interests, as well as their proximity to humans.

Canada's freshwater herpetofauna occupy habitats near shorelines, which are often valuable for land development and other economic activities (Lesbarrères et al. 2014). As such, the conservation status of these species is often assessed to consider potential threats related to land degradation. Stakeholder biases and political pressures to encourage development across the municipal, provincial, and federal levels may also be influential (Lesbarrères et al. 2014). Because northern range herpetofauna have limited suitable habitat in Canada, they often find themselves in densely populated areas such as southern Ontario and southern British Columbia where the climate is milder (Lesbarrères et al. 2014). Therefore, they are typically well-studied species because of their proximity to dense networks of anthropogenic activity.

3.5. Freshwater birds

There are 678 species of birds reported in Canada, with 144 species (21%) requiring fresh water to complete their life cycle (Wild Species Report 2015, in CESCC 2016). We evaluated the conservation status of all 144 freshwater-dependent bird species and found that 12 species (8.3%) were considered "Endangered"; 17 species (11.8%) as "Threatened"; 109 species (75.7%) were not considered to be at risk (21 species as "Special Concern"; 88 species as "Not at Risk"); and five species (3.5%) as "Data Deficient". Additionally, one species, *Plegais falcinellus*, was not assigned a status as it rarely occurs in Canada. Our analysis showed that 29 species (20.1%) of all freshwater birds in Canada are considered to be at risk. Out of the 24 families, nine had 100% of their species ranked as "Not at Risk" (Accipitridae, Alcedinidae, Cinclidae, Icteridae, Pandionidae, Passerellidae, Pelecanidae, Troglodytidae, Tyrannidae), eight of the families had 50% or more of their species ranked as "Not at Risk" (Anatidae, Gaviidae, Gruidae, Hirundinidae, Laridae, Phalacrocoracidae, Rallidae, Recurvirostridae), and seven families had less than 50% of their species ranked as "Not at Risk" (Ardeidae, Charadriidae, Haematopodidae, Parulidae, Podicipedidae, Scolopacidae, Threskionithidae). Three of the five assessments ranked as "Data Deficient" were in the Laridae family. Scolopacidae (shorebirds) had the most species classified as at risk, with eight assessments ranked as "Special Concern", eight considered "Threatened", and three as "Endangered".

The conservation status of freshwater birds differs greatly among the 24 families of freshwater birds analyzed (Fig. 5). The most noticeable trend was observed in the Scolopacidae, which had the most significant declines in species populations. Scolopacidae is a family of waders or shorebirds. Canada's shorebirds are among the most vulnerable groups of birds in the nation with a 40% decline within populations reported since the 1970s (NABCI 2019). Shorebirds with longer-distance migrations have shown even steeper population declines in comparison to shorter-distance migrators due to the overall declining availability and degrading quality of stop-over habitats (Sutherland et al. 2012; NABCI 2019). Additional threats such as climate change, urban encroachment, industrial development, disturbance, increased predation, hunting, and pollution have been highlighted in contributing to the current population declines (Butler et al. 2004; Lafferty et al. 2006; Goss-Custard et al. 2006; Murray et al. 2014; Drever et al. 2018; Reed et al. 2018). Canada has a particularly unique and important position in that it provides over 75% of the breeding range of North American shorebird species and thus has a major responsibility in ensuring the conservation of these species (Donaldson et al. 2000).

Other shorebird families included in our analysis (e.g., Recurvirostridae, Haematopodidae, Charadriidae) should also be carefully monitored for their conservation status as shorebird populations as a whole are vulnerable to declines.

The family Laridae is a group of seabirds including gulls, terns, and skimmers. This family is defined as a group of seabirds; however, these species are widespread throughout Canada and thus inhabit areas far from the sea and can be fully reliant on fresh waters. Although half of the species in the Laridae family are listed in stable conservation categories, 42% of species are showing population declines and have been considered to be at risk or lack enough data to be fully assessed. Gulls are the most generalist species of all seabirds, occupying a variety of habitats from the arctic to seacoasts, to inland marshes (Burger and Gochfeld 2001). They are also generalist feeders, consuming anything from fish to invertebrates, small mammals, songbirds and famously, garbage (Ewins et al. 1994; Fox et al. 1990). Gull species have long been used as bioindicator species due to their generalist behaviours, as well as their rapid response to changing conditions (Hebert et al. 1999; Furness and Camphuysen 1997; Mallory et al. 2010). Our results should raise some concern considering that bioindicator species reflect the conditions of their environment. Declining populations of Laridae ultimately suggest the degradation of their aquatic habitats. We suggest future studies focus on gathering more information on "Data Deficient" species as well as closely monitoring all members of the Laridae family; this is not only to gain a better understanding of species trends, but to also help monitor the status and quality of their freshwater habitats.

3.6. Freshwater mammals

A total of seven mammal species that were deemed freshwater-dependent were evaluated for their conservation status: beaver (*Castor canadensis*), muskrat (*Ondatra zibethicus*), mink (*Mustela vison*), river otter (*Lutra canadensis*), star-nosed mole (*Condylura cristata*), and two species of water shrew (*Sorex palustris* and *Sorex bendirii*). All of the species have had conservation assessments performed. Among species identified, only one species (14%), the Pacific water shrew (*Sorex bendirii*), was assessed as "Endangered". The remaining six species (86%) were deemed "Not at Risk".

The Pacific water shrew is likely endangered due to habitat degradation in its already limited geographic range. The shrew's habitat consists of wetlands in the areas of southwest British Columbia that are being rapidly urbanized (SCCP 2020; COSEWIC 2006). Population trends are generally unknown for this shrew making it difficult to assess the species throughout its range. Multiple populations of the Pacific water shrew have been known to reside in abundance along the west coast of the United States, making this species only endangered in Canada (Cassola 2016). A recovery strategy for the Canadian populations was proposed in 2014; however, the last known assessment was completed in 2006 (Environment Canada 2014). An updated conservation assessment is needed for evaluating further declines or rebounding populations of this species.

The remaining six species that were assessed as "Not at Risk" include keystone species such as beaver and river otter. Keystone species are those that have a disproportionately high impact on their surrounding environment and that influence the survival of other species (Bond 1994); thus, maintaining the "Not at Risk" conservation status of river otter and beaver is important. Interestingly, the comeback of the beaver from intensive hunting in the 1700s and 1800s is a major success story in mammal conservation (Naiman et al. 1988). Currently, there are multiple conservation programs monitoring these keystone species at both a provincial and national level (e.g., National Conservancy Canada, Ontario Fur Managers Federation, Canadian Wildlife Federation). While these species appear to be stable at the national level, there may be regional differences that could warrant the conservation of specific populations at a more limited geographic scale. Similar to all the previous taxonomic groups included in our analysis, freshwater mammals still face local and global threats such as habitat degradation, water pollution, and climate change (He et al. 2017). Although potentially more resilient and common than some of the other groups discussed, it remains important to monitor freshwater-reliant mammal species for changes in population numbers.

3.7. All taxonomic groups

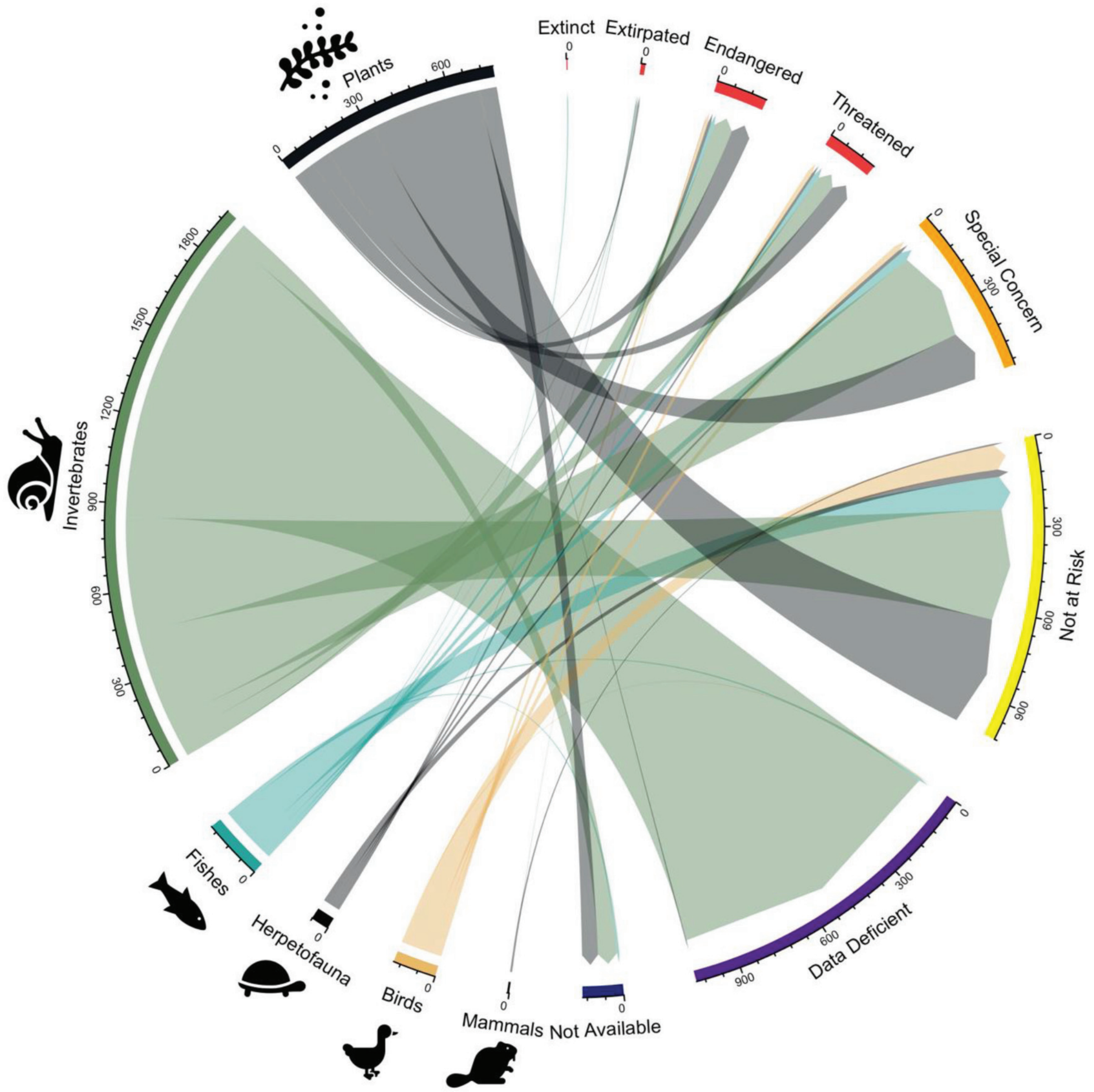
Out of 16 384 available assessments of Canada's native species (CESCC 2016), a total of 3130 species were included in this study, suggesting ~19.1% of all macroscopic species in Canada rely on fresh water to complete part of their life cycle. One-third of all vertebrate species on Earth are confined to freshwater habitats, yet datasets on these organisms remain largely incomplete even within well-studied taxa such as fishes (Stiassny 2002; Dudgeon et al. 2006). Our findings highlight the large data deficiency among freshwater macroscopic species, with a total of 37.9% (1186; Fig. 6; Supplementary Table S1[1]) of all freshwater species lacking enough information for proper conservation status assessment, with a majority of data deficiency observed within the invertebrate taxa. This information is considered crucial to understanding the status of freshwater biodiversity. It is also important to recognize that although species may be listed as "Not at Risk" or as "Special Concern", they could be exposed to rapid habitat destruction and could decrease in abundance at a similar rate. Conservation assessments do not necessarily represent the immediate status of particular species, though they are important in providing a robust description of the state of biodiversity in Canada.

Data deficiencies were especially evident for the invertebrate species evaluated in this report. Our results supported previous research where globally, invertebrates are the most data deficient in terms of status and diversity of species (Dudgeon et al. 2006). Invertebrates represented most of the species included in this study (62.4%), yet less than half were assessed for their conservation status, compared to 95% of vertebrates having assessments and 92% of plants. Invertebrates have high species richness and play critical functional roles, yet have received little attention in comparison to vertebrates. Invertebrates are generally not considered charismatic and do not garner as much public interest for motivating conservation initiatives relative to vertebrates (Bland et al. 2012; Barua et al. 2012; Collier et al. 2016). This bias hinders our ability to properly assess the extinction risk that invertebrates face (Bland et al. 2012). Considering the high species richness and the urgency to protect freshwater biodiversity, we suggest implementing management strategies that assess areas of high biodiversity rather than assessing each species individually. This review of the current state of species assessments in Canada's fresh waters clearly indicates a need to raise awareness among the general public, while bridging the gap between the scientific community and government policymakers (e.g., Rose et al. 2018).

Other major taxonomic groups such as plankton and bacteria also play fundamental roles in ecosystem health but are missing in our analyses due to a dearth of information. The lack of data are largely due to the difficulties associated with monitoring microeukaryotes, which can prove to be a challenging feat due to their microscopic size and vast species richness (Xiong et al. 2020). However, metabarcoding approaches are becoming increasingly popular (Hering et al. 2018) and will likely facilitate further efforts to study the distribution and dynamics of these poorly studied taxonomic groups within Canada.

Anthropogenic threats such as habitat degradation, invasive species, and climate change continue to impair freshwater ecosystems, contributing to rapid biodiversity loss (Garcia-Moreno et al. 2014). Efforts to understand freshwater biodiversity must be employed as soon as possible for all freshwater taxa to prevent further loss under increased anthropogenic pressures. Canada

Fig. 6. A visual representation of the distribution of conservation statuses (on the right) for each of the six taxonomic groups (on the left). Invertebrates represent the most species-rich taxa, followed by plants, fishes, birds, herpetofauna, and mammals. Invertebrates also have the largest proportion of Data Deficient assessments, whereas fishes are the only group that have been assessed as "Extinct". The plot was generated using circlize (v.0.4.12; Gu et al. 2014; https://cran.r-project.org/package=circlize) with R (v.4.0.2; https://www.r-project.org/) in RStudio (v.1.3.1093; https://rstudio.com/). [Colour online.]

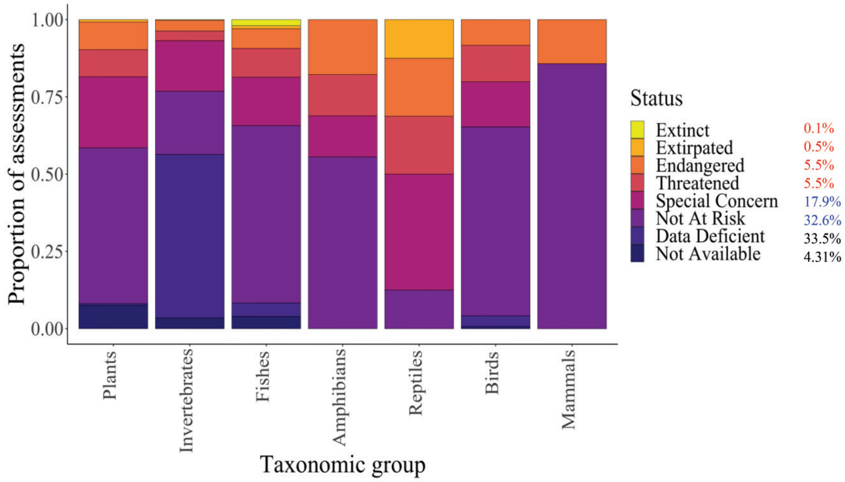


has the third largest national reservoir of fresh water in the world (Food and Agriculture Organization of the United Nations (FAO) 2003), and the global need for fresh waters may put added pressure on Canada and its freshwater biota in the future.

The largest proportion of at-risk assessments were observed in reptiles and amphibians (Fig. 7). The overall rankings were distinguished as follows, from most to least at risk: 50% (eight species) of freshwater reptiles; 31.1% (14 species) of freshwater amphibians; 20.1% (29 species) of freshwater birds; 18.6% (38 species) of freshwater fishes; 18.5% (141 species) of freshwater plants; and 14.3% (one species) of freshwater mammals. Our study reveals that a total of 11.7% (367 species) of Canada's freshwater biodiversity is currently at risk, which could be either an over- or underestimate, depending on the remaining 37.9% (1186 species) that lack a status ranking. An additional 17.9% of species are ranked as "Special Concern" and could progress to more severe assessments if threats are not addressed. Research shows that freshwater invertebrates, fishes, and herpetofauna in North America are facing extinction rates as much as five times higher than their terrestrial counterparts (Ricciardi and Rasmussen 1999). It is crucial to acknowledge the current state of Canada's freshwater biology to bend the curve in biodiversity loss.

While our Canada-wide study identifies substantial proportions of at risk and data deficient species, similar trends have been observed on many scales across the globe. Abundances of freshwater insects (Sánchez-Bayo and Wyckhuys 2019; Wagner 2020), freshwater fish populations (Freyhof and Brooks 2017; WWF 2021), especially large fishes such as sturgeon and paddlefish (Carrizo et al. 2017; He et al. 2019), as well as freshwater reptiles (Gibbons et al. 2000) and amphibians (Gibbons et al. 2000; Vences and Köhler 2007), have been declining at local and regional scales throughout a range of latitudes (Albert et al. 2021). The Living Planet Index, which evaluates closely monitored vertebrates by considering species richness, also shows that freshwater

Fig. 7. The overall status of freshwater biodiversity in Canada represented by the proportion of conservation status listings in each major taxonomic group. [Colour online.]



populations have been experiencing declines of 84% between 1970 and 2014. While it is important to note that the quantity of data prior to 1970 was limited and advances in conservation biology led to a shifting baseline syndrome (i.e., Pauly 1995; Papworth et al. 2009), the decline of freshwater biodiversity is still outpacing both the marine and terrestrial environments (WWF 2020).

Data deficiency has been identified as one of the major ongoing issues in assessing or monitoring the state of freshwater biodiversity (Balian et al. 2007). Studies that assess the state of freshwater biodiversity report high occurrences of "Data Deficient" assessments (e.g., 60% of Canada's sub-watersheds, 31.3% in the Eastern Himalayas, 21% in Central Africa, and 14.1% in North Africa; WWF-Canada 2020; Allen 2010; Brooks et al. 2011; García et al. 2010, respectively). The lack of data on the conservation status of freshwater-dependent species in Canada and throughout the rest of the world has been a limiting factor in establishing and achieving conservation goals (Darwall et al. 2011). Although some studies advocate for data deficiency to be perceived as "presumed threatened", we opted to provide a more accurate description of the current state of biodiversity by suggesting that not all data deficient species are likely to be at risk. It is important to acknowledge that conservation initiatives tailored towards addressing data deficiency can be vastly different from those that target threatened species; both are important for safeguarding biodiversity.

Considering the general declining trends and paucity in data, we advocate that it is essential to bridge the gap between freshwater ecology and conservation regardless of incomplete knowledge to ensure sustainable freshwater resources (Strayer and Dudgeon 2010; Albert et al. 2021). Targeting key areas and unique ecosystems that are home to a diversity of taxa (e.g., key biodiversity areas, Eken et al. 2004) can prevent further decline while avoiding taxonomic bias. As we improve protocols and grow reference libraries, it is possible that major leaps forward in biodiversity assessments across landscapes and through time (by studying natural archives such as lake sediment cores) will be possible by adopting environmental DNA analyses in routine monitoring programs (Bálint et al. 2018; Pérez-Jvostov et al. 2020). Although the current state of freshwater biodiversity in Canada is alarming, the future will be largely shaped by the timely implementation of the Emergency Recovery Plan to bend the curve of freshwater biodiversity loss (Tickner et al. 2020). This plan recommends a number of actions that targets key threats, such as improving water quality, implementation of environmental flows, protecting and restoring critical habitats, managing the exploitation of freshwater ecosystem resources, preventing and controlling non-native species invasions, and restoring river connectivity (Tickner et al. 2020). Implementing the plan will require the collective action of many including practitioners (Twardek et al. 2021) and communities (Arthington 2021).

4.0. Conclusion

Canada has the third largest reservoir of fresh waters of any country. Yet, there is a paucity of knowledge surrounding the status of much of Canada's freshwater biodiversity. To address this knowledge gap, the most recent data on the conservation status of freshwater species in Canada were compiled and analysed. Our analysis revealed that 11.7% (367) of freshwater species were considered to be at risk, 50.5% (1575) of species were not considered to be at risk ("Special Concern" or "Not at Risk"). The remaining 37.9% (1186) of species could not be classified due to the lack of available data. Given the importance of freshwater biodiversity to ecosystems and societies alike, the 11.7% that were at risk, extirpated or extinct, and the 37.9% without data to assess their status, suggests emergency action is needed. We advocate for a coordinated call-to-action by public and private sectors as well as citizens to improve our state-of-knowledge on freshwater biodiversity, to overcome knowledge gaps, and to work to reduce if not reverse the freshwater biodiversity declines.

We acknowledge that knowing the state of freshwater biodiversity is not a prerequisite for embracing the emergency action plan (Tickner et al. 2020) but doing so will be important to assess progress. Although we certainly call for more monitoring and assessment (such as the recent GEO BON initiatives that are being downscaled and in Canada will presumably lead to a CAN BON initiative; see https://www.theglobeandmail.com/canada/article-harmonizing-co-ordinating-scientific-initiatives-key-to-filling-gaps/), we also recognize the importance of action. Indeed, a recent analysis in Canada suggested that although lack of knowledge about the status of biodiversity was important, the most significant barrier to conservation action were mechanisms to translate knowledge to action (Buxton et al. 2021). Some actions can be undertaken without explicit knowledge about the state of all aspects of biodiversity. For example, we suggest that resources be allocated towards protecting functional ecosystems that include high levels of species richness from all taxonomic groups (e.g., key biodiversity areas, Eken et al. 2004) to prevent taxonomic bias in conservation initiatives. There are also opportunities to embrace additional conservation approaches such as citizen (or community) science (Chandler et al. 2017), Indigenous knowledge systems (Reid et al. 2021; Buxton et al.

2021), and emerging technologies (such as environmental DNA; Deiner et al. 2015) to help address these deficiencies. The vast amount of fresh water in Canada does not make the country immune to freshwater threats and biodiversity loss. This paper should serve as a call to action for academia, governments, and community members alike. Freshwater biodiversity and healthy freshwater ecosystems are foundational to the well-being of all beings and peoples in Canada, and it is clear that we have major knowledge gaps that need to be overcome if we are to better ensure the continuation and effective protection of fresh waters and their biota well into the future.

Competing interests

The authors declare there are no competing interests.

Contributors' statement

This project was conceptualized by SJC, DH, PC, JED, JC, EJH, AMJ, JAR, and SS as part of a graduate course offered by SJC at Carleton University. JED, JC, EJH, AMJ, JAR, and SS contributed to the data collection and writing. JED generated figures and performed major edits. JRB, JPS, TR, JJT, ALM, AKW, JM, MKT, CMO, SAR, AJR, IFC, IG-E, NWRL, SJC, PC, and DH provided comments and guidance that greatly improved the quality of this manuscript.

Funding statement

Funding for this project was made possible through the Fulbright Canada Fellowship awarded to PC, the Social Sciences and Humanities Research Council of Canada Knowledge Synthesis Grant awarded to SJC, JB, IC, JPS, and IGE, and support from the Canada Research Chairs program and the Natural Sciences and Engineering Research Council of Canada.

Data availability statement

Data are available with the published manuscript online through the journal website.

Acknowledgements

We thank the two anonymous reviewers for their input that greatly improved the quality of this manuscript.

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