Fisheries and Oceans Canada
Pêches et Océans Canada

Ecosystems and Oceans Science
Sciences des écosystèmes et des océans

National Screening-Level Risk Assessment (SLRA) of Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie in Canada

J.M. Hill[1], M. Simard[1], A.M. Weise[1], J. Hubbard[2], S. Kingsbury[3]

[1]Fisheries and Oceans Canada
Maurice Lamontagne Institute
850 route de la mer
Mont-Joli, QC G5H 3Z4
Canada

2Department of Physical and Environmental Sciences
University of Toronto Scarborough
1265 Military Trail
Scarborough, Ontario, M1C 1A4
Canada

3Fisheries and Oceans
BIO, Polaris Building 5Th Floor
1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2
Canada

December 2025

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Correct citation for this publication:

Hill, J.M., Simard, M., Weise, A.M., Hubbard, J., and Kingsbury, S. 2025. National Screening-Level Risk Assessment (SLRA) of Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2025/023. ix + 90 p.

Aussi disponible en français:

Hill, J.M., Simard, M., Weise, A.M., Hubbard, J., et Kingsbury, S. 2025. Évaluation nationale sommaire des risques (ESR) du poisson rouge, de la carpe Prussienne, du brochet maillé et de la marigane noire au Canada. Secr. can. des avis sci. du MPO. Doc. de rech. 2025/023. ix + 103 p.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Aquatic invasive species (AIS) are species introduced or spread to ecosystems beyond their natural range that threaten biodiversity, economy, and society. Recently, four freshwater fishes were identified as being of concern for Canadian freshwaters: Goldfish (*Carassius auratus*), Prussian Carp (*Carassius gibelio*), Black Crappie (*Pomoxis nigromaculatus*) and Chain Pickerel (*Esox niger*). The latter two species are native in some regions of Canada, while the carps are strictly non-indigenous. All four species currently have at least one non-indigenous population established in Canada and are undergoing range expansions. A screening-level risk assessment (SLRA) was performed using an adaptation of the Canadian Marine Invasive Screening Tool (CMIST) to identify the level of risk (high, moderate, or low) of these four species across freshwater ecoregions in Canada. SLRAs help decision-makers identify which species pose substantial threats to native species/ecosystems and which may consequently require detailed-level risk assessments. Of the four species assessed, Goldfish presented the highest invasion risk across Canada, especially in southern ecoregions. Prussian carp was a high-risk species in ecoregions within Western Canada and invasion risk of both carps was moderate in all remaining ecoregions. Chain Pickerel was of high risk in New Brunswick and Nova Scotia (and moderate elsewhere, but low in the Arctic), while Black Crappie was of moderate risk everywhere except the Arctic (low risk). High frequency of arrival and a strong potential for dispersal via anthropogenic mechanisms can be correlated to the presence of established AIS populations within an ecoregion (or adjacent ecoregions), because established AIS populations increase future introduction potential. These three correlated factors were the primary likelihood of invasion drivers underpinning risk predictions in this work. Evidence in the literature of impacts on populations, communities, ecosystem functioning, and habitat in their native or invaded range were the primary impact of invasion factors which contributed to elevated final risk levels. A lack of information on the impacts of Black Crappie invasion lowered its risk levels and associated certainty, showing that the availability of information (e.g., on impacts and dispersal mechanisms) played an important role in final determinations of risk. For all four fishes across Canadian ecoregions, some uncertainty in the data means that assessments of moderate risk may reflect the middle point of two potential extremes (i.e. high and low), but true risk may be anywhere from high to low. Low risk is unlikely to be no risk, but nor is it likely to be high risk. Consequently, heatmaps showing risk levels should be used in conjunction with biplots of likelihood and impact scores in order to understand the range in scoring and the certainty associated with likelihood and impact of invasion scores underpinning risk for each fish in each ecoregion. High uncertainty around anthropogenic introductions and activities and the spatial scales over which they operate contribute to greater uncertainty of the risk level for all fishes. Detailed-level risk assessments at finer spatial scales may be pertinent to complete for each species and ecoregion identified here as at high risk for invasion.

GLOSSARY

ABBREVIATIONS

AIS: Aquatic Invasive Species

CMIST: Canadian Marine Invasive Screening Tool (see Drolet *et al.* 2016)

DFO: Fisheries and Oceans Canada

SLRA: Screening-level Risk Assessment

DLRA: Detailed-level Risk Assessment

SME: Subject Matter Expert

DEFINITIONS

Aquatic invasive species: A non-indigenous aquatic species (e.g., fish, animal, or plant species) that may have a negative ecological, human health, and/or economic impact after its introduction, establishment, and/or spread into a new ecosystem. Aquatic invasive alien species, non-indigenous species (NIS), non-native species, nuisance species, invaders, exotic, and introduced species are often used as synonyms in the literature.

Biplots: Graphs showing the mean likelihood of invasion score on the y-axis and the mean impact of invasion score on the x-axis, with the associated 95% confidence (certainty) intervals for each fish species and ecoregion.

Heatmap: Visual representation of the final risk category for each fish species across Canadian ecoregions, categorized in three levels: low, moderate, and high.

Impact of invasion score: The mean impact of invasion score calculated across questions 9 to 17 and subsequently categorized in three levels: low, moderate, and high. Impact of invasion estimates the potential for a species to affect ecosystem functioning and services, native species population abundances or assemblages, and affect vulnerable species such those listed under the *Species At Risk Act*.

Likelihood of invasion score: The mean likelihood of invasion score calculated across questions 1 to 8 and subsequently categorized in three levels: low, moderate, and high. Likelihood of invasion estimates the potential for a species to be introduced, establish, and reproduce within an assessment area.

Native species: A species that occurs naturally in a given area or habitat (i.e., historical range), as opposed to an introduced species or invasive species. Indigenous species is used as a synonym in the literature.

Native range: The geographical area where a species originated from.

Pathway: The mode, mechanism, and activity (including the geographic route) by which an invasive species is transferred from one ecosystem to another.

Propagule: Viable organisms (plant, animal, spore, or part thereof, capable of independent growth) that functions in propagating an organism to the next stage in its life cycle.

Risk score: The score representing final assessments of screening-level risk for each fish species and ecoregion. This is calculated by multiplying together the mean likelihood score by the mean impact score, after being adjusted using confidence intervals drawn from Monte Carlo probability distributions based on associated certainty estimates (i.e., adjusted CMIST score).

Risk scores are then categorized as low (CMIST scores of 1 to 3), moderate (CMIST scores of 3.1 to 6), or high (CMIST scores of 6.1 to 9) levels of risk.

Vector: The physical means by which an invasive species is transported from one area to another. These vectors can be natural (e.g., wind, currents, and animals) or anthropogenic (e.g., ballast water, hull fouling, aquaculture, and aquarium trade).

1. INTRODUCTION

Aquatic invasive species (AIS) are species that are introduced or spread to ecosystems beyond their natural range that have net negative impacts on ecosystem functioning, including (but not limited to) impacts on freshwater biodiversity (Bellard *et al.* 2016), ecosystem services (Kumschick *et al.* 2015), and/or human health and wellbeing (Ogden *et al.* 2019; Jones *et al.* 2017), and which often have serious economic consequences (Jackson 2015; Diagne *et al.* 2021). A variety of invasion pathways contribute to the ongoing spread of species farther from their native ranges, at faster and in greater numbers than historically seen, both within Canada and on a global scale (Ricciardi 2007; Seebens *et al.* 2017). However, there is some evidence that recognition of important pathways of introduction and secondary spread, and efforts to manage these pathways maybe, slowing the rate of introduction in some regions. For example, recent regulations mandating saltwater flushing of ballast water (Government of Canada 2006; Saint Lawrence Seaway Development Corporation 2008) have plausibly contributed to a reduction of invasive species establishment in the Great Lakes (Ricciardi and MacIsaac 2022). However, other pathways of introduction are of substantial concern to Canada, despite some regulatory progress in some provinces (e.g., Davidson *et al.* 2021). Pathways of concern include (but are not limited to) live food and aquarium trades (Crossman and Cudmore 1999; Chan *et al.* 2022), recreational fishing (Mills *et al.* 1993; Kilian *et al.* 2012; Drake and Mandrak 2014), compassionate/spiritual release (Campbell *et al.* 2021), and through unaided dispersal via connectivity between Canadian water bodies and those of the United States (Currie et al. 2012; Brown and Therriault 2022). Furthermore, the deliberate illegal movement and stocking of native species to some regions in Canada has contributed to range expansion and the introduction of these species outside their native range, which has the potential to cause negative impacts on the recipient ecosystems, e.g., Smallmouth Bass *Micropterus dolomieu* (Lacepède 1802; Chaput and Caissie 2010; O'Sullivan *et al.* 2020) and Northern Pike *Esox lucius* (Linnaeus 1758; Cathcart *et al.* 2019).

Recently, the potential ecological impacts of four freshwater fish species were identified as being of particular concern across Canada: Goldfish *Carassius auratus* (Linnaeus 1758), Prussian Carp *Carassius gibelio* (Bloch 1782), Chain Pickerel *Esox niger* (Lesueur 1818) and Black Crappie *Pomoxis nigromaculatus* (Lesueur 1829). The latter two species are native in certain regions of Canada, while Goldfish and Prussian Carp are strictly non-indigenous. Currently, all four species have at least one established non-indigenous population in Canada (often more) and are undergoing range expansions.

Originally a cyprinid native to China, the popularity of Goldfish in the aquarium trade has resulted in widespread distribution throughout the world (Welcomme 1988; Courtenay and Stauffer 1984). It is believed to have arrived in North America in the late 17th century and is considered the first non-indigenous fish to have become established in the United States (Ford and Beitinger 2005). Goldfish is thought to have been originally spread via deliberate releases by the U.S. Fish Commission (McDonald 1887; McDonald 1893), by hobbyists and fishers using them as live bait (Courtenay and Stauffer 1984), and through escape from outdoor ponds during flood events (Courtenay *et al.* 1984). Its current primary pathway of introduction is thought to be through the aquarium and water garden trade (Rixon *et al.* 2005; Gertzen *et al.* 2008). In recent years, Goldfish has been increasingly documented in the media due to substantial numbers, conspicuous aggregations, and impressive size of wild populations (Dalbey and Staff 2018). At least one established Goldfish population has been reported from the majority of Canadian provinces and territories (Nico *et al.* 2022; Bernatchez and Giroux 2012) and tens of thousands of Goldfish have been found in stormwater ponds across the country, including the provinces of British Columbia, Alberta, Manitoba, Saskatchewan and Ontario (Franklin 2020; Van Dongen 2021; Boston *et al.* 2023; CBC News 2023), with ever increasing densities in associated local

wetlands and adjacent waterways (Dhopade 2021; Butler 2022). The capacity of Goldfish to tolerate anoxic and/or disturbed environments, combined with extremely wide temperature tolerances (e.g., Moyle 2002) allows it to outcompete native fishes for both space and food resources in many freshwater systems. Consequently, there is substantial concern that Goldfish invasions may significantly reduce ecosystem biodiversity (Richardson 1991; Richardson and Whoriskey 1992; Richardson *et al.* 1995; Monello and Wright 2001; Kolmakov and Gladyshev 2003; Morgan and Beatty 2004).

Prussian Carp is a cyprinid originally native to central Europe, Siberia, and northern China (Kottelat and Freyhof 2007 cited in Britton, 2011). It has been introduced and cultured for food production in Europe since the 1600s (Savini *et al.* 2010) and was intentionally introduced to western Europe for angling, resulting in extensive spread (Vetemaa *et al.* 2005; Tarkan et al. 2012). The only known established populations of Prussian Carp in continental North America are in southern Alberta and southern Saskatchewan waterways, where large abundances have been documented (Elgin *et al.* 2014, Docherty *et al.* 2017; Halas *et al.* 2018). Prussian Carp has been identified as a distinct carp species (Kottelat 1998; Fricke *et al.* 2024), but historically has been known by a variety of names including wild Goldfish, Gibel Carp, and Silver Crucian Carp (Zhou *et al.* 2000; Copp *et al.* 2005a; Tsipas *et al.* 2009; Kottelat and Freyhof 2007). With the variety of names and a history of misidentification (Vetemaa *et al.* 2005, Kottelat and Freyhof 2007; Paulovitis *et al.* 2014), its current global distribution is likely due to its inadvertent transportation with stocks of other carp species (Kottelat and Freyhof 2007) for sale in the live food and/or aquarium trade pathways (Elgin *et al.* 2014). With ecosystem impacts similar to those of Goldfish (and other carps), Prussian Carp is considered a high risk species for the contiguous US (USFWS 2019) and the Laurentian Great Lakes (Fusaro *et al.* 2016).

Chain Pickerel's native distribution includes the Atlantic coastal plains, from Maine to southern Florida, and passes through the Gulf of Mexico states to the Nevasota River in Texas. Its range follows the Mississippi River basin up to the Tennessee River in Alabama, and then north to Kentucky and Missouri (Coffie 1998; Fuller *et al.* 1999). In Canada, Chain Pickerel is considered native to the Eastern townships in southern Quebec and north to the St. Lawrence River (Scott and Crossman 1998; Coffie 1998; Carlson *et al.* 2016). Extensive translocations of Chain Pickerel to promote new sportfishing opportunities have been reported dating as far back as 1819 in Canada (Williamson 1832 cited in Whittier *et al.* 1997) and have resulted in detections in Lake Ontario (Fuller *et al.* 1999; Hoyle and Lake 2011), New Brunswick (Scott and Crossman 1959), and Nova Scotia (Gilhen and Pentz 1974). Recently, a catch-and-retain policy has been implemented in some invaded ecosystems, where a few provinces now have regulations which prohibit their release into other waterbodies (N.S. Reg. 212/2012). The species is not an important sport fish in Quebec compared with other species in the province (Scott and Crossman 1998) and while the species is considered invasive in Nova Scotia and New Brunswick, Quebec is planning to designate Chain Pickerel as threatened or vulnerable (MELCCFP 2023) within its provincial borders. Chain Pickerel is an ambush and opportunistic predator with a variable diet, including fishes, insects, crayfish, snake, frogs, and mice (Scott and Crossman 1998, Coffie 1998). Low water turbidity (Meyers and Muncy 1962), slowly moving current, and good macrophyte cover contribute to its predatory success (Armbruster 1959). Combined with wide pH (Duplinsky 1982), temperature (Scott and Crossman 1998), and salinity tolerances (Lee *et al.* 1980), this species has led to the decline of multiple native fish populations in Nova Scotia (Edge and Gilhen 2001; Bradford *et al.* 2004; Mitchell *et al.* 2012) and is considered a threat to some species at risk, in particular Rainbow Smelt *Osmerus mordax* (Mitchill 1814) in Lake Utopia, New Brunswick (Gautreau and Curry 2020) and Atlantic whitefish *Coregonus huntsmani* Scott, 1987 in Nova Scotia (DFO 2018).

Black Crappie was included in this work because of its recent invasion into Big Lake, Millville, New Brunswick in 2019 (McAlpine *et al.* 2020; Powell 2022). There is a need to evaluate the potential risk of spread through the main watersheds of the province, especially the Saint John and Mactaquac rivers, and to determine the likelihood of impacts on native fish ecology and fishery activities (Powell 2022). In North America, introductions for recreational angling purposes began in the 1800s, followed by aquaculture activities for the stocking of sport fishing ponds (Culpepper and Allen 2016; Fuller *et al.* 2022). Due to these widespread governmental stocking events and illegal introductions to create new fishing opportunities (Fuller *et al.* 1999; Page and Burr 2011), the original native distribution of Black Crappie is unclear. However, Black Crappie is currently considered native to eastern and central North America, with a wide-ranging distribution that includes multiple US states (western Alabama, Florida, central Texas, Oklahoma, South and North Dakota, eastern Montana and western New York). In Canada, its native distribution is considered to be southern Quebec, and the Great Lakes in southwestern Ontario (Scott and Crossman 1998; Fuller *et al.* 1999; Pariseau *et al.* 2009; USGS 2022). As a consequence of repeated historical stocking events (Mosindy 1995; VanBroeck 1995; Kerr 2006) and due to the opening of the Rideau and Trent-Severn canals, illegal releases into new watersheds and natural dispersal through connected streams (Krishka *et al.* 1996), Black Crappie is now distributed along the Great Lakes and northwestern Ontario to parts of southern Manitoba (Scott and Crossman 1998; Kerr 2006; Holm *et al.* 2021). It has also been introduced to British Columbia (Quinn and Paukert 2009; Carl and Guiguet 1958 cited in Powell 2022). Black Crappie is tolerant to anthropogenic disturbance (Whittier *et al.* 1997), suggesting it may have higher fitness in these areas than other native fishes.

Both carp species have adaptations that might provide competitive advantages over other species, and which help them survive Canadian winters. Goldfish can survive days or weeks without oxygen at low temperatures (Lutz and Nilsson 1997; Nilsson 2001; Bickler and Buck 2007) by using their skeletal muscles to convert anaerobically produced lactic acid into ethanol, which can diffuse freely across their gills into the surrounding water (Shoubridge and Hochachaka 1980; Fagernes *et al.* 2017). Prussian Carp can hide in mud at the bottom of lakes or ponds to avoid freezing (DeGiosa *et al.* 2014), survive anoxia for 5 - 6 months (Blazhka 1958, 1960 cited in Holopainen *et al.* 1997), and at low temperatures, will accumulate glycogen in its liver a few months before winter to support fasting under the ice. The remaining two species, Black Crappie and Chain Pickerel can survive at low oxygen levels (Cooper and Washburn, 1949; Tang *et al.* 2020) and tolerate low water temperatures, as they are both active feeders under ice, making them popular ice fishing sport fishes (Parsons and Reed 1998; Scott and Crossman 1998).

Screening-level risk assessments (SLRA) are tools used to estimate the invasion risk of potentially invasive or problematic species, facilitating the development of policy and management procedures in particular areas/regions/watersheds for the purpose of preventing/mitigating the impacts of biological invasions (Copp *et al.* 2016a). Through the use of SLRAs, decision-makers can concentrate limited resources to areas of high likelihood of invasion and where ecosystems are expected to be heavily impacted by non-indigenous species. Additionally, SLRAs help prioritize species and areas that might require comprehensive (detailed-level) risk assessments (DLRA) and identify knowledge gaps where further research is needed (Copp *et al.* 2005b, Copp *et al.* 2016a; Mumford *et al.* 2010; Mandrak *et al.* 2012; Mandrak and Cudmore 2015). Unlike SLRAs, DLRAs typically involve detailed examination of the likelihood and magnitude of risks of: (i) introduction; (ii) survival; (iii) establishment (of one or more self-sustaining populations); (iv) dispersal (secondary spread); and (v) impacts (to native biodiversity, ecosystem function and services etc.), using data/information more specific to certain areas/regions/watersheds (Mandrak *et al.* 2012). Canadian examples of DLRAs include that for New Zealand mud snail (Therriault *et al.* 2011) and dreissenid mussels (Therriault *et al.*

2012; Wilcox *et al.* 2024) in Canada, and grass carp in the Great Lakes basin (Cudmore *et al.* 2017).

None of these four species are listed in the DFO Aquatic Invasive Species Regulations (SOR/2015-121), and a lack of understanding on their potential impacts in Canadian ecosystems, hampers the ability of AIS managers to prioritize these species for listing and subsequent action where needed, such as population controls or prevention of new introductions. Consequently, the Aquatic Invasive Species National Core Program requested SLRAs for Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel to identify regions at risk of invasion, and to inform decision-making and the prioritization of management actions aimed at preventing their introduction and spread in Canadian waters.

Recommendations stemming from this science advice could be used to inform management and policy on mitigating freshwater fish invasions across Canada. The objectives of this advisory process were to:

1. Perform a SLRA for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie in Canadian freshwater ecoregions, considering their likelihood of introduction, potential ecological impacts, and changes in absolute risk under a current and projected climate scenario; and,

2. Determine how results across freshwater ecoregions influence conclusions at the national level.

2. MATERIALS AND METHODS

2.1. CANADIAN MARINE INVASIVE SCREENING TOOL AND MODIFICATIONS

The Canadian Marine Invasive Screening Tool (CMIST) is a score-based SLRA that includes a series of 17 questions (each of which is also scored for certainty) used to estimate the risk of aquatic non-indigenous species (DFO 2014; Drolet *et al.* 2016). The CMIST questions are designed to broadly evaluate the likelihood of invasion (present status and potential of introduction, survival, establishment, and spread; questions 1-8) and the potential ecological impacts (questions 9-17) of an AIS in a defined assessment area (Drolet *et al.* 2016). For this SLRA, some CMIST questions were answered using a combination of individual, separately scored variables (where each variable was scored separately with associated certainty), to incorporate multiple factors which might influence each question. A brief description of the scoring considerations for each question is provided in Table 2 and detailed guidance on how each question and associated certainty was scored (including how to determine final scoring for each question which incorporated multiple variables) can be found in Appendix 1. Due to lack of information (and certainty) pertaining to species' impacts on socio-economics, CMIST question 16 was excluded from this SLRA.

2.2. ECOREGIONS

The CMIST scores were determined for each species (Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie) for each Canadian freshwater ecoregion (21 ecoregions) as defined by Abell *et al.* (2008;available at https://www.feow.org/), which used cluster analyses of distinct fish community assemblages within freshwater communities to categorize watersheds into ecoregions across the globe (Figure 1, Table 1). This approach, outlined in Brown and Therriault (2022), permits assessment of AIS across Canada's complex landscape, which is not only extensive but has one of the largest and most diverse ranges of freshwater habitats in the world (Messager *et al.* 2016). Fishes were not assessed within their native ranges, considered here to be Ontario (ecoregion 116, Great Lakes only) and Quebec (117) for Black Crappie; and

Quebec (117) only for Chain Pickerel (Scott and Crossman 1998; Coffie 1998; Holm *et al.* 2021).

2.3. INCORPORATING EXPERT OPINION

Expert opinion was gathered from panels of subject matter experts (SMEs) with local knowledge/experience, across seven DFO regions (Gulf, Maritimes, Newfoundland and Labrador, Quebec, Ontario and Prairie, Pacific, Arctic). SMEs were comprised of federal and provincial biologists, and academic researchers who were invited to answer the CMIST subject to the most regional variability (i.e. 1, 2, 3, 6, 7, 8, 15). SME knowledge contributed to region-specific information and filled knowledge/data gaps on some species and/or ecoregions. Questions and pertinent background information for each species (gathered via literature reviews to support the CMIST assessments) were sent out to panel participants prior to discussion. Panel discussions took place virtually and panel members discussed the background information and personal observations, and then each expert provided a likelihood (Q1-3, Q6-8) or impact of invasion (Q15) score along with associated certainty for these questions. Final expert-opinion scores were determined via panel consensus. Expert-opinion scores were incorporated into the scoring rubric for this SLRA as described in Table 2 and Appendix 1.

As ecoregions regularly overlapped multiple provincial and territorial boundaries, and SME knowledge was often applicable to general areas within their regions of expertise (e.g., southern Alberta), SME knowledge was applied to ecoregions where the SME was confident in their knowledge and to ecoregions that overlapped with their regions of expertise. For example, the Ontario and Prairie (O&P) DFO region includes four provinces and 10 ecoregions and not all SMEs had the same expertise across all ecoregions. Consequently, final ecoregion risk scores were based on the opinion of the SME with the most experience in the ecoregion that primarily overlapped with their area of focus. For example, in the O&P DFO region, the SME from Alberta determined the risk scores for ecoregions 104 and 107, where the SME from Manitoba determined the risk scores for ecoregions 109 and 142. In cases where an ecoregion spanned multiple provinces, only the opinion of the SME working in the province that encompassed the majority of the ecoregion was considered.

Finding SMEs for ecoregions in Nunavut, the Northwest Territories, Labrador and Nunavik was more complicated, with no availability for panel discussions and minimal information on AIS. Some information was provided for question 1 from biologists working in these regions, however, little else was available. Due to the knowledge gaps in northern ecoregions, and broadscale climate similarities among these regions, they were grouped and scored by SMEs as a single region ("Arctic") and SME knowledge was then applied to all Arctic ecoregions.

2.4. SCORING

For each fish species in each ecoregion, as directed by the CMIST tool (Drolet *et al.* 2016), each question was assigned a score ranking the likelihood or impact of invasion (1 = low, 2 = moderate, 3 = high) and the certainty (or confidence level) the assessor had in that score (1 = low certainty, 2 = moderate certainty, 3 = high certainty; modified here from Drolet *et al.* 2016; Drolet *et al.* 2017). Certainty was assessed by the confidence the assessor had in the data used to answer each question (quality and quantity) and does not represent ecological variability. For example, scoring of the impact of invasion questions were based primarily on the quantity of published studies demonstrating impacts of invasive fishes on native species or ecosystems. However, to be conservative in the impact of invasion scoring, opposing outcomes (i.e. studies that showed no or opposite impacts) were not considered, as these do not invalidate the impacts seen elsewhere. However, in this assessment almost no opposing outcomes were

identified for any of the invasive fishes. For CMIST questions that incorporated multiple variables, each variable was scored separately (for both likelihood/impact of invasion scores and associated certainty) and then a final score (and certainty) for each question was determined following the guidance in Appendix 1. In general, certainty was considered high when:

- Historical and best available data were used;

- Experts had experience with the AIS in the assessment area;

- There was agreement between the scores of the different variables in a question; and/or,

- When multiple published studies were available showing a particular type of impact.

Full details on how likelihood/impact of invasion scores and certainty scores were determined for each question (including information on data sources) can be found in Appendix 1.

To better understand if currently suitable environmental conditions will be affected by a changing climate (e.g., Canadian temperatures at northern latitudes are warming rapidly, potentially increasing suitable AIS habitat in these regions) and if these changes will affect invasion risk for Goldfish, Prussian Carp, Chain Pickerel and Black Crappie Canadian freshwater ecoregions, two questions (Q4-5) were re-scored using the Euclimatch R package (Hubbard *et al.* 2023) and the same climate-match procedure outlined in Appendix 1, under the Worldclim v2.1, period 2081-2100, and projected SSP5-8.5 high emissions climate scenario. Although there are multiple time periods and projection scenarios available, this assessment's climate scenario was selected to provide an estimate of species risk in a 'worst-case' scenario. Projected changes in global temperature and precipitation are readily available (e.g., WorldClim, CHELSA) and were considered to directly influence scoring for questions 4 (How much of the assessment area offers suitable environmental conditions for the species to survive?) and 5 (Are the species' reproductive requirements available in the assessment area?). Consequently, these questions were rescored under the projected climate scenario, which when combined with all other unchanged scores, provided an assessment of risk under this future climate scenario.

2.5. ASSESSMENT OF RISK LEVEL (I.E. INVASION RISK)

The CMIST tool calculates a CMIST score (ranging from 1 to 9) by multiplying the mean likelihood of invasion score by the mean impact of invasion score, after being adjusted by 95% confidence intervals drawn from Monte Carlo probability distributions based on the certainty estimates (see Drolet *et al.* 2016). This calculation means that each question in the CMIST tool is considered to contribute equally to the final CMIST score (Drolet *et al.* 2016; but see also limitations section of this document). For this SLRA, final CMIST scores were calculated for each fish species in each ecoregion using the CMISTScore function in the CMISTR package (Daigle, 2021) using R (version 4.1.3; R Core Team 2022).

The risk level of each fish species in each ecoregion was then categorized as low (L = CMIST scores of 1 to 3), moderate (M = CMIST scores of 3.1 to 6), or high (H = CMIST scores of 6.1 to 9) based on the calculated CMIST score. Score categorization was completed recognizing that specific numeric values of invasion risk (CMIST score 1-9) are meant to estimate risk at a screening-level only and are not DLRAs, which usually require evaluation of actual probabilities of introduction, survival, establishment, spread, and impacts. Categorization of scores enabled risk visualization over a spectrum, instead of presenting single, arbitrarily assigned values.

2.6. VALIDATION OF SCORING WITH ADDITIONAL ASSESSORS

To evaluate assessor bias, three separate assessors were given the scoring guidance document (Appendix 1) and were asked to independently score (both risk and certainty) questions for all species in all required ecoregions. Risk and certainty scores were then compared among assessors by examining the variances between assessors for each question.
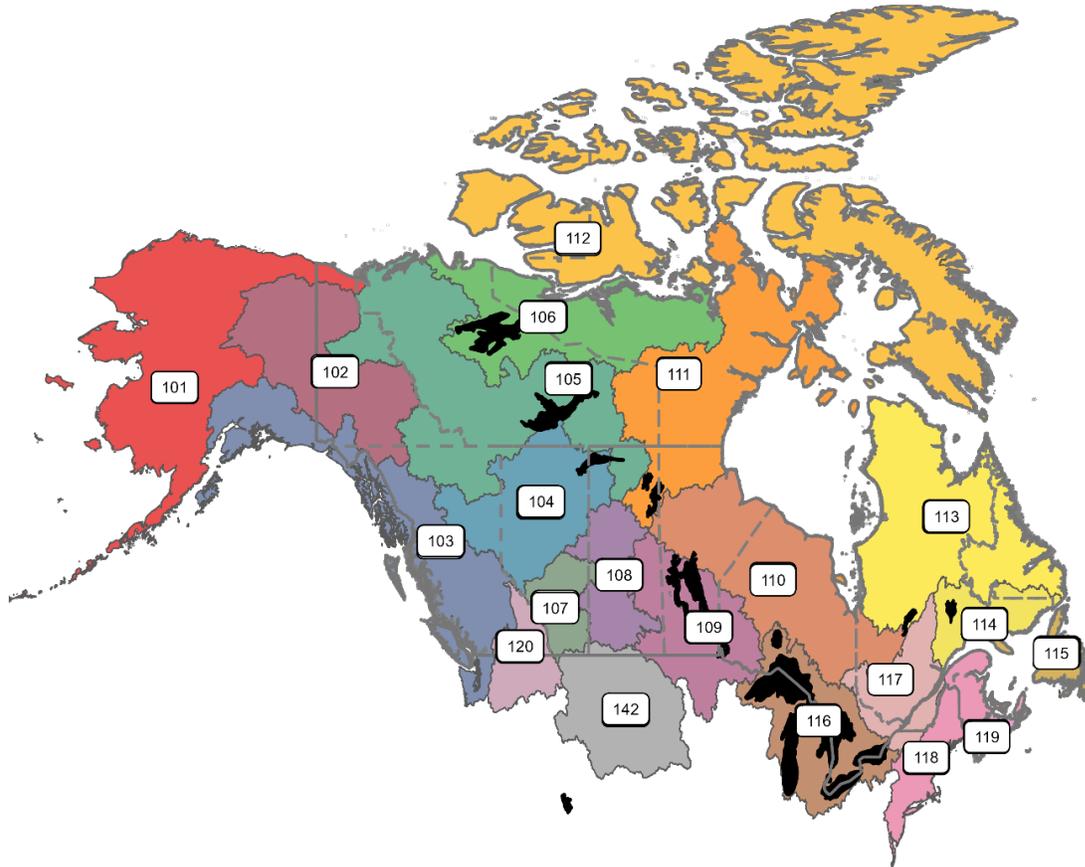
Figure 1. Freshwater ecoregions in Canada (after Abell et al. 2008).

Table 1. Canadian ecoregions defined by Abell et al. (2008; available at https://feow.org/) and associated provinces/territories. Provinces/Territories listed in decreasing order of proportion of ecoregion falling within provincial boundaries.

Ecoregion #	Freshwater ecoregions	Provinces/Territories
101	Alaskan Coastal	Y.T., N.W.T.
102	Upper Yukon	Y.T., B.C.
103	Alaska & Canadian Pacific Coastal	B.C., Y.T.
104	Upper Mackenzie	Alta., B.C., Sask., N.W.T.
105	Lower Mackenzie	N.W.T., Y.T., B.C., Sask., Alta.
106	Central Arctic Coastal	Nvt., N.W.T.
107	Upper Saskatchewan	Alta., Sask.
108	Middle Saskatchewan	Sask., Alta.
109	English-Winnipeg Lakes	Man., Sask., Ont.
110	Southern Hudson Bay	Ont., Man., Que., Sask.
111	Western Hudson Bay	Nvt., N.W.T., Man., Sask.
112	Canadian Arctic Archipelago	Nvt.
113	Eastern Hudson Bay-Ungava	Que., N.L.
114	Gulf of St. Lawrence Coastal Drainages	Que., N.L.
115	Canadian Atlantic Islands	Que., P.E.I., N.L.
116	Laurentian Great Lakes	Ont.
117	St. Lawrence	Que., Ont.
118	Northeast US and Southeast Canada Atlantic Drainages	N,B., Que.
119	Scotia – Fundy	N.S.
120	Columbia Glaciated	B.C.
142	Upper Missouri	Alta., Man.

Table 2. CMIST questions (Drolet et al. 2016) with a summary of scoring considerations. Data sources/references (in superscript) are listed below the table. Additional information on how questions and certainties were scored and weighed are described in detail in Appendix 1.

# CMIST	CMIST Questions	Scoring Considerations
1	Is the species established in the assessment area?	Expert opinion and literature review[1]
2	How frequently and in what numbers is the species expected to arrive into the assessment area?	Aquarium trade risk[2], expert opinions on unauthorized activities/releases, freshwater connectivity[3], and expert opinion on spread dispersal
3	How much of the assessment area offers suitable habitat for the species?	Expert opinion for available habitat
4	How much of the assessment area offers suitable environmental conditions for the species to survive?	Climate Match (Historical 1981-2000)[4]
5	Are the species' reproductive requirements available in the assessment area?	Climate Match (Historical 1981-2000)[4]
6	To what extent could natural control agents slow the species' population growth in the assessment area?	Resistance to invasion[5] and expert opinion on likelihood of natural control factors
7	What is the range of the species' potential natural dispersal in the assessment area?	Freshwater connectivity[3] and expert opinion on natural dispersal constraints linked to natural/artificial barriers
8	What is the range of the species' potential dispersal in the assessment area from anthropogenic mechanisms?	Expert opinion on unauthorized activities/releases and on anthropogenic dispersal constraints linked to natural/artificial barriers
9	What level of impact could the species have on population growth of other species in the assessment area?	Impact on population growth (scientific literature)
10	What level of impact could the species have on communities in the assessment area?	Impact on communities (scientific literature)

# CMIST	CMIST Questions	Scoring Considerations
11	What level of impact could the species have on habitat in the assessment area?	Impact on habitat (scientific literature)
12	What level of impact could the species have on ecosystem function in the assessment area?	Impact on ecosystem function (scientific literature)
13	What level of impact could the species' associated diseases, parasites, or travelers have on other species in the assessment area?	Impact of associated diseases, parasites, or travelers on other species (scientific literature)
14	What level of genetic impact could the species have on other species in the assessment area?	Genetic impact on other species (scientific literature)
15	What level of impact could the species have on at-risk or depleted species in the assessment area?	Expert opinion on impact of species at risk and COSEWIC listed AIS threats reported for species at risk[6]
16	What level of impact could the species have on aquaculture and commercially fished species in the assessment area?	Question removed.
17	Is the species known or generally considered to be invasive anywhere in the world?	Literature review (scientific literature)

[1]iNaturalist (2022), EDDMapS (2022), U.S. Geological Survey (2022), GBIF.org (2023); [2]Chan *et al.* (2022), [3]Lehner and Grill (2013), [4] Campbell *et al.* (2022), Anas and Mandrak (2021), Marcer *et al.* 2022, Froese and Pauly 2022, Lehner and Grill 2013, Crombie *et al.* 2008; Pheloung 1996, Abell *et al.* 2008, Bomford *et al.* 2010; Howeth *et al.* 2016, Fick and Hijmans 2017, R Core Team 2022, www.worldclim.org, [5]Chu *et al.* (2015), [6]Potts *et al.* (2023).

3. RESULTS

Overall, species had a higher likelihood of invasion (Figure 2; larger-scale biplots available in Supplementary Material B) in southern Canada, especially if an ecoregion had already, or was near another ecoregion with, an established population of these AIS. In most ecoregions, most species had, at a minimum, moderate ecosystem impacts at a minimum (Figure 2). These biplots allow detailed comparisons of the likelihood and impacts of invasion of the four fish species between ecoregions, but do not represent final assessments of risk. Final screening-level assessments of risk are presented as heatmaps (Figure 3) and were higher for southern Canada than northern Canada, reflecting the combination of likelihood and impact of invasion scores. Due to the differences driving species' risk scores and associated uncertainty, the heatmaps (Figure 3) should be interpreted alongside the biplots (Figure 2).

3.1. GOLDFISH

The likelihood of invasion and impacts of invasion scores for Goldfish were moderate-high in all ecoregions except 101, 105, and 111 to 114 (Figure 2, Supplementary Material B), which represent most of northern Canada. Likelihood scores were driven by the presence of established populations, the potentially high frequency of arrival, substantial suitable habitat, a high climate match for survival and reproduction (except in ecoregions 106, 111 and 112), and an elevated potential to disperse through natural and anthropogenic vectors (Table 3). Impact of invasion scores were driven primarily by substantial impacts on population growth rates and community interactions of native species and species at risk, impacts on ecosystem function, being carriers of multiple reportable diseases, and the ability to act as ecosystem (habitat) engineers (Table 4). Overall, certainty around impact of invasion scores was higher than that of likelihood of invasion. Heatmaps of invasion risk for Goldfish illustrated that all southern ecoregions were at high risk for invasion, while other ecoregions in Canada were at moderate risk. No ecoregion was determined to be at low risk (Figure 3).

3.2. PRUSSIAN CARP

The likelihood of invasion and impacts of invasion scores for Prussian Carp were moderate-high in all ecoregions except in 105 and 112 to 115 (Figure 2, Supplementary Material B). Likelihood of invasion scores were higher than Goldfish in 11 out of 21 ecoregions. The ability of the species to establish and spread were underpinned by the same drivers identified for Goldfish, but with fewer established populations, a slightly higher climate match for survival and reproduction, and lower resistance to invasion (expert opinion on the presence of natural control factors and ecoregion associated biodiversity and stress metrics evaluated in Chu *et al.* 2015). Although underpinned by similar drivers and additional reproductive interference, impact scores were lower than Goldfish, due to the lack of reportable diseases and lack of evidence for impacts on at-risk or depleted species. Overall, certainty around impact of invasion scores was higher than that of likelihood of invasion scores. Final assessments of risk indicated that the ecoregions spanning most of Saskatchewan, Alberta, and British Columbia (103, 104, 107, 108) were at high risk of invasion, and all other ecoregions were at moderate risk to Prussian Carp invasion (Figure 3).
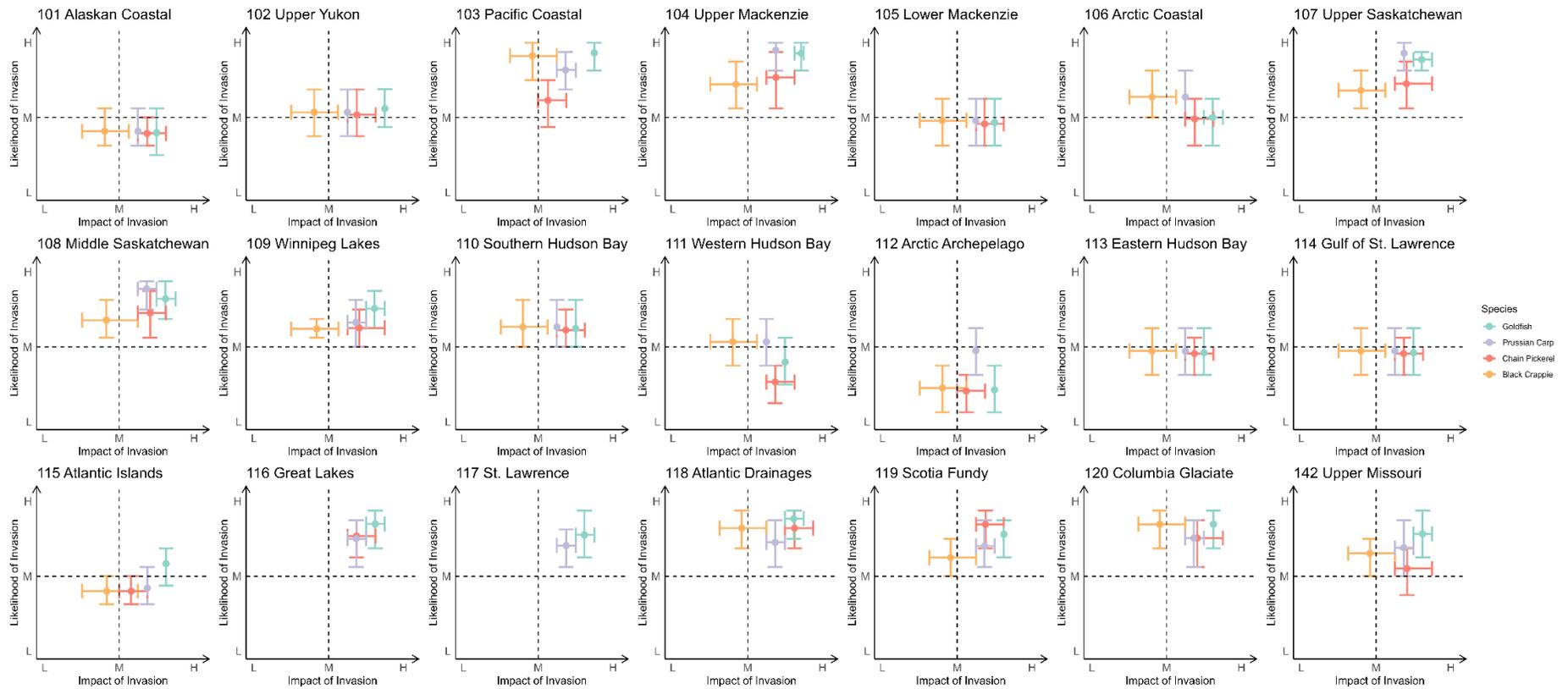
Figure 2. Likelihood and impact scores (low (L), moderate (M), and high (H)) for each numbered ecoregion (panels) for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie. 95% confidence intervals are represented by error bars which indicate overall certainty for each axis. Here certainty describes confidence in data quality and not ecological variation.

Goldfish
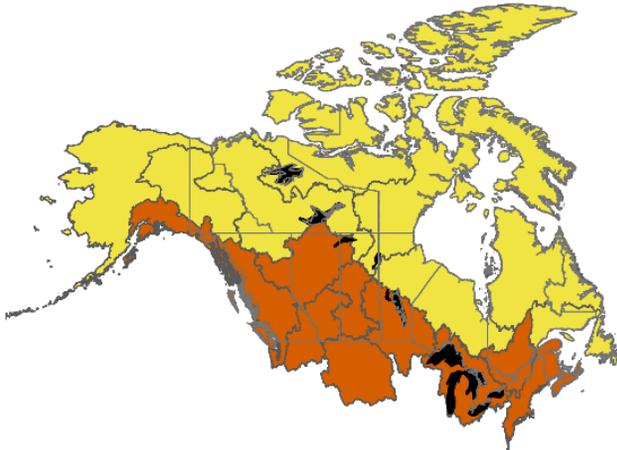
Prussian Carp
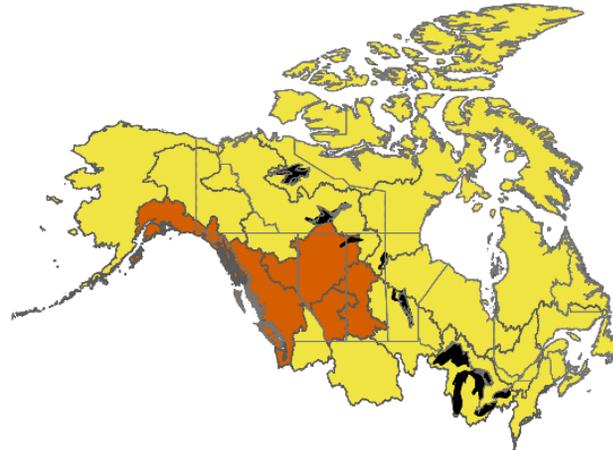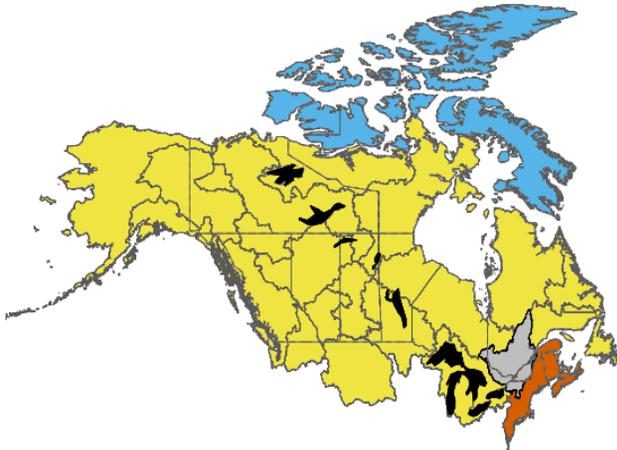
Chain Pickerel

Black Crappie

Risk Score

- low
- moderate
- high
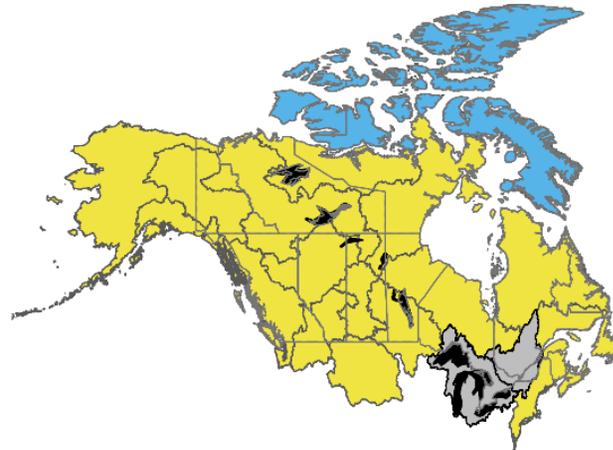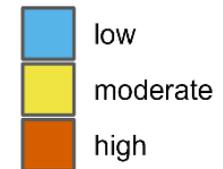
Figure 3. Heatmaps showing the final screening-levels assessments of invasion risk for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie across Canadian ecoregions. Ecoregions in grey represent native range of the species that were not scored.

3.3. CHAIN PICKEREL

Likelihood and impact of invasion scores were moderate-high in 12 out of 21 ecoregions (102, 103, 104, 107 to 110, 116, 118 to 142), which predominantly span southern Canada (with the exception of 102 and 104) (Figure 2, Supplementary Material B). High likelihood of invasion scores were driven by high frequency and number of arrivals, substantial suitable habitat, high climate match (except for ecoregions 106, 111 and 112) and an elevated potential to disperse through natural vectors (but only a moderate potential through anthropogenic vectors). Fewer established invasive populations are currently reported for Chain Pickerel than for Goldfish across Canada. Impact of invasion scores were similar to those for the two carp species, but here driven primarily by the impacts on population growth and communities of native fish species and species at risk, ecosystem function, and its ability to hybridize with other native species. There was no evidence of impacts on habitat or from associated reportable diseases. Certainty around impact of invasion scores was higher than that of likelihood of invasion scores. Final assessments of risk indicate ecoregions 118 and 119 (Figure 3) were at high risk of invasion by Chain Pickerel, whereas all remaining ecoregions were at moderate risk of invasion, with the exception of the Arctic Archipelago (112), where risk was low.

3.4. BLACK CRAPPIE

Likelihood of invasion scores was similar to Chain Pickerel in the majority of ecoregions, with a few exceptions (Figure 2, Supplementary Material B). Few established populations reported in Canada, along with a high frequency and number of arrivals, substantial suitable habitat, high climate match for survival and reproduction (except in ecoregion 112), and an elevated potential to disperse through natural vectors (but low potential through anthropogenic vectors) underpin these scores. Conversely, impacts of Black Crappie invasion were consistently lower than other fish species across all ecoregions due to only a few reported impacts on communities, and no evidence of impacts on population growth, habitat or ecosystem function. However, there is evidence that Black Crappie carries VHS (a reportable disease) and could threaten Endangered Western Silvery Minnow *Hybognathus argyritis* (Girard 1856). Certainty was lower for impact of invasion scores than for likelihood of invasion scores. Final assessments of risk show that all ecoregions were at moderate risk of invasion from Black Crappie, with the exception of the Arctic Archipelago (112), where risk was low.

3.5. CLIMATE CHANGE

Within the CMIST tool, only questions 4 (How much of the assessment area offers suitable environmental conditions for the species to survive?) and 5 (Are the species' reproductive requirements available in the assessment area?) were considered to directly influence final assessments of risk under a projected climate scenario. Given that all fishes in this work had a high climate match for the majority of all ecoregions under the historical climate scenario, there were very few instances where ecoregion climate matching was significantly higher (Appendix 1, Table 2), and no instances where the revised scoring for questions 4 and 5 changed the final risk level under the projected climate scenario. Changes in climate are likely to influence/interact with multiple biotic and abiotic ecosystem factors/stressors (e.g., habitat availability, species interactions, hydrological regimes, DO (dissolved oxygen), pH, etc.; see the limitations sections for more detail), but these cumulative effects could not be accurately assessed in this work. Consequentially, the complex interactions between species and ecosystems driven by changes in climate may increase/decrease both likelihood and impact of invasion scores and ultimately the final assessment of risk in future climate scenarios. Understanding the potentially synergistic effects of multiple co-occurring stressors, climate change in particular, on the establishment and

ecological impact of invasive species should be a priority for future risk assessments under projected climate scenarios (Ricciardi *et al.* 2021), but was out of the scope of this work.

3.6. VALIDATION OF SCORING BIAS

Assessor scores (likelihood/impact and certainty) were comparable across ecoregions for each fish species. Small variations were seen in some questions (e.g., Q1 for ecoregions 113 and 114 for Goldfish, Chain Pickerel and Black Crappie; ecoregions 104, 107, 108, 113 and 114 for Chain Pickerel and Black Crappie; Q7 for ecoregions 103 and 105 for most species; Q13 for Chain Pickerel in all ecoregions; Q15 for Goldfish in ecoregions 102 and 104). Discussions with each assessor after scoring was completed permitted an understanding of factors driving variations in scoring. Primarily, the variations were attributed to a misinterpretation of the scoring/certainty protocol, errors in ecoregion identification and in some cases, one assessor did not properly follow the scoring instructions. The scoring guidance document (Appendix 1) was subsequently revised to improve clarity for questions where assessor scoring varied. Results of this comparison can be seen in Supplementary Material C.

*Table 3. Summary of answers to likelihood of invasion questions (questions 1 to 8) for each species. Ecoregions which scored high = **H** and those which scored low = **L** are identified by number (cross reference with Table 1), all remaining ecoregions had moderate scores. The total number of ecoregions for each category is found in brackets (example: Goldfish scored high in 9 ecoregions for Q2). Fishes were not scored in their native ecoregions.*

Questions	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Established ? (Q1)[1]	Already established in the majority of southern ecoregions. **Yes:** 103, 104, 107, 109, 115 – 142 (9) **No:** 101, 105, 106, 110-114 (10)	Established in 3 ecoregions **Yes:** 104, 107, 108 (3) **No:** All remaining ecoregions (18)	Established in 3 ecoregions + native in 1 (117) **Yes:** 116, 118, 119 (3) **No:** All remaining ecoregions (17)	Established in 5 ecoregions + native in 2 (116, 117) **Yes:** 103, 109, 118, 120, 142 (5) **No:** All remaining ecoregions (14)
Arrival + frequency (Q2)[2]	Arrival (frequency and numbers) was high in 9 and moderate in 11 ecoregions, based on aquarium trade risk, unauthorized activities/ releases, freshwater connectivity and spread /dispersal risk. **H:** 103, 104, 106-108, 110, 116-118 (9) **L:** (0)	Arrival (frequency and numbers) was high in 9 and moderate in 11 ecoregions, based on aquarium trade risk, unauthorized activities/ releases, freshwater connectivity and spread /dispersal risk. **H:** 103, 104, 106-108, 110, 116-118 (9) **L:** 115 (1)	Arrival (frequency and numbers) was high in 7 and moderate in 12 ecoregions, based on aquarium trade risk, unauthorized activities/ releases, freshwater connectivity and spread /dispersal risk. **H:** 104, 106-108, 110, 118, 119 (7) **L:** 115, 142 (2)	Arrival (frequency and numbers) was high in 7 and moderate in 13 ecoregions, based on aquarium trade risk, unauthorized activities/ releases, freshwater connectivity and spread /dispersal risk. **H:** 103, 104, 106-108, 110, 118 (7) **L:** 115 (1)
Suitable habitat (Q3)	High amount of suitable habitat in majority of southern ecoregions. **H:** 103, 104, 107, 108, 115, 116, 118-120 (9) **L:** 101, 102, 105, 106, 110-114 (9)	High amount of suitable habitat in southern ecoregions. **H:** 103, 104, 107, 108, 118-120 (7) **L:** 101, 102, 105, 106, 110-114 (9)	Moderate to high amount of suitable habitat in all ecoregions. **H:** 103, 104, 107-109, 118-120, 142 (10) **L:** (0)	High amount of suitable habitat in southern ecoregions. **H:** 103, 104, 107, 108, 118-120 (7) **L:** 101, 102, 105, 106, 110-114 (9)
Suitable environmental conditions (Q4) and reproductive requirements (Q5)[3]	High climate match for majority of ecoregions **H:** 101-105, 107-110, 113-142 (18) **L:** 112 (1)	High climate match for all ecoregions **H:** 101-142 (21) **L:** (0)	High climate match for majority of ecoregions **H:** 101, 102, 104, 105, 107-110, 113-116, 118-142 (16) **L:** 111, 112 (2)	High climate match for majority of ecoregions **H:** 101-111, 113-115, 118-142 (18) **L:** 112 (1)

Questions	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Natural control agents slow the species' population growth (Q6) **(High risk: unlikely to slow invasive species' pop. growth** **Low risk: likely that species pop. growth will be restricted)**[4]	Natural control factors were moderately likely to slow population growth in the majority of ecoregions based on resistance to invasion and expert opinion. **H:** 103, 104, 119, 120, 142 (5) **L:** 101 (1)	Natural control factors were moderately likely to slow population growth in the majority of ecoregions based on resistance to invasion and expert opinion. **H:** 103, 104, 107, 116, 119, 120, 142 (7) **L:** 101 (1)	Natural control factors were moderately likely to slow population growth in the majority of ecoregions based on resistance to invasion and expert opinion. **H:** 103, 104, 119, 120, 142 (5) **L:** 101 (1)	Natural control factors were moderately likely to slow population growth in the majority of ecoregions based on resistance to invasion and expert opinion. **H:** 103, 104, 120, 142 (4) **L:** 101 (1)
Species' potential natural dispersal in the assessment area (Q7)	Potential natural dispersal within the assessment area was high for most of the southern ecoregions. **H:** 103, 104, 106-110, 116-118, 120, 142 (12) **L:** 101, 105, 112-115 (6)	Potential natural dispersal within the assessment area was high for most of the southern ecoregions. **H:** 103, 104, 106-110, 116-142 (13) **L:** 101, 105, 112-115 (6)	Potential natural dispersal within the assessment area was high for most of the southern ecoregions. **H:** 103, 104, 106-108, 110, 116, 118-120 (10) **L:** 101, 105, 112-115, 142 (7)	Potential natural dispersal within the assessment area was high for most of the southern ecoregions. **H:** 103, 104, 106-108, 110, 118, 120 (8) **L:** 101, 105, 112-115 (6)
Species' potential dispersal in the assessment area from anthropogenic mechanisms (Q8)	Potential anthropogenic dispersal within the assessment area was high for most of southern ecoregions. **H:** 103, 104, 107-109, 116-142 (11) **L:** (0)	Potential anthropogenic dispersal within the assessment area was high for most of southern ecoregions. **H:** 103, 104, 107-109, 116-118, 120, 142 (10) **L:** 115 (1)	Potential anthropogenic dispersal within the assessment area was moderate in the majority of ecoregions. **H:** 103, 118-120 (4) **L:** 115 (1)	Potential anthropogenic dispersal within the assessment area was low to moderate for the majority of ecoregions. **H:** 103, 118, 120 (3) **L:** 104, 107, 108, 115 (4)

[1]iNaturalist (2022); EDDMapS (2022); USGS (2022); GBIF (2023). [2]Lehner and Grill (2013); Chan *et al.* (2022). [3]Pheloung (1996); Abell *et al.* (2008); Crombie *et al.* (2008);); Bomford *et al.* (2010); Lehner and Grill (2013); Howeth *et al.* (2016); Fick and Hijmans (2017); Anas and Mandrak (2021); Campbell *et al.* (2022); Froese and Pauly (2022); Marcer *et al.* (2022); R Core Team (2022); https://worldclim.org/, [4]Chu *et al.* (2015).

Table 4. Summary of answers to impact of invasion questions (questions 9 to 17) for each species. Fishes were not scored in their native ecoregions.

Question	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Impacts on population growth (Q9)	Declines of multiple species (salamanders, aquatic vegetation, invertebrates, multiple native fish species, phytoplankton).[1]	Declines of multiple native fish and benthic invertebrate species, commercial carp, plankton. Decline due to sexual parasitism (gynogenetic reproduction).[2]	Decreases in fish richness, diversity and reduced fish abundance and fish size Declines of native fish species, including preventing salmon stocking.[4]	No impacts on population growth reported in the literature–- potentially suppresses Yellow Perch and Walleye.[3]
Impacts on community (Q10)	Altered competition dynamics in fish communities and community composition of aquatic plants.[5]	Altered community composition of native fishes, invertebrates and mussel populations, including reproductive interference through gynogenetic reproduction.[6]	Decreased watershed biodiversity of fish, fish abundance and size, including preventing salmon stocking.[8]	Modified fish community structure.[7]
Impacts on habitat (Q11)	Reduction of aquatic vegetation and increased turbidity. Amplification of cyanobacteria and subsequent algal blooms.[9]	Habitat degradation and alteration, increases turbidity, creates eutrophic conditions.[10]	No evidence.[12]	No evidence.[11]
Impacts on ecosystem function (Q12)	Declines of multiple species (salamanders, aquatic vegetation, invertebrates, multiple native fish species, phytoplankton).[1]	Alters ecosystem trophic functioning and dynamics. Decline in spawning sites and lake quality, increases turbidity.[13]	Reduced fish and freshwater mussel abundance, reduced fish size distribution and ecosystem richness.[14]	No evidence.[11]
Impacts of species' associated diseases, parasites, or travelers (Q13)	Epizootic Ulcerative Syndrome and Infectious Pancreatic Necrosis affects at least one native species in each ecoregion. Diseases reported in WOAH and CFIA.[15]	Carp Edema Virus impacts carp species only. No native carps in any ecoregions. Disease reported in WOAH only.[16]	No diseases reported on WOAH or CFIA	Viral Haemorrhagic Septicaemia Virus affects many fish species. Affects at least one native species in each ecoregion. Diseases reported in WOAH and CFIA.[17]

Question	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Hybridization with native fish species (Q14)	No.[18]	No.[19]	Yes[22]. Redfin Pickerel which is native to 116 (and 117)[12] Grass Pickerel which is native to 116 (and 117)[23] Northern Pike is not native in ecoregions 103, 112, 115, and 119 only[24] Chain Pickerel was not evaluated in its native ecoregion of 117.	No. White Crappie[21] which is native to ecoregion 116[12] Black Crappie was not evaluated in its native ecoregion of 116.
Impacts on at-risk or depleted species (Q15)[25]	Lake Chubb and Lake Chubsucker	No evidence	Yellow Lampmussel and Rainbow Smelt	Lake Chubsucker (but only in 116, thus it was not scored) and Western Silvery Minnow
Invasive in other parts of the world? (Q17)	Many countries[26]	Europe[27]	USA[28]	USA, Mexico, Panama[29]

[1]Deacon *et al.* (1964); Richardson and Whoriskey (1992); Richardson *et al.* (1995); Monello and Wright (1999); Carosi *et al.* (2017, 2019); Kolmakov and Gladyshev (2003). [2]Hrbáček, *et al.* (1961); Halačka *et al.* (2003); Lusk *et al.* (2010); Tarkan *et al.* (2012); Ruppert *et al.* (2017). [3]Schiavone (1983, 1985); Kerr and Grant (2000); Broda *et al.* (2022). [4]Warner *et al.* (1968); Warner (1972); Mirza and Chivers (2000); Bradford *et al.* (2004); Mitchell *et al.* (2012). [5]Deacon *et al.* (1964); Richardson *et al.* (1995). Busst and Britton (2015); Carosi *et al.* (2017, 2019). [6]Paschos *et al.* (2004); Perdikaris *et al.* (2012); Tarkan *et al.* (2012); Ruppert *et al.* (2017). [7]Warner (1972); Schiavone (1983). [8]Mitchell *et al.* (2012). [9]Richardson (1991); Richardson and Whoriskey (1992); Richardson *et al.* (1995); Kolmakov and Gladyshev (2003); Morgan and Beatty (2007). [10]Richardson and Whoriskey (1992); Crivelli (1995); Richardson *et al.* (1995). [11]Scott and Crossman (1998); Kerr and Grant (2000); Warren (2009). [12]Scott and Crossman (1998). [13]Richardson and Whoriskey (1992); Crivelli (1995); Richardson *et al.* (1995); Paulovits (1998); Paschos *et al.* (2004); Perdikaris (2012); Tarkan *et al.* (2012). [14]Warner (1972); Bradford *et al.* (2004); Mitchell (2012). [15]CFIA (2013, 2020a, 2020b, 2022); WOAH (2019, 2022a); OIE (2022). [16]WOAH (2022b). [17]CFIA (2020c); WOAH (2021). [18]Taylor and Mahon (1977); Hume *et al.* (1983); Pullan and Smith (1987); Hänfling *et al.* (2005); Smartt (2007); Kucinski *et al.* (2015); Mezhzherin *et al.* (2019); Kramer *et al.* (2020). [19]Hänfling *et al.* (2005); Papoušek *et al.* (2008); Mezhzherin *et al.* (2012).[21]Smith *et al.* (1994); Travnichek *et al.* (1996). [22]Embody (1918); Raney (1955); McCarraher

(1960); Crossman and Buss (1965); Serns and McKnight (1977) Scott and Crossman (1998). [23]Scott and Crossman (1998); Crossman and Holm (2005). [24]Scott and Crossman (1998); Harvey (2009). [25]Potts *et al.* (2023). [26]Courtenay *et al.* (1984); Courtenay and Stauffer, (1984); Courtenay, (1993); Lorenzoni *et al.* (2007); Lorenzoni *et al.* (2010); Haynes *et al.* (2012); Bonham and Siriwardena (2022). [27]Vetemaa *et al.* (2005); Komiyama *et al.* (2009); Rylkova *et al.* (2010); Savini *et al.* (2010); Takada *et al.* (2010); Britton (2022); GBIF (2022). [28]Coffie (1998); Scott and Crossman (1998). [29]Welcomme (1988); Sanderson *et al.* (2009); Fuller *et al.* (2023).

4. DISCUSSION

All fishes had a high climate match to the majority of ecoregions with the exception of two Arctic ecoregions (111 and 112), and were only moderately likely to have natural control factors that might slow invasive fish population growth. Natural dispersal was predicted to be high in the southern ecoregions, where large amounts of suitable habitat were available for all fish species (except for Chain Pickerel, which had suitable habitat in every ecoregion across Canada), thus the potential for establishment of all four fishes following an introduction event is substantial. High frequency of arrival and a strong potential for dispersal via anthropogenic mechanisms was correlated to the presence of established AIS populations within an ecoregion (or adjacent ecoregions), because established AIS populations increase future introduction potential. These three correlated factors were the primary likelihood of invasion drivers underpinning risk predictions in this work, resulting in the moderate-high risk levels for each species. Evidence in the scientific literature of impacts on populations, communities, ecosystem functioning, and habitat in their native or invaded range were primary impacts of invasion factors contributing to these elevated risk levels. For example, carps have a propensity for destroying habitat and changing ecosystem functioning (i.e. habitat engineers) and demonstrate a plethora of impacts of population growth and communities of other species. Although neither Black Crappie nor Chain Pickerel were reported to have impacts on habitat, Chain Pickerel has well-known impacts on population growth and communities of other species and impacts on ecosystem function. Where knowledge gaps existed (e.g., Arctic ecoregions, Black Crappie impacts), the overall risk of invasion was typically lower.

In the context of this SLRA for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie across Canadian ecoregions, some uncertainty in the data means that assessments of moderate risk may reflect the middle point of two potential extremes (i.e. high and low), but true risk may be anywhere from high to low. Low risk is unlikely to be no risk, but nor is it likely to be high risk. Thus heatmaps of risk should be used in conjunction with biplots to understand the spectrum of certainty associated with likelihood and impact of invasion scores for each fish species in each ecoregion. Overall, certainty was higher for the potential impacts of invasion associated with Goldfish, Prussian Carp, and Chain Pickerel, while certainty was lower around the potential impacts associated with the establishment of Black Crappie. By using both biplots and heatmaps, managers will have a better understanding of which species/ecoregions are of elevated risk, but also how certainty affects the final risk level. High uncertainty around anthropogenic introductions and activities and the spatial scales over which they operate contribute to greater uncertainty of the risk level for all fishes. Detailed-level risk assessments at finer spatial scales may be pertinent to complete for each species and ecoregion identified as at high risk for invasion.

4.1. GOLDFISH AND PRUSSIAN CARP

The high risk of Goldfish in the southern ecoregions of Canada reflects its current establishment (GBIF 2022; iNaturalist 2022; EDDMaps 2022) because it increases the anticipated frequency of secondary introduction events and the number of individuals expected to arrive with each secondary introduction event (i.e. propagule pressure) in current and adjacent ecoregions. Its northern-most occurrence in Canada is reportedly Whitehorse, Yukon (Government of Yukon, 2023). Considered a nuisance species, with high abundances in Alberta, (pers. comm N. Kimmel 2023), other reports from western Canada and Newfoundland indicate presently low abundances. Comparatively, Prussian Carp is of high risk in Alberta, Saskatchewan and British Columbia, reflecting, in part, the well-established Albertan populations stemming from introductions in the early 2000s, which subsequently spread to many of the provinces'

waterways (three of the provinces watersheds; Elgin *et al.* 2014; Docherty *et al.* 2017; Ruppert *et al.* 2017). Established populations of Prussian Carp have also been reported in neighbouring Saskatchewan, thought to be facilitated by human mediated transport as well as linked to a range expansion from the Alberta population (Docherty *et al.* 2017; Hamilton 2021). Unfortunately, taxonomic confusion has complicated the understanding of invasion histories of both Goldfish and Prussian Carp. Prussian Carp regularly hybridizes with other carp species (Vetemaa *et al.* 2005; Komiyama *et al.* 2009; Rylkova *et al.* 2010; Takada *et al.* 2010; Fuad *et al.* 2021) and are often morphologically indistinguishable from Goldfish (Elgin *et al.* 2014; Ribeiro *et al.* 2015), making its taxonomic identification difficult without genetic analyses (Rylkova *et al.* 2010). This has likely contributed to delayed detections of Prussian Carp (Hänfling *et al.* 2005; Wouters *et al.* 2012; Elgin *et al.* 2014; Ribeiro *et al.* 2015), which likely arrived in North America unintentionally in shipments of Goldfish and/or other commercially sourced fish (a common vector for new introductions; Slavík and Bartoš 2004; Kottelat and Freyhof 2007; Elgin *et al.* 2014).

Expected frequency of arrival (and the numbers in which they are expected to arrive) were high for both carp species, where the aquarium and water garden trades are the principal primary pathways of arrival (Chan *et al.* 2022). Subsequent release into stormwater ponds, municipal/public ponds, and other ecosystems (Rixon *et al.* 2005; Funnel *et al.* 2009; Tweedley *et al.* 2017, Butler 2022) likely drives spread of Goldfish and is the main vector of anthropogenic dispersal for this species. Even releases into environments with no watershed connections (e.g., stormwater and ornamental ponds) can speed secondary spread, when heavy rains and associated floods temporarily connect these otherwise isolated ecosystems (Tweedley *et al.* 2017). Unsurprisingly, these intentional and accidental releases are most frequently found where human population is high (Chan *et al.* 2022). Comparatively, natural dispersal of Prussian Carp, which thrives in artificial habitats including irrigation canals, underpins concerns of continued spread via unaided range expansions between Alberta and the U.S. (Post *et al.* 2006; Docherty *et al.* 2017) and other adjacent Canadian ecoregions such as neighbouring British Columbia. Anthropogenic dispersal of Prussian Carp also scored high, as the original management strategy for control of Prussian Carp in Southern Alberta was to encourage recreational fishers to catch, kill and/or eat the fish. Unfortunately, this strategy led to recreational fisher-driven translocation of Prussian Carp into new waterways, aiming to develop new sport fishing and comestible opportunities (Nicole Kimmel pers. comm.).

Moreover, scientific literature has documented substantial invasion impacts of Goldfish and Prussian Carp, which further elevated their final assessment of risk. Their capacity to engineer the ecosystems they inhabit (Richardson and Whoriskey 1992; Richardson *et al.* 1995; Kolmakov and Gladyshev 2003; Morgan and Beatty 2004; Razlutskij *et al.* 2021) make them especially problematic. Benthic behaviours such as spitting, sucking, and pitting can increase water turbidity that, in combination with high fish densities, can alter nutrient cycling, destroy aquatic plant cover, reduce foraging success of native fish species, and reduce macroinvertebrate populations (Richardson 1991, Richardson and Whoriskey 1992, Richardson *et al.* 1995; Razlutskij *et al.* 2021). Goldfish feeding behaviours have affected drainage diversion systems (Morgan and Beatty 2004), and promoted toxic algal blooms (Kolmakov and Gladishev 2003). Both Goldfish and Prussian Carp compete with native species for food and space and are associated with declines in salamanders, macrophytes, benthic and pelagic invertebrates, and some fish species (Deacon *et al.* 1964; Monelleo and Wright 1999; Richardson *et al.* 1995, Halačka *et al.* 2003; Ruppert *et al.* 2017; Carosi *et al.* 2017, 2019). Goldfish (but not Prussian Carp) has been reported to carry Epizootic Ulcerative Syndrome (EUS) and Infectious Pancreatic Necrosis (IPN) (both CFIA reportable diseases and with EUS listed by the WOAH), which could negatively affect native fish communities (CFIA 2020a, 2022; WOAH 2022a). Both species have wide ranges of tolerance to multiple environmental parameters (Magurran 1984,

Ford and Beitinger 2005; MacKey *et al.* 2019), high growth rates (Van der Veer and Nentwig 2015; Docherty *et al.* 2017), and opportunistic and varied diets (Deacon *et al.* 1964; Richardson *et al.* 1995; Meyer *et al.* 1998; Morgan and Beatty 2004). This permits a tolerance to disturbance (Robison and Buchanan1988; Jia *et al.* 2019), allowing both carp species to persist and/or thrive, in areas where native species may not (Gandar *et al.* 2016; Lisser *et al.* 2017; Jacquin *et al.* 2019). Goldfish and Prussian Carp are known to hybridize with other carp species (Hänfling *et al.* 2005; Vetemaa *et al.* 2005; Komiyama *et al.* 2009; Rylkova *et al.* 2010; Takada *et al.* 2010; Fuad *et al.* 2021), but Prussian Carp is also able to reproduce asexually by gynogenetic reproduction (Paschos *et al.* 2004; Leonardos *et al.* 2007; Perdikaris *et al.* 2012; Khul *et al.* 2022). Using sperm from other cyprinid males to activate egg development and produce genetic clones (Paschos *et al.* 2004; Leonardos *et al.* 2007), Prussian Carp may parasitize other cyprinid fish through reproductive. In Alberta, Ruppert *et al.* (2017) suggested that the reduction in Fathead Minnow *Pimephales promelas* (Rafinesque, 1820) and Lake Chub *Couesius plumbeus* (Agassiz 1850) populations may have been due to the gynogenetic reproduction of Prussian Carps living in the same watershed. The additional capacity of Prussian Carp to alter its reproductive strategy (sexual vs. asexual) allows them to maximize energy investiture (Emiroglǔ *et al.* 2012; Tarkan *et al.* 2012) and have success in stochastic systems (Barbuti *et al.* 2012). Goldfish is identified in COSEWIC calculators as a threat to Lake Chub and Lake Chubsucker *Couesius sucetta* (Potts *et al.* 2023), and Prussian Carp may have reduced Lake Chub populations through reproductive interference (Ruppert *et al.* 2017) in Alberta. Given the similarity in other invasion impacts between the carp species (aside from associated diseases), the relatively short invasion history of Prussian Carp in North America, its limited distribution and identified overlap with threatened native species and the difficultly in morphologically distinguishing the two species, it is possible that risks associated with Prussian Carp invasion are higher than what is presented here.

4.2. CHAIN PICKEREL AND BLACK CRAPPIE

Chain Pickerel and Black Crappie are established in fewer ecoregions than Goldfish, despite a similarly high climate match across Canada and large amounts of suitable habitat. In particular, Chain Pickerel is considered to have suitable habitat in both southern and northern ecoregions, while suitable habitat for Black Crappie, much like the carp species, is found predominantly in the southern ecoregions. In Canada, Chain Pickerel is considered native to the St. Lawrence River (Scott and Crossman 1998; Coffie 1998; Carlson *et al.* 2016), with historical translocations associated with sportfishing (Williamson 1832 cited in Whittier *et al.* 1997) resulting in detections in Lake Ontario (Fuller *et al.* 1999; Hoyle and Lake 2011), New Brunswick (Scott and Crossman 1959), and Nova Scotia (Gilhen and Pentz 1974). In Atlantic Canada, Chain Pickerel has now been detected in approximately 380 lakes/rivers in New Brunswick and Nova Scotia (Swinemar *et al.* 2021; Atlantic Canada Chain Pickerel Database), which contributes to the high risk for this species in both provinces. Comparatively, while the historical native distribution of Black Crappie is unclear, its native Canadian distribution is considered to be the Great Lakes and St. Lawrence River (Scott and Crossman 1998; Fuller *et al.* 1999; Pariseau *et al.* 2009; USGS 2022). Similar to Chain Pickerel, repeated historical stocking events (Mosindy 1995; VanBroeck 1995; Kerr 2006), illegal releases, and natural dispersal (Krishka *et al.* 1996 cited in Kerr and Grant 2000) have resulted in established Black Crappie populations in southern Manitoba (Scott and Crossman 1998; Kerr 2006; Holm *et al.* 2021), and southern British Columbia (Wydoski and Whitney 2003; Quinn and Paukert 2009; Carl and Guiguet1958 cited in Powell 2022), although abundance is these areas is presently low (Manitoba: Hauger 2020; British Columbia: Nowosad and Taylor 2012). Most recently, an invasion into Big Lake, New Brunswick (McAlpine *et al.* 2020, Powell 2022) has generated concerns of spread into the nearby Saint John and Mactaquac rivers and the Nackawic watershed.

The expected frequency of arrival (and associated propagule pressure) is moderate-high for both fishes, but overall, our understanding of the frequency of arrival (and in what numbers) that Black Crappie and Chain Pickerel enter each ecoregion, and what happens once these fishes establish, is poor. Expert opinion suggests that secondary spread between ecoregions is most likely the result of natural dispersal through connected systems rather than intentional releases (although illegal fishing introductions are likely more important in Eastern Canada), but there are little data to support these assumptions. Historically, both species have been introduced legally through stocking events or illegally through fisher-mediated translocations (Coffie 1998; Fuller *et al.* 2022). Consequently, the fisher translocation and/or live-bait pathways are considered important vectors for the invasion/spread of Chain Pickerel and Black Crappie (Knapp 1953; Courtenay and Hensley 1979; Courtenay *et al.* 1984; Pflieger 1997 cited in Nico *et al.* 2022; Mitchell *et al.* 2012), and although both are heavily regulated throughout the majority of Canada, compliance is often low and is hard to police (Drake and Mandrak 2014a; Drake *et al.* 2015). For example, in New Brunswick and Nova Scotia, it is likely that fishermen illegally introduced Chain Pickerel into new watersheds to create new sport fishing opportunities (Coffie 1998). The introduction of Black Crappie into the privately owned Big Lake, NB was likely a deliberate stocking effort by the lake's former owner (McAlpine *et al.* 2020). Furthermore, risks of invasion can be potentially exacerbated by provincial and federal regulations/managerial practices, which are not always well adapted to the reality of invasive species. For example, the Maritime Provinces Fishery Regulations (NB, PEI and NS) ([SOR/93-55](#)) prohibits the use of live/dead bait of Chain Pickerel, Goldfish and other carp species, but permits live bait of other unlisted fish species caught within the provinces. The Nova Scotia Live Fish Possession Regulations ([N.S. Reg. 212/2012](#)) prohibits the movement of live fish between waterbodies without a permit, but allows the use of live bait if bait is captured from the same waterbody where it is used. The Newfoundland and Labrador Wildlife Act makes it illegal to import wild animals, but the regulation is not applicable to species in schedule B, which includes Goldfish ([CNLR 1156/96](#)). Federally, the Aquatic Invasive Species Regulations ([SOR/2015-121](#)) prohibits the importation of certain fish species into specific geographic regions of Canada, however none of the species considered here are on this list. The stocking of private ponds is not strongly regulated in Canada, but could serve as a periodic source of introduction during flooding events, where high water levels provide access to adjacent lakes and rivers. A better understanding of invasion risks associated with the live bait pathway in particular (e.g., Drake and Mandrak 2014a, 2014b, Drake *et al.* 2015; Smith *et al.* 2020; McEachran *et al.* 2022; Mulligan *et al.* 2023) has led to the province of Quebec prohibiting the use of any live fish bait (MELCCFP 2023) and to the implementation of regulations on bait transportation/use by bait management zones in Ontario (Government of Ontario 2023). However, although anglers are generally in favor of management strategies preventing introductions and/or spread of non-indigenous species, compliance with bait regulations can be hard to predict. Drake et al. (2014a) reported that, despite a long history of targeted education and outreach strategies explaining the risks associated with AIS, a large proportion of Ontario fishers still released live bait because it was convenient and they believed that the bait provided forage for game fish. While outreach campaigns on AIS awareness, and strategies encouraging environmental stewardship and conservation, are essential in changing human behaviour, the complexity of perceptions and behaviours in both the live bait and fisher translocation pathways will likely require regular revision of regulatory and managerial practices across Canada (Drake and Mandrak 2014a, Drake *et al.* 2015).

Impact scores for Chain Pickerel and Black Crappie were somewhat lower than Goldfish and Prussian Carp due to either a lack of available information (i.e. no published studies) or a lack of reported evidence (i.e. studies exist, but there is little or no evidence suggesting impacts in either their native or invaded range). For example, while Chain Pickerel has been reported to

impact ecosystem functioning by simplifying fish communities and reducing ecosystem biodiversity in Maine and Nova Scotian lakes (Warner 1972, Mitchell *et al.* 2012), there is no evidence to suggest that its behaviour has any direct impact on habitat. Conversely, impacts of Chain Pickerel on both population growth and communities are well-known, with its predatory nature resulting in the declines of native fish and mussel species (Edge and Gilhen 2001; Bradford *et al.* 2004, Mitchell *et al.* 2012; COSEWIC 2013), reductions of fish community richness and diversity, species abundances, and in some cases the truncation of native fish size distributions (Bradford *et al.* 2004; Mitchell *et al.* 2012). It has also been reported that Chain Pickerel limits the effectiveness of salmon stocking through high predation (Warner *et al.* 1968; Warner1972), and produces chemical cues which may alter the behaviour of other fish species (Mirza and Chivers 2000).

Comparatively, there is less evidence in the literature on Black Crappie, with no impacts reported on habitat or ecosystem function and only one study which reported that the introduction of Black Crappie modified fish community structure by altering species abundances through dietary competition over a 5-10 year time scale (Schiavone 1983). The varied diet of Black Crappie (Keast 1968; Gablehouse 1984; Pelham *et al.* 2001; Bonar *et al.* 2004; Sanderson *et al.* 2009) certainly suggests that direct or indirect competition for food would be possible with other species in its invaded range. No clear evidence is available in the literature on the impacts of Black Crappie on the population growth of other species, although a number of studies speculate on the cumulative effects of multiple stressors in relation to Walleye, Yellow Perch, and Black Crappie populations where all three species coexist. For example, Schiavone (1983; 1985) suggested that competition for food, loss of Yellow Perch forage, and direct predation of fry and fingerlings, combined with angling exploitation of Walleye/Perch, may lead to declines in Walleye/Perch abundance in lakes where Black Crappie are introduced. Mosindy *et al.* (1984) and Krishksa *et al.* (1996 as cited in Kerr and Grant 2000) postulated that a reduction in Yellow Perch forage due to potential competition with introduced Black Crappie may theoretically explain reduced Yellow Perch abundance (a preferred prey of Walleye) and the ultimate suppression of Walleye recruitment. Broda *et al.* (2022) identified declines of Walleye abundance in electrofishing transects and concurrent increases in Black Crappie catches in fyke nets. However, researchers cautioned against causal inferences between Black Crappie presence and Walleye declines as both populations are likely driven by fishing-pressure, climate change, and lack of regulations for panfish angling. Conversely, high abundance of adult Walleye has negatively impacted Black Crappie populations (Mosindy 1997), which is perhaps not surprising given that many historical introductions of Black Crappie were done to provide forage for gamefish such as Walleye (McNeil1992; Krishka *et al.*1996). There is some concern by managers that in Eastern Canada, where there is an absence of functionally similar native species, that the ultimate impacts of invasion by Chain Pickerel and Black Crappie could be more substantial than elsewhere. CMIST question 6 asks if natural control agents (e.g., predators) could suppress new species invasions. Eastern Canada lacks predator species (e.g., Northern Pike) with gape sizes large enough to consume adult Chain Pickerel or Black Crappie. Furthermore, due to lack of functionally similar species, evidence of alteration in food web dynamics in Eastern Canada has been reported relative to Chain Pickerel invasion (addressed in CMIST Question 12; L. Campbell pers comm.). However, data gaps in the literature, for Black Crappie in particular, currently limit our understanding of how they will behave in novel ecosystems, consequently lowering risk scores and associated certainty.

4.3. LIMITATIONS

The majority of SLRA tools (e.g., AS-ISK; Copp *et al.* 2016b; CMIST; Drolet *et al.* 2016; ESSR; Marcot *et al.* 2019) incorporate the establishment status of an AIS in an assessment area in their final determination of risk. This results in a higher risk potential associated with long

established and more widespread AIS, relative to a newly introduced species which may be more localized. Thus for a widely established invasive species, the level of risk may be overstated. This could be especially pertinent for Goldfish, which is widespread in Southern Canada and has a long history of deliberate stocking North America, dating back almost two centuries. Furthermore, by evaluating invasion risk in an ecoregion where the AIS is already established, this study assumes that suitable uninvaded watersheds within an ecoregion may remain, although this may not always be true. This accentuates the need for questions related to the establishment (or lack of) of an AIS within a region/neighbouring region which are more likely to have similar environmental conditions based on topography, geomorphology, and climate. Impacts of invasion are also equally important in SLRA tools, as an AIS with a high likelihood of invasion does not necessarily have high invasion impacts, thus robust SLRA tools consider both these concepts when evaluating final assessments of risk. Applying a SLRA however, may not be needed if an introduced species has no ability to establish. Ideally, a comprehensive watchlist process would be the first step, and include initial list(s) of candidate species, filtered to remove species that have no chance of survival in an assessment area (e.g., tropical species being assessed in Arctic ecoregions), followed by SLRAs and subsequent DLRAs where needed. Additionally, a SLRA is not designed to evaluate cumulative effects or magnitude of impacts of a non-indigenous species in an assessment area. In addition, it does not address the concept that invasion is a stepwise process; and that each step in the pathway must be achieved before passing to the next (Theoharides and Dukes 2007; Blackburn *et al.* 2011, Lockwood *et al.* 2013). For example, reproduction of a species in an ecoregion is irrelevant where survival is impossible, and survival in an ecoregion is only important if arrival is achieved. Although each question in the CMIST tool is given equal weight in its contribution to level of risk, it is likely that accuracy and precision would be improved with a variable weighting scheme (Drolet *et al.* 2016).

CMIST and other SLRA tools are designed to provide a broad overview of invasion risk to help decision-makers in the allocation of resources and allow the identification of species which pose an elevated threat to native species/ecosystems/ecoregions and consequently may require DLRAs (Copp *et al.* 2005b, Copp *et al.* 2016a; Vilizzi *et al.* 2022). For non-indigenous species that warrant a DLRA (which is not included in this work and cannot be done using a SLRA tool), statistical probabilities of introduction, survival, establishment, spread and associated impacts would be evaluated, often incorporating aspects of habitat modelling to comprehensively assess invasion risks across different regions, watersheds and climate scenarios.

Using CMIST to assess species invasion risk under a projected climate scenario did not produce different results for these fishes due to their broad environmental tolerances and the limited number of variables available to complete the climate matching. The rescoring of species under current and projected climate scenarios will likely only be useful when evaluating species with strict thermal requirements. For thermally plastic species, it is more likely that changes in climate will drive shifts in patterns of introduction, establishment, ecological interactions and ecosystem functioning. Only two of the CMIST questions (questions 4 and 5 relating to ecoregion suitability for survival and reproduction) were considered to directly influence risk scores under a projected climate scenario. Given that all fishes considered in this work had a high climate match for the majority of all ecoregions under the historical climate scenario, there were very few instances where ecoregion climate matching was significantly higher (Appendix 1, Table 2), and no instances where the revised scoring for questions 4 and 5 changed the overall risk score under the projected climate scenario. While climate change may influence multiple biotic and abiotic ecosystem factors (e.g., habitat availability, species interactions, DO, pH, etc.), only projected changes in global temperature and precipitation are readily available (e.g., WorldClim, CHELSA) and thus are assumed in this work to be the prime mechanism underpinning AIS distribution, impacts, and subsequent invasion risk. However, in reality, the

cumulative effects of habitat availability, precipitation, extreme weather events (flooding and drought), increased evapotranspiration, changes in salinity, lower water levels and associated dissolved oxygen levels, and a multitude of other environmental factors (Magnuson *et al.* 1997; Schindler 1997, 2001; Hudon and Létourneau 2018; Finch *et al.* 2021), varying in magnitude by ecoregion, will affect species interactions, fish survival, establishment and dispersal in a warming climate. Understanding the potentially synergistic effects of climate change on the establishment and ecological impacts of invasive species should be a priority for future risk assessments under projected climate scenarios (Ricciardi *et al.* 2021), without which, it is unlikely that SLRA tools will be able to estimate risk in a meaningful way under projected climate scenarios.

Finally, data gaps in the literature, databases and/or expert opinion affected risk assessment outcomes. A lack of information in the primary literature on the interactions, ecology and potential impacts of Black Crappie in its native and invaded ranges, hampered CMIST scoring and reduced associated certainty for impact of invasion questions in the present work. The assessment of impact of invasion questions may also be biased towards species with longer invasion histories, given that newly introduced AIS may have less documentation on the consequences of invasion. Region-specific understanding of human-mediated introductions and transfers was not consistent across fishes/ecoregions, and was less clear for Chain Pickerel and Black Crappie in particular. The Northwest Territories, Yukon, Nunavut and Prince Edward Island (PEI) were also poorly represented in this study, due to a lack of baseline ecoregion or AIS information, primary literature and/or experts with local knowledge, including information on First Nations fisheries and associated ecosystems. Additionally, given the changes made in the approach and application of CMIST in the context of this work (e.g., removal of question 16), users should be cautious when directly comparing this work with other studies using CMIST.

4.4. SOURCES OF UNCERTAINTY

The CSAS review panel for this work considered Chain Pickerel to be native to ecoregion 116 only and Black Crappie to ecoregions 116 and 117 (and were thus not scored in these ecoregions). However, the native Canadian distributions of both Chain Pickerel and Black Crappie have been obscured by a long history of stocking and translocations, thus it is possible that the original native distributions are different than identified here. For example, a French language account of fisher oral history by Montpetit (1897) suggests that Black Crappie is not native to Quebec, but arrived from the Great Lakes after the construction of the Rideau, Grenville and de Carillon canals, eventually spreading into the St. Lawrence River. Determining original native distributions can be challenging for many species and may impact decision-making at multiple scales, as control/mitigation measures are rarely enacted for native species.

The variety of ecoregions and associated habitats in each province complicated expert opinion in our regional discussions. The province of Quebec for example, touches five different ecoregions and it was difficult to properly assess the extent of appropriate habitat or AIS dispersal across all ecoregions, as regional expertise was often focused more on specific species and less on habitat characteristics.

While climate matching was used to better understand the amount of suitable habitat permitting the survival and reproduction for all 4 non-indigenous fishes (questions 4 and 5), only historical and projected datasets of global surface temperature and precipitation are readily available (e.g., WorldClim, CHELSA). Realistically however, the cumulative effects of habitat availability, temperature, precipitation, water level, pH, salinity, flooding/drought, evapotranspiration, dissolved oxygen levels and many other environmental factors will determine how much of an ecoregion is suitable for the survival and reproduction of a non-indigenous species.

There are also large knowledge gaps in the literature on the parasites/viruses/pathogens associated with the fishes considered in this work. Literature focused primarily on aquaculture scenarios or presented exhaustive lists of diseases/parasites/pathogens which were common among multiple native fishes, but also present in AIS (e.g., Trujillo-Gonzales *et al.* 2018). AIS can transport diseases which may create a multitude of situations (benefits, disadvantages, no effect) for native or invasive species and/or their already associated pathogen loads (Foster *et al.* 2021). These all depend on the success of the co-evolution between the emerging disease and their target hosts (Kelly *et al.* 2011; Ogden *et al.* 2019). This knowledge gap in literature complicated assessment of this question, where more taxon-specific vector information and ecosystem consequences of subsequent infection are needed to assess the risk associated with each species. Consequently, we considered only diseases/parasites/pathogens identified as of concern by either the World Organization for Animal Health and the Canadian Food Inspection Agency.

Although invasive species commonly invade ecosystems similar to their native habitat, species may also demonstrate novel behaviour or act unpredictably outside of their native ranges (Mooney and Cleland 2001; Peterson and Vieglais 2001; Brand *et al.* 2021). Ecosystem resistance to invasion can be a fragile network of checks and balances (Groffman *et al.* 2006; Liu *et al.* 2015) due to complex predator-prey interactions (Martinez 1991; Feiner *et al.* 2013), community responses, feeding behaviours and environmental pressures (Galinat *et al.* 2002; Egertson and Downing 2004; Kennedy *et al.* 2002; Downing *et al.* 2012; Havel *et al.* 2015; Sikora *et al.* 2021). The introduction of a non-indigenous species, with no evolutionary history in a recipient ecosystem, may allow it to outperform native species (Strauss *et al.* 2006). Moreover, growth will likely be faster in a warming climate (Hauger 2020), which may shift the balance to either increased predation rates or during absence of predators, create increased abundance of certain fish species, altering future dynamics (Tarkan 2016). Habitat changes can create unpredictable consequences or opportunities, inducing feeding strategy and/or trophic dynamics modifications (Broderson *et al.* 2015; Salgado *et al.* 2019; Vagnon *et al.* 2022). Consequently, there is some uncertainty surrounding the potential impacts of invasion available in literature, where conclusions are inferred from data in native ranges.

4.5. OTHER CONSIDERATIONS

There has been recent growth in online marketplaces for the trade of ornamental species in the aquarium and water garden trades (Olden *et al.* 2021). The expansion of online marketplaces may affect the introduction of Goldfish and other ornamental species. In addition, the aquaponic sector is a potentially new vector to consider in future screening-level or detailed-level risk assessments, as it is rising in popularity across Canada in both the sustainable food (Savidov *et al.* 2007; Blom *et al.* 2022) and cannabis sectors (Khan 2019; Taylor 2019). Currently, Tilapia is the preferred fish species for both food and cannabis growers in Canada; however, internationally, carps, crappies, and some esocids are found amongst many other fish species in aquaponic systems, with Goldfish, which are easily available and easy to keep, the most popular aquaponic fish species on a global scale (Love *et al.* 2014). Shifts towards sustainable agriculture and more environmentally friendly approaches to food production may eventually lead to AIS concerns, if aquaponics systems are stocked with non-indigenous species.

5. CONCLUSIONS

- A Screening-Level Risk Assessment (SLRA) was completed on the potential invasiveness of four freshwater fish species - Goldfish (*Carassius auratus*), Prussian Carp (*Carassius gibelio*), Chain Pickerel (*Esox niger*), and Black Crappie (*Pomoxis nigromaculatus*) - across

21 Canadian freshwater ecoregions using an adaptation of the Canadian Marine Invasive Screening Tool (CMIST).

- CMIST applies a series of questions about the invasion process and associated certainty levels. Invasion risk was estimated as the likelihood of invasion (potential for natural and anthropogenic movement, habitat suitability, and establishment) multiplied by invasion impacts (multiple impacts on aquatic populations, communities, habitat, and ecosystem function).

- High risk species were Goldfish in the majority of southern ecoregions, Prussian Carp in most of Alberta, Saskatchewan and British Columbia, and Chain Pickerel in Nova Scotia and New Brunswick. Black Crappie was not identified as a high risk species.

- Six ecoregions, located across five provinces, were predicted to have high invasion risk from two species; Goldfish and Prussian Carp in British Columbia, Saskatchewan and Alberta; and Goldfish and Chain Pickerel in Nova Scotia and New Brunswick.

- Southern ecoregions were more at risk due to a higher likelihood of invasion than northern ecoregions. Southern ecoregions had greater potential for human-mediated introductions and a greater likelihood of secondary spread.

- Results represent status quo ecological and anthropogenic conditions. Data on how climate change will affect the likelihood of invasion and impact were not available to inform this SLRA. Similarly, data on predicted changes to human-mediated introductions were not available.

- Important knowledge gaps include limited availability of biological, habitat, and climate data for the Arctic and sub-Arctic regions, and limited information on Black Crappie invasion impacts. These knowledge gaps increased uncertainty in the likelihood of invasion in the Arctic and impacts from Black Crappie, reducing the precision of these invasion risk results.

- Mapped invasion risk and plots of likelihood and invasion risk, produced in this SLRA, should be interpreted together to better understand the variation among ecoregions.

- Conducting detailed-level risk assessments for high-risk species identified in this SLRA would contribute to a better understanding of invasion potential and key knowledge gaps, which may inform management responses.

6. ACKNOWLEDGEMENTS

7. REFERENCES CITED

Abell, R. , Thieme, M., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., Coad, B., Mandrak, N., Balderas, S., Bussing, W., Stiassny, M., Skelton, P., Allen, G., Unmack, P., Naseka, A., Ng, R., Sindorf, N., Robertson, J., Armijo, E., Petry, P. 2008. Freshwater Ecoregions of the World: A New Map of Biogeographic Units for Freshwater Biodiversity Conservation. BioScience, 58: 403–414. https://doi.org/10.1641/B580507

Abramenko, M.I. 2011. Adaptive mechanisms of distribution and population dynamics of *Carassius auratus gibelio* in the Ponto-Caspian region (with reference to the Azov basin). Russian Journal of Biological Invasions, 2: 139-154. https://doi.org/10.1134/S2075111711030027.

Anas, M.U.M., Mandrak, N.E. 2021. Drivers of native and non-native freshwater fish richness across North America: Disentangling the roles of environmental, historical and anthropogenic factors. Global Ecology and Biogeography, 30: 1232–1244. https://doi.org/10.1111/geb.13298.

Aquatic Invasive Species Regulations, SOR/2015-121. 2015. [Online], https://laws-lois.justice.gc.ca/PDF/SOR-2015-121.pdf.

Armbruster, D.C. 1959. Observations on the natural history of the Chain Pickerel (*Esox niger*). The Ohio Journal of Science. 59(1): 55-58. https://kb.osu.edu/bitstream/handle/1811/4599/V59N01_055.pdf?sequence=1

Batzer, D.P., Pusateri, C.R., Vetter, R. 2000. Impacts of fish predation on marsh invertebrates: direct and indirect effects. Wetlands, 20(2) : 307-312. https://doi.org/10.1672/0277-5212(2000)020[0307:IOFPOM]2.0.CO;2.

Beatty, S.J., Allen, M.G., Whitty, J.M., Lymbery, A.J., Keleher, J.J., Tweedley, J.R., Ebner, B.C., Morgan, D.L. 2017. First evidence of spawning migration by Goldfish (*Carassius auratus*); implications for control of a globally invasive species. Ecology of Freshwater Fish, 26(3): 444-455. https://doi.org/10.1111/eff.12288.

Bellard, C., Cassey, P., Blackburn, T.M. 2016. Alien species as a driver of recent extinctions. Biology Letters, 12(2): 4pp. https://doi.org/10.1098/rsbl.2015.0623.

Bernatchez, L., Giroux, M. 2012. Les poissons d'eau douce du Québec et leur répartition dans l'est du Canada. 348pp. Boucherville, QC: Broquet.

Bickler, P.E., Buck, L.T. 2007. Hypoxia tolerance in reptiles, amphibians, and fishes: life with variable oxygen availability. Annual Review of Physiology, 69: 145–170. https://doi.org/10.1146/annurev.physiol.69.031905.162529.

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarołík, V., Wilson, J.R.U. Richardson, D.M. 2011. A proposed unified framework for biological invasions. Trends in Ecology and Evolution, 26: 333-339. https://doi.org/10.1016/j.tree.2011.03.023

Blom, C.D.B., Steegeman, P., Voss, C., Sonneveld, B.G.J.S. 2022. Food in the cold: exploring food security and sovereignty in Whitehorse, Yukon, International Journal of Circumpolar Health, 81: 2025992. https://doi.org/10.1080/22423982.2022.2025992

Bomford, M., Barry, S.C., Lawrence, E. 2010. Predicting establishment success for introduced freshwater fishes: a role for climate matching. Biological Invasions,12: 2559-2571. https://doi.org/10.1007/s10530-009-9665-3.

Bonar, S.A., Bolding, B.D., Divens, M., Meyer, W. 2005. Effects of Introduced fishes on wild juvenile Coho Salmon in three shallow Pacific Northwest lakes. Transactions of the American Fisheries Society, 134: 641-652. https://doi.org/10.1577/T04-154.1.

Bonham, V., Siriwardena, S. 2022. *Carassius auratus auratus* (goldfish), CABI Compendium. CABI International. https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.90563.

Bradford, R, Longard, D.L., Longue, P. 2004. Status, trends, and recovery considerations in support of an allowable harm assessment for Atlantic Whitefish (*Coregonus huntsmani*). DFO Canadian Science Advisory Secretariat Research Document. 2004/109. 37 pp.

Bradford, R.G., Schaefer, H., Stevens, G. 2004. Scope for human-induced mortality in the context of Atlantic Whitefish (*Coregonus huntsmani*) survival and recovery. Canadian Science Advisory Secretariat. Research Document 2004/110. 50 pp.

Brand, J.A., Martin, J.M., Tan, H., Mason, R.T., Orford, J.T., Hammer, M.P., Chapple, D.G., Wong, B.B.M. 2021. Rapid shifts in behavioural traits during a recent fish invasion. Behavioral Ecology and Sociobiology, 75(9): 134. https://doi.org/10.1007/s00265-021-03077-2.

Britton, R. 2011. *Carassius gibelio* (Prussian Carp). CABI Compendium. [Online], https://doi.org/10.1079/cabicompendium.90562. Accessed May 5, 2022.

Broda, S.P., Feiner, Z.S., Mrnak, J.T., Shaw, S.L., Sass, G.G. 2022. Black Crappie Influences on Walleye Natural Recruitment in Northern Wisconsin Lakes. North American Journal of Fisheries Management, 42: 1202-1214. https://doi.org/10.1002/nafm.10814.

Brodersen, J., Howeth, J., Post, D. 2017. Emergence of a novel prey life history promotes contemporary sympatric diversification in a top predator. Nature Communications, 6 (8115): 9p. https://doi.org/10.1038/ncomms9115.

Brown, N.E.M., Therriault, T.W. 2022. The hidden risk of keystone invaders in Canada: a case study using non-indigenous crayfish. Canadian Journal of Fisheries and Aquatic Sciences, 79(9): 1479-1496. https://doi.org/10.1139/cjfas-2021-0245.

Busst, G.M.A., Britton, J.R. 2017. Comparative trophic impacts of two globally invasive cyprinid fishes reveal species-specific invasion consequences for a threatened native fish. Freshwater Biology, 62: 1587–1595. https://doi.org/10.1111/fwb.12970.

Butler, C. 2022. Ontario's feral Goldfish population is exploding and climate change may be to blame. CBC News, London. Published May 2, 2022. [Online]. https://www.cbc.ca/news/canada/london/ontario-wild-Goldfish-climate-change-1.6434384. Accessed on February 27, 2023.

Campbell, S.E., Hubbard, J.A.G., Mandrak, N.E. 2022. Changing community dynamics and climate alter invasion risk of freshwater fishes historically found in invasion pathways of the Laurentian Great Lakes. Diversity and Distributions, 28: 1620–1634. https://doi.org/10.1111/ddi.13530.

Campbell, T., Shaw, B., Hammond, E., Bao, L., Yang, S., Jurich, P., Fox, S. 2021. Qualitative interviews of practitioners of Buddhist life release rituals residing in the United States: implications for reducing invasion risk. Management of Biological Invasions, 12: 178–192. https://doi.org/10.3391/mbi.2021.12.1.12.

Canagaratnam, P. 1959. Growth of fishes in different salinities. Journal of the Fisheries Board of Canada, 16(1) : 121-130. https://cdnsciencepub.com/doi/10.1139/f59-013.

Carey, M.P., Sanderson, B.L., Barnas, K.A., Olden, J.D. 2012. Native invaders – challenges for science, management, policy, and society. Frontiers in Ecology and the Environment, 10: 373-381. https://doi.org/10.1890/110060.

Carl, G.C., Guiguet, C.J. 1958. Alien animals in British Columbia, British Columbia Provincial Museum, Department Education, Handbook 14. Victoria, BC. Accessed at : https://ibis.geog.ubc.ca/biodiversity/efauna/AlienSpeciesinBritishColumbiaHistoricalRecords.html#FishFrogs

Carlson, D.M., Daniels, R.A., Wright, J.J. 2016. Atlas of inland fishes of New York. published jointly by the New York State Education Department and Department of Environmental Conservation. https://www.nysm.nysed.gov/sites/default/files/atlasofinlandfishes.pdf

Carosi, A., Ghetti, L., Lorenzoni, M. 2017. Invasive *Carassius spp*. in the Tiber River basin (Umbria, Central Italy): population status and possible interactions with native fish species. Cybium, 41: 11–23. https://archive.org/search?query=external-identifier%3A%22urn%3Adoi%3A10.26028%2Fcybium%2F2017-411-002%22.

Carosi, A., Ghetti, L., Padula, R., Lorenzoni, M. 2019. Potential effects of global climate change on fisheries in the Trasimeno Lake (Italy), with special reference to the goldfish *Carassius auratus* invasion and the endemic southern pike *Esox cisalpinus* decline. Fisheries Management and Ecology, 26(6): 500-511. https://doi.org/10.1111/fme.12318.

Cathcart, C.N., Dunker, K.J., Quinn, T.P., Sepulveda, A., von Hippel, F.A., Wizik, A., Young, D.B., Westley, P.A.H. 2019. Trophic plasticity and the invasion of a renowned piscivore: a diet synthesis of northern pike (*Esox lucius*) from the native and introduced ranges in Alaska, U.S.A.. Biological Invasions, 21: 1379–1392. https://link.springer.com/article/10.1007/s10530-018-1909-7.

CBC News, 2023, B.C. conservation group warns of Goldfish invasion in Kelowna pond. CBC News, British Columbia. Published February 7, 2023. [Online] https://www.cbc.ca/news/canada/british-columbia/Goldfish-munson-pond-kelowna-1.6738922. Accessed on February 7, 2023.

CFIA, 2013. Herpès virose de la carpe koï- Fiche de renseignement. [Online]. Accessed May 25, 2022. https://inspection.canada.ca/sante-des-animaux/animaux-aquatiques/maladies/maladies-declarables/l-herpesvirose-de-la-carpe-koi/fiche-de-renseignements/fra/1336682711769/1336682801247.

CFIA. 2020a. Facts about infectious pancreatic necrosis. https://inspection.canada.ca/animal-health/aquatic-animals/diseases/reportable-diseases/infectious-pancreatic-necrosis/fact-sheet/eng/1330099413455/1330099555496. [Online]. Accessed May 5, 2023.

CFIA. 2020b. Facts about spring viremia of carp. https://inspection.canada.ca/animal-health/aquatic-animals/diseases/reportable-diseases/spring-viraemia-of-carp/fact-sheet/eng/1337230510145/1337230669570. [Online]. Accessed May 5, 2023.

CFIA. 2020c. Viral Hemorrhagic Septicemia (VHS). https://inspection.canada.ca/animal-health/aquatic-animals/diseases/reportable-diseases/vhs/eng/1327208906158/1327209371030. [Online]. Accessed May 5, 2023.

Chan, F.T., Drake, D.A.R, Therriault, T.W. 2022. The Risk of Introducing Live Organisms by the Aquarium, Water Garden, and Seafood Trades in Canada. DFO Canadian Science Advisory Secretariat Research Document. 2021/036. 139 pp. https://publications.gc.ca/collections/collection_2022/mpo-dfo/fs70-5/Fs70-5-2021-036-eng.pdf

Chaput, G., Caissie, D. 2010. Risk assessment of smallmouth bass (*Micropterus dolomieu*) introductions to rivers of Gulf Region with special consideration to the Miramichi River (N.B.). DFO Canadian Science Advisory Secretariat Research Document. 2010/065. 39pp. https://publications.gc.ca/collections/collection_2011/mpo-dfo/Fs70-5-2010-065.pdf

Chu, C., Minns, C.K., Lester, N.P., Mandrak, N.E. 2014. An updated assessment of human activities, the environment, and freshwater fish biodiversity in Canada. Canadian Journal of Fisheries and Aquatic Sciences, 72(1): 135-148. https://doi.org/10.1139/cjfas-2013-0609.

CLNR. Consolidated Newfoundland and Labrador Regulations under the Wild Life Act, CNLR 1156/96. 1996. [Online], https://www.assembly.nl.ca/legislation/sr/regulations/rc961156.htm. Accessed December 10, 2022.

Coffie, P.A. 1998. Status of Chain Pickerel, *Esox niger*, in Canada. The Canadian Field Naturalist, 112: 140. https://www.biodiversitylibrary.org/page/34257477#page/141/mode/1up

Cooper, G.P., Washburn, G.N. 1949. Relation of dissolved oxygen to winter mortality of fish in Michigan lakes. Transactions of the American Fisheries Society, 76(1): 23-33. https://doi.org/10.1577/1548-8659(1946)76[23:RODOTW]2.0.CO;2

Copp, G.H., Bianco, P.G., Bogutskaya, N.G., Eros, T., Falka, I., Ferreira, M.T., Fox, M.G., Freyhof, J., Gozlan, R.E., Grabowska, J., Kováč, V., Naseka, A.M., Peňáz, M., Povž, M., Przybylski, M., Robillard, M., Russel, I.C., Stakėnas, S., Šumer, S., Vila-Gispert, A., Wiesner, C. 2005a. To be, or not to be, a non-native freshwater fish? Journal of Applied Ichthyology, 21: 242–262. https://doi.org/10.1111/j.1439-0426.2005.00690.x.

Copp, G.H., Garthwaite, R.,Gozlan, R.E. 2005b. Risk identification and assessment of non-native freshwater fishes: a summary of concepts and perspectives on protocols for the UK. Journal of Applied Ichthyology, 21: 371-373. https://doi.org/10.1111/j.1439-0426.2005.00692.x

Copp, G.H., Russell, I.C., Peeler, E.J., Gherardi, F., Tricarico, E., Macleod, A., Cowx, I.G., Nunn, A.D., Occhipinti-Ambrogi, A., Savini, D., Mumford, J. and Britton, J.R. 2016a. European Non-native Species in Aquaculture Risk Analysis Scheme – a summary of assessment protocols and decision support tools for use of alien species in aquaculture. Fisheries Management and Ecology, 23: 1-11. https://doi.org/10.1111/fme.12074

Copp, G.H., Vilizzi, L., Tidbury, H., Stebbing, P.D., Tarkan, A.S., Moissec,L., Goulletquer, P. 2016b. Development of a generic decision-support tool for identifying potentially invasive aquatic taxa: AS-ISK. Management of Biological Invasions, 7: 343-350. https://doi.org/10.1111/j.1539-6924.2008.01159.x

COSEWIC. 2013. COSEWIC status appraisal summary on the Yellow Lampmussel *Lampsilis cariosa* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xxiii pp.

Courtenay, W.R., Stauffer, J.R. 1984. Distribution, biology, and management of exotic fishes. Johns Hopkins University Press. 430 pp. https://openlibrary.org/search/inside?q=Distribution+of+exotic+fishes+in+the+continental+United+States

Courtenay, W.R., Stauffer, J.R. 1984. The introduced fish problem and the aquarium fish industry. Journal of the World Aquaculture Society. 21(3): 145-159.

Courtenay, W.R.J. 1993. Biological pollution through fish introductions. In B.N. McKnight (Ed.), Biological pollution : the control and impact of invasive exotic species: proceedings of a symposium held at the University Place Conference Center, Indiana University-Purdue University at Indianapolis on October 25 & 26, 1991. Indiana Academy of Science. Indianapolis, IN. pp 35-62.

Crivelli, A.J. 1995. Are fish introductions a threat to endemic freshwater fishes in the northern Mediterranean region? Biological Conservation, 72: 311–319. https://doi.org/10.1016/0006-3207(94)00092-5.

Crombie, J., Brown, L., Lizzio, J., Hood, G. 2008. Climatch user manual. Bureau of Rural Sciences: Canberra.

Crossman, E.J., Buss, K. 1965. Hybridization in the family Esocidae. Journal of Fisheries Research Board of Canada, 22(5): 1261-1292. https://doi.org/10.1139/f65-108.

Crossman, E.J., Cudmore, B.C. 1999. Summary of North American fish introductions through the aquarium/horticulture trade. In R., Claudi, J.H. Leach (Eds.), Non-indigenous freshwater organisms - Vectors, Biology and Impacts. Lewis Publishers. Boca Raton, FL. pp 129-133.

Cudmore, B., Jones, L.A., Mandrak, N.E., Dettmers, J.M., Chapman, D.C., Kolar, C.S, Conover, G. 2017. Ecological risk assessment of Grass Carp (*Ctenopharyngodon idella*) for the Great Lakes Basin. DFO Canadian Science Advisory Secretariat Research Document. 2016/118. 115 pp.

Culpepper III, C.M., Allen, P.J. 2016. Aquaculture techniques for crappie, *Pomoxis spp*., culture. Journal of the World Aquaculture Society, 47(3) : 314-326. https://doi.org/10.1111/jwas.12283.

Currie, W.J.S., Cuddington, K.M.D., Stewart, T.J., Zhang, H., Koops, M.A. 2012. Modelling spread, establishment and impact of Bighead and Silver Carps in the Great Lakes. DFO Canadian Science Advisory Secretariat Research Document. 2011/11374 pp.

Daigle, R. 2021. CMISTR: Canadian Marine Invasive Screening Tool in R. Available from https://github.com/remi-daigle/CMISTR.

Dalbey, B., Staff, P. 2018. Tiny goldfish create monster problem when released in fresh water. Patch. Spokane, WA. Published April 26, 2018. [Online], https://patch.com/washington/spokane/goldfish-create-monster-sized-problem-washington-lake. Accessed February 28, 2023.

De Giosa, M., Czerniejewski, P., Rybczyk, A. 2014. Seasonal changes in condition factor and weight-length relationship of invasive *Carassius gibelio* (Bloch, 1782) from Leszczynskie Lakeland, Poland. Advances in Zoology, 678763: 1-7. https://doi.org/10.1155/2014/678763.

Deacon, J.E., Hubbs, C., Zahuranec, B.J. 1964. Some effects of introduced fishes on the native fish fauna of southern Nevada. Copeia, 1964: 384-388.

DeRoche, S., Foye, R. 1954. First Record of the Black Crappie, *Pomoxis nigromaculatus*, in Maine. Copeia, 1:75. https://doi.org/10.2307/1440658.

DFO. 2014. Science advice for screening-level risk assessment protocols for non-indigenous freshwater organisms in trade in Canada. DFO Canadian Science Advisory Report. 2014/009. 18 pp.

DFO. 2018. Recovery strategy for the Atlantic Whitefish (*Coregonus huntsmani*) in Canada. Species at Risk Act Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa. xiii + 62 pp.

Dhopade, P. 2021. The Goldfish invasion of Hamilton Harbour. Maclean's. Published February 3, 2021. [Online]. https://www.macleans.ca/society/environment/the-Goldfish-invasion-in-hamilton-harbour/. Accessed February 27, 2023.

Diagne, C., Leroy, B., Vaissière, A. C., Gozlan, R.E., Roiz, D., Jarić, I., Salles, J-M., Bradshaw, C.J.A. Courchamp, F. 2021. High and rising economic costs of biological invasions worldwide. Nature, 592: 571-576. https://doi.org/10.1038/s41586-022-05100-6.

Docherty, C., Ruppert, J., Rudolfsen, T., Hamann, A., Poesch, M.S. 2017. Assessing the spread and potential impact of Prussian Carp *Carassius gibelio* (Bloch, 1782) to freshwater fishes in western North America. BioInvasions Records, 6: 291–296. https://www.reabic.net/journals/bir/2017/Issue3.aspx

Downing, A.S., van Nes, E.H., Mooij, W.M., Scheffer, M. 2012. The resilience and resistance of an ecosystem to a collapse of diversity. PLoS One, 7(9): e46135. https://doi.org/10.1371/journal.pone.0046135.

Drake, D.A.R., Mandrak, N.E. 2014a. Ecological risk of live bait fisheries: A new angle on selective fishing. Fisheries, 39: 201–211. https://doi.org/10.1080/03632415.2014.903835.

Drake, D.A.R., Mandrak, N.E. 2014b. Bycatch, bait, anglers, and roads: Quantifying vector activity and propagule introduction risk across lake ecosystems. Ecological Applications, 24(4): 877–894. http://www.jstor.org/stable/24432197.

Drake, D.A.R., Mercader, R., Dodson, T., 2015. Can we predict risky human behaviour involving invasive species? A case study of the release of fishes to the wild. Biological Invasions, 17: 309-326. https://doi.org/10.1007/s10530-014-0729-7.

Drolet, D., DiBacco, C., Locke, A., McKenzie, C.H., McKindsey, C.W., Moore, A.M., Webb, J.L., Therriault, T.W. 2016. Evaluation of a new screening-level risk assessment tool applied to non-indigenous marine invertebrates in Canadian coastal waters. Biological Invasions, 18: 279–294. https://doi.org/10.1007/s10530-015-1008-y.

Drolet, D., DiBacco, C., Locke, A., McKenzie, C.H., McKindsey, C.W., Therriault, T.W. 2017. Optimizing screening protocols for non-indigenous species: are currently used tools over-parameterized? Management of Biological Invasions, 8: 171–179. https://doi.org/10.3391/mbi.2017.8.2.05.

Duplinsky, P.D. 1982. Sperm motility of northern pike and Chain Pickerel at various pH levels. Transactions of the American Fisheries Society, 111: 768-771. https://doi.org/10.1577/1548-8659(1982)111<768:SMONPA>2.0.CO;2.

EDDMapS. University of Georgia- Center for Invasive Species and Ecosystem Health. [Online], https://www.eddmaps.org. Accessed September 2, 2022.

Edge, T., Gilhen, J. 2000. Updated COSEWIC status report on the Atlantic Whitefish *Coregonus huntsmani* in Canada. In: COSEWIC assessment and update status report on the Atlantic Whitefish *Coregonus huntsmani* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. 35 pp.

Egertson, C.J., Downing, J.A. 2004. Relationship of fish catch and composition to water quality in a suite of agriculturally eutrophic lakes. Canadian Journal of Fisheries and Aquatic Sciences, 61(9): 1784-1796. https://doi.org/10.1139/f04-109.

Elger, M., Hentschel, H. 1981. The glomerulus of a stenohaline fresh-water teleost, *Carassius auratus gibelio*, adapted to saline water: A scanning and transmission electron-microscopic study. Cell and Tissue Research, 220 : 73-85. https://doi.org/10.1007/BF00209967.

Elgin, E., Tunna, H., Jackson, L. 2014. First confirmed records of Prussian Carp, *Carassius gibelio* (Bloch, 1782) in open waters of North America. BioInvasions Records, 3: 275-282. http://dx.doi.org/10.3391/bir.2014.3.4.09.

Embody, G.C. 1918. Artificial hybrids between pike and pickerel: Crossing which is possible artificially appears sometimes to occur in nature—Peculiar specimens which are occasionally found are probably not mutants, but true hybrids. Journal of Heredity, 9(6): 253–256. https://doi.org/10.1093/oxfordjournals.jhered.a111958.

Fagernes, C.E., Stensløkken, K.O., Røhr, Å.K., Berenbrink, M., Ellefsen, S., Nilsson, G.E. 2017. Extreme anoxia tolerance in crucian carp and goldfish through neofunctionalization of duplicated genes creating a new ethanol-producing pyruvate decarboxylase pathway. Scientific Reports, 7(1): 7884. https://doi.org/10.1038/s41598-017-07385-4.

Fick, S.E.. Hijmans, R.J. 2017. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37 (12): 4302-4315.

Finch, D.M., Butler, J.L., Runyon, J.B., Fettig, C.J., Kilkenny, F.F., Jose, S., Frankel, S.J., Cushman, S.A., Cobb, R.C., Dukes, J.S., Hicke, J.A., Amelon, S.K. 2021. Effects of Climate Change on Invasive Species. In T.M. Poland, T. Patel-Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, V.M. Lopez (Eds), Invasive Species in Forests and Rangelands of the United States (p. 57-83). Springer International Publishing. https://doi.org/10.1007/978-3-030-45367-1_4.

Ford, T., Beitinger, T.L. 2005. Temperature tolerance in the Goldfish, *Carassius auratus*. Journal of Thermal Biology, 30 (2): 147-152. https://doi.org/10.1016/j.jtherbio.2004.09.004.

Foster, R., Peeler, E., Bojko, J., Clark, P.F., Morritt, D., Roy, H.E., Stebbing, P., Tidbury, H.J., Wood, L.E., Bass, D. 2021. Pathogens co-transported with invasive non-native aquatic species: implications for risk analysis and legislation. NeoBiota, 69: 79-102. https://doi.org/10.3897/neobiota.69.71358.

Franklin, M. 2020. More than 40 000 invasive Goldfish found in one Alberta pond, officials say. CTV News, Calgary. Published November 7, 2020. [Online]. https://calgary.ctvnews.ca/more-than-40-000-invasive-goldfish-found-in-one-alberta-pond-officials-say-1.5179185. Accessed February 27, 2023.

Fricke, R., Eschmeyer, W.N., van der Laan, R. (eds) 2024. Eschmeyer's Catalog of Fishes: Genera, Species, References. http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp. Froese, R., Pauly, D. 2022. FishBase. World Wide Web electronic publication. www.fishbase.org.

Fuad, M.M.H., Vetešník, L., Šimková, A. 2021. Is gynogenetic reproduction in gibel carp (*Carassius gibelio*) a major trait responsible for invasiveness? Journal of Vertebrate Biology, 70: 1-13. https://doi.org/10.25225/jvb.21049.

Fuller, P. Larson, J., Makled, T.H., Lower, E., Fusaro, A. 2022. *Esox niger* (Lesueur, 1818): U.S. Geological Survey, Non-indigenous Aquatic Species Database, Gainesville, FL. [Online], https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=681. Revision Date: 9/12/2019, Peer Review Date: 1/30/2015. Accessed July 7, 2022.

Fuller, P., Cannister, M., Neilson, M. 2023. *Pomoxis nigromaculatus* (Lesueur in Cuvier and Valenciennes, 1829): U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL, https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=409, Revision Date: 8/28/2019, Peer Review Date: 5/29/2012, Access Date: 7/4/2023.

Fuller, P.L., Nico, L.G., Williams, J.D. 1999. Nonindigenous fishes introduced into inland waters of the United States. American Fisheries Society, Special Publication 27, Bethesda, Maryland. 636 pp.

Fusaro, A., Baker, E., Conard, W., Davidson, A., Dettloff, K., Li, J., Nunez-Mir, G., Sturtevant, R.A., Rutherford, E.S. 2016. A risk assessment of Great Lakes aquatic invaders. NOAA Technical Memorandum GLERL-169. NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 1638 pp. https://www.glerl.noaa.gov/pubs/tech_reports/glerl-169/tm-169.pdf

Gablehouse, D.W., Jr. 1984. An assessment of crappie stocks in small midwestern private impoundments. North American Journal of Fisheries Management, 4: 371-384. https://doi.org/10.1577/1548-8659(1984)4<371:AAOCSI>2.0.CO;2.

Galinat, G.F., Willis, D.W., Blackwell, D.W., Hubers, M.J. 2002. Influence of a Saugeye (Sauger × Walleye) introduction program on the Black Crappie population in Richmond Lake, South Dakota. North American Journal of Fisheries Management, 22: 1416–1424. https://doi.org/10.1577/1548-8675(2002)022<1416:IOASSW>2.0.CO;2.

Gandar, A., Jean, S., Canal, J., Marty-Gasset, N., Gilbert, F., Laffaille, P. 2016. Multi-stress effects on goldfish (*Carassius auratus*) behavior and metabolism. Environmental Science and Pollution Research, 23: 3184-3194. https://doi.org/10.1007/s11356-015-5147-6.

GBIF Secretariat. 2022. GBIF Backbone Taxonomy. Checklist Dataset. via GBIF.org. Available online: https://doi.org/10.15468/39omei. Accessed 3 May, 2023.

Gertzen, E.L., Midwood, J.D, Wiemann, N., Koops, M.A. 2008. Ecological Consequences of Grass Carp, *Ctenopharyngodon idella*, in the Great Lakes Basin: vegetation, fishes and birds. DFO Canadian Science Advisory Secretariat Research Document. 2016/117. 52 pp.

Gilhen, J. and Pentz, D. 1974. The Fishes of Nova Scotia's Lakes and Streams. Nova Scotia Museum, Halifax, NS. 49 pp.

Goldsmit, J., McKindsey, C.W., Stewart, D.B., Howland, K.L. 2021. Screening for high-risk marine invaders in the Hudson Bay Region, Canadian Arctic. Frontiers in Ecology and Evolution, 9: 627497. https://doi.org/10.3389/fevo.2021.627497.

Gordon, D.R., Gantz, C.A., Jerde, C.L., Chadderton, W.L., Keller, R.P., Champion, P.D. 2012. Weed Risk Assessment for Aquatic Plants: Modification of a New Zealand System for the United States. PLoS ONE 7(7): e40031. https://doi.org/10.1371/journal.pone.0040031

Government of Canada. 2006. Ballast water control and management regulations. Canada Gazette. https://laws-lois.justice.gc.ca/eng/regulations/SOR-2011-237/.

Government of Yukon, 2023. Aquatic invasive species. [Online], https://yukon.ca/en/aquatic-invasive-species. Accessed March 3, 2023.

Groffman, P., Baron, J., Blett, T., Gold, A., Goodman, I., Gunderson, L., Levinson, B., Palmer, M., Paerl, H., Peterson, G., Poff, N., Rejeski, D., Reynolds, J., Turner, M., Weathers, K., Wiens, J. 2006. Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems, 9:1-13. https://doi.org/10.1007/s10021-003-0142-z.

Halačka, K., Lusková, V., Lusk, S. 2003. *Carassius gibelio* in fish communities of the Czech Republic. Ecohydrology and Hydrobiology, 3: 133-138.

Halas, D., Lovejoy, N., Mandrak, N. E. 2018. Undetected diversity of goldfish (*Carassius spp.*) in North America. Aquatic Invasions, 13(2) : 211-219. http://www.aquaticinvasions.net/2018/issue2.html.

Hamilton, S.N. 2021. Expansion of invasive Prussian carp (*Carassius gibelio*) into Saskatchewan, Canada: current distribution and food-web reconstruction using stable isotopes. MSc Thesis. University of Regina. 73 pp.

Hänfling, B., Bolton, P., Harley, M. Carvalho, G.R. 2005. A molecular approach to detect hybridisation between crucian carp (*Carassius carassius*) and non-indigenous carp species (*Carassius spp.* and *Cyprinus carpio*). Freshwater Biology, 50: 403-417. https://doi.org/10.1111/j.1365-2427.2004.01330.x.

Hanson, J.M. Qadri, S.U. 1980. Observations on the biology of black crappie (*Pomoxis nigromaculatus*) in the Ottawa River. Le Naturaliste Canadien, 107: 35-42.

Hardy, J.D., Jr. 1978. Vol. 3. Aphredoderidae through Rachycentridae. In J.D. Hardy Jr. (Eds.), Development of fishes of the Mid-Atlantic Bight. Fish and Wildlife Service, U.S. Department of the Interior, Washington DC. Pp 273-277.

Harvey, B. 2009. A biological synopsis of northern pike (*Esox lucius*). Canadian Manuscript Report of Fisheries and Aquatic Sciences. 2885: 31 pp.

Hauger, M. 2020. Investigating Black Crappie (*Pomoxis nigromaculatus*) populations using age and growth data in Whiteshell Provincial Park, Manitoba. MSc Thesis, University of Manitoba. 99 pp.

Havel, J.E., Kovalenko, K.E., Thomaz, S.M., Amalfitano, S., Kats, L.B. 2015. Aquatic invasive species: challenges for the future. Hydrobiologia, 750:147-170. https://doi.org/10.1007/s10750-014-2166-0.

Haynes, G.D., Gongora, J., Gilligan, D.M., Grewe, P., Moran, C., Nicholas, F.W. 2012. Cryptic hybridization and introgression between invasive cyprinid species *Cyprinus carpio* and *Carassius auratus* in Australia: implications for invasive species management. Animal Conservation, 15: 83-94. https://doi.org/10.1111/j.1469-1795.2011.00490.x.

Hijmans R (2023). _raster: Geographic Data Analysis and Modeling_. R package version 3.6-20, <https://CRAN.R-project.org/package=raster>.

Hirner, J.L.M., Cox, S.P. 2007. Effects of rainbow trout (*Oncorhynchus mykiss*) on amphibians in productive recreational fishing lakes of British Columbia. Canadian Journal of Fisheries and Aquatic Sciences, 64: 1770–80. https://doi.org/10.1139/f07-139.

Holm, E., Mandrak, N.E., Burridge, M.E. 2021. A field guide to freshwater fishes of Ontario. Royal Ontario Museum, Toronto, Ontario. 488 pp.

Holopainen, I.J., Tonn, W.M., Paszkowski, C.A. .1997. Tales of two fish: the dichotomous biology of crucian carp (*Carassius carassius* (L.)) in northern Europe. Annales Zoologici Fennici, 34: 1-22.

Howeth, J.G., Gantz, C.A., Angermeier, P.L. Frimpong, E.A., Hoff, M.H., Keller, R.P., Mandrak, N.E., Marchetti, M.P., Olden, J.D., Romagosa, C.M., Lodge, D.M. 2016. Predicting invasiveness of species in trade: climate match, trophic guild and fecundity influence establishment and impact of non-native freshwater fishes. Diversity and Distributions, 22:148–160. https://doi.org/10.1111/ddi.12391.

Hoyle, J.A., Lake, C. 2011. First occurrence of Chain Pickerel (*Esox niger*) in Ontario: possible range expansion from New York waters of eastern Lake Ontario. Canadian Field Naturalist, 125(1): 16–21. https://doi.org/10.22621/cfn.v125i1.1116.

Hrbáček, J. Dvořakova, M., Kořínek, V., Procházkóva, L. 1961. Demonstration of the effect of the fish stock on the species composition of zooplankton and the intensity of metabolism of the whole plankton association. Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verhandlungen, 14: 192-195. https://doi.org/10.1080/03680770.1959.11899269.

Hubbard, J.A.G., Drake, D.A.R., Mandrak, N.E. 2023. Euclimatch: Euclidean climatch algorithm. Retrieved from https://cran.r-project.org/package=Euclimatch

Hubbard, J.A.G., Drake, D.A.R., Mandrak, N.E. 2023. Estimating potential global sources and secondary spread of freshwater invasions under historical and future climates. Diversity and Distributions, 29: 986–996. https://doi.org/10.1111/ddi.13695.

Hudon, C., Jean, M., Létourneau, G. 2018. Temporal (1970–2016) changes in human pressures and wetland response in the St. Lawrence River (Québec, Canada). Science of the Total Environment, 643: 1137-1151. https://doi.org/10.1016/j.scitotenv.2018.06.080.

Hughes, R.M., Herlihy, A.T. 2012. Patterns in catch per unit effort of native prey fish and alien piscivorous fish in 7 Pacific Northwest USA rivers. Fisheries. 37(5): 201-211. https://afspubs.onlinelibrary.wiley.com/doi/pdf/10.1080/03632415.2012.676833.

Hume, D.J., Fletcher, A.R., Morison, A.K. 1983. Interspecific hybridization between carp (*Cyprinus carpio* L.) and goldfish (*Carassius auratus* L.) from Victorian Waters. Marine and Freshwater Research, 34(6): 915-919. https://doi.org/10.1071/MF9830915.

Hunt, L.M., Phaneuf, D.J., Abbott, J.K., Fenichel, E.P., Rodgers, J.A., Buckley, J.D., Drake, A.R. Johnson, T. 2021. The influence of human population change and aquatic invasive species establishment on future recreational fishing activities to the Canadian portion of the Laurentian Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences, 78(3): 232-244. http://doi.org/10.1139/cjfas-2020-0159.

iNaturalist. © Copyright 2022 California Academy of Sciences. [Online], Available at https://www.inaturalist.org/. Accessed July 12, 2022.

Jackson, T. 2015. Addressing the economic costs of invasive alien species: some methodological and empirical issues. International Journal of Sustainable Society, 7: 221–240. https://doi.org/10.1504/IJSSOC.2015.071303.

Jacquin, L., Gandar, A., Aguirre-Smith, M., Perrault, A., Le Hénaff, M., De Jong, L., Paris-Palacios, S., Lafaille, P., Jean, S. 2019. High temperature aggravates the effects of pesticides in goldfish. Ecotoxicology and Environmental Safety, 172: 255-264. https://doi.org/10.1016/j.ecoenv.2019.01.085.

Jia, Y., Liu, Y., Chen, K., Sun, H., Chen, Y. 2019. Climate, habitat and human disturbance driving the variation of life-history traits of the invasive Goldfish *Carassius auratus* (Linnaeus, 1758) in a Tibetan Plateau river. Aquatic Invasions, 14(4): 724-737. https://doi.org/10.3391/ai.2019.14.4.11.

Jones, B.A. 2017. Invasive species impacts on human well-being using the life satisfaction index. Ecological Economics,134: 250–257. https://doi.org/10.1016/j.ecolecon.2017.01.002.

Keast, A. 1968. Feeding biology of the black crappie, *Pomoxis nigromaculatus*. Journal of the Fisheries Board of Canada, 25(2): 285-297. https://doi.org/10.1139/f68-024.

Kelly, A.M., Engle, C.R., Armstrong, M.L., Freeze, M., Mitchell, A.J. 2011. History of introductions and governmental involvement in promoting the use of grass, silver, and bighead carps. In D.C. Chapman, M.H. Hoff (Eds.), Invasive Asian carps in North America. American Fisheries Society, Bethesda, MD. pp. 163–174.

Kennedy, T.A., Naeem, S., Howe, K.M., Knops, J.M., Tilman, D., Reich, P. 2002. Biodiversity as a barrier to ecological invasion. Nature, 417: 636-638. https://doi.org/10.1038/nature00776.

Kerr, S.J. 2006. An historical review of fish culture, stocking and fish transfers in Ontario, 1865-2004. Fish and Wildlife Branch. Ontario Ministry of Natural Resources. Peterborough, Ontario. 154 pp.

Kerr, S.J., Grant. R. E. 2000. Ecological impacts of fish introductions: Evaluating the risk. Fish and Wildlife Branch, Ontario Ministry of Natural Resources, Peterborough, Ontario. 473 pp.

Khan, I. 2019. Canadian cannabis uses the power of aquaponics. Fishfarmingexpert.com. Published August 22, 2019. [Online]. https://www.fishfarmingexpert.com/canada-cannabis-food/canadian-canna. Accessed Oct 27, 2023.

Kilian, J.V., Klauda, R.J., Widman, S., Kashiwagi, M., Bourquin, R., Weglein, S., Schuster, J. 2012. An assessment of a bait industry and angler behavior as a vector of invasive species. Biological Invasions,14:1469–1481.

Kolmakov, V.I., Gladyshev, M.I. 2003. Growth and potential photosynthesis of cyanobacteria are stimulated by viable gut passage in crucian carp. Aquatic Ecology, 37(3): 237-242.

Komiyama, T., Kobayashi, H., Tateno, Y., Inoko, H., Gojobori,T., Ikeo, K. 2009. An evolutionary origin and selection process of goldfish. Gene. 430(1-2): 5-11. https://doi.org/10.1016/j.gene.2008.10.019.

Kottelat, M. 1998. European freshwater fishes. Environmental Biology of Fishes, 51(1): 116. https://doi.org/10.1023/A:1007452304138.

Kottelat, M., Freyhof, J. 2007. Handbook of European freshwater fishes. Publications Kottelat. Cornol, CH. 646 pp.

Kramer, A.G., Gomelsky, B., Warner, J.L., Novelo, N.D., Thomas, B.L. 2020. Reproductive ability of triploid ornamental (koi) carp (*Cyprinus carpio* L.) × goldfish (*Carassius auratus* L.) hybrids and characteristics of their offspring. Aquaculture Research, 51(7): 2824-2830.

Krishka, B.A., Cholmondeley, R.F. Dextrase, A.J., Colby, P.J. 1996. Impacts of introductions and removals on Ontario percid communities. Percid Community Synthesis, Ontario Ministry of Natural Resources, Peterborough, Ontario. 111 pp.

Kucinski, M., Demska-Zakes, K., Zarski, D., Liszewski, T., Fopp-Bayat, D., Jankun, M., Furgala-Selezniow, G. 2015. The morphological, histological and cytogenetic characteristics of goldfish *Carassius auratus* (L.)× common carp *Cyprinus carpio* (L.) hybrids. Caryologia, 68(2): 77-83.

Küçük, S. 2013. The effects of salinity on growth of goldfish, *Carassius auratus* and crucian carp, *Carassius carassius*. African Journal of Biotechnology. 2013; 12(16): 2082-2087

Kuhl, H., Du, K., Schartl, M., Kalous, L., Stöck, M., Lamatsch, D. K. 2022. Equilibrated evolution of the mixed auto-/allopolyploid haplotype-resolved genome of the invasive hexaploid Prussian carp. Nature Communications,13(1): 4092. https://doi.org/10.1038/s41467-022-31515-w.

Kumschick, S., Bacher, S., Evans, T., Marková, Z., Pergl, J., Pyšek, P., Vaes-Petignat, S., van der Veer, G., Vilà, M., Nentwig, W. 2015. Comparing impacts of alien plants and animals in Europe using a standard scoring system. Journal of Applied Ecology, 52: 552-561. https://doi.org/10.1111/1365-2664.12427.

Kumschick, S., Gaertner, M., Vilà, M. , Essl, F., Jeschke, J.M., Pyšek, P. Ricciardi, A., Bacher, S., Blackburn, T.M., Dick, J.T.A, Evans, T., Hulme, P.E., Kühn, I., Mrugała, A., Pergl, J., Rabitsch, W., Richardson, D.M., Sendek, A., Winter, M. 2015. Ecological impacts of alien species: quantification, scope, caveats, and recommendations. Bioscience, 65: 55–63.

Lawson, E.O., Alake, S.A. 2011. Salinity adaptability and tolerance of hatchery reared comet goldfish *Carassius auratus* (Linnaeus 1758). International Journal of Zoological Research, 7(1): 68-76.

Lee, D.S., Burgess, G.H., Lee, D.S., Platania, S.P. 1980. Atlas of North American freshwater fishes (No. C/597.9297 A8). North Carolina State Museum of Natural History. 854 pp.

Lehner, B., Grill G. 2013. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. https://doi.org/10.1002/hyp.9740.

Leonardos, I.D., Kagalou, I., Tsoumani, M., Economidis, P.S. 2008. Fish fauna in a protected Greek lake: biodiversity, introduced fish species over a 80-year period and their impacts on the ecosystem. Ecology of Freshwater Fish, 17: 165-173. https://doi.org/10.1111/j.1600-0633.2007.00268.x.

Lockwood, J.L., Hoopes, M.F., and Marchetti, M.P. 2013. Invasion ecology. Wiley-Blackwell Publishing, West Sussex, 444 pp Lisser, D.F., Lister, Z.M., Pham-Ho, P.Q., Scott, G.R., Wilkie, M.P. 2017. Relationship between oxidative stress and brain swelling in goldfish (*Carassius auratus*) exposed to high environmental ammonia. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 312(1): 114-124.

Liu, J. Kattel, G., Arp, H.P.H., Yang, H. 2015. Towards threshold-based management of freshwater ecosystems in the context of climate change. Ecological Modelling, 318: 265-274.

Lorenzoni, M., Corboli, M., Ghetti, L., Pedicillo, G., Carosi, A. 2007. Growth and reproduction of the goldfish *Carassius auratus* : A case study from Italy. In F. Gherardi (Eds.), Biological invaders in inland waters : Profiles, distribution, and threats. 2: 259-273. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-1-4020-6029-8_13.

Lorenzoni, M., Dolciami, R., Ghetti, L., Pedicillo, G., Carosi, A. 2010. Fishery biology of the goldfish *Carassius auratus* (Linnaeus, 1758) in Lake Trasimeno (Umbria, Italy). Knowledge and Management of Aquatic Ecosystems, 396(1): 01. https://doi.org/10.1051/kmae/20010001.

Love, D.C., Fry, J.P., Genello, L., Hill, E.S., Frederick, J.A., Li, X., Semmens, K. 2014. An international survey of aquaponics practitioners. PLoS One, 9(7): e102662. https://doi.org/10.1371/journal.pone.0102662.

Lusk, S., Lusková, V., Hanel, L. 2010. Alien fish species in Czech Republic and their impact on the native fish fauna. Folia Zoologica, 59(1): 57-72. https://doi.org/10.25225/fozo.v59.i1.a9.2010.

Lutz, P.L., Nilsson, G.E. 1997. Contrasting strategies for anoxia brain survival—glycolysis up or down. Journal of Experimental Biology, 200: 411–419.

Mackey, T., Hasler, C.T., Enders, C.T. 2019. Summary of Temperature Metrics for Aquatic Invasive Fish Species in the Prairie Region. Canadian Technical Report of Fisheries and Aquatic Sciences. 3308: 62 pp.

Magnuson, J.J., Webster, K.E., Assel, R.A., Bowser, C.J., Dillon, P.J., Eaton, J.G., Evans, H.E., Fee, E.J., Hall, R.I., Mortsch, L.R., Schindler, D.W., Quinn, F.H. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian Shield Region. Hydrological Processes, 11(8): 825-871.

Magurran, A. 1984. Gregarious Goldfish. New Scientist, 103: 32-33.

Mandrak, N.E., Cudmore, B.C.. 2015. Risk assessment: cornerstone of an aquatic invasive species program. Journal of Aquatic Ecosystem Health and Management, 18: 312-320. https://doi.org/10.1080/14634988.2015.1046357

Mandrak, N.E., Cudmore, B., Chapman, P.M. 2012. National detailed-level risk assessment guidelines: assessing the biological risk of aquatic invasive species in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/092. vi + 17 p.

Marcer, A., Chapman, A.D., Wieczorek, J.R., Xavier Picó, F., Uribe, F., Waller, J., Ariño, A.H. 2022. Uncertainty matters: ascertaining where specimens in natural history collections come from and its implications for predicting species distributions. Ecography, 9: 1–17. https://doi.org/10.1111/ecog.06025.

Marcot, B.G., Hoff, M.H., Martin, C.D., Jewell, S.D., Givens, C.E. 2019. A decision support system for identifying potentially invasive and injurious freshwater fishes. Management of Biological Invasions 10(2): 200–226. https://doi.org/10.3391/mbi.2019.10.2.01

Maritime Provinces Fishery Regulation, SOR/93-55.1993. Online]. https://laws-lois.justice.gc.ca/PDF/SOR-93-55.pdf. Accessed December 10, 2022.

Martinez, N.D. 1991. Artifacts or attributes? Effects of resolution on the Little Rock Lake food web. Ecological Monographs, 61(4) : 367-392.

Massicotte P, South A (2023). _rnaturalearth: World Map Data from Natural Earth_. https://docs.ropensci.org/rnaturalearth/, https://github.com/ropensci/rnaturalearth.

McAlpine, D.F., Connell, C.B., Seymour, P.D. 2020. Introduction of Southern White River Crayfish (*Procambarus zonangulus*) to New Brunswick. The Canadian Field-Naturalist, 134(4): 375-378.

McCarraher, D.B. 1960. Pike hybrids (*Esox lucius* x *E. vermiculatus*) in a sandhill lake, Nebraska. Transactions of the American Fisheries Society, 89(1): 82-83.

McDonald, M. 1887. Report on Distribution of Fish and Eggs by the US Fish Commission for the Season 1885-86. [Online], https://www.penbay.org/usfc/usfc1886_fisheggdistrib2.html. Accessed May 24, 2022.

McDonald, M. 1893. Report of the Commissioner for 1889 to 1891. Part XVII. US Comm. Fish Fish., Washington, DC.

McEachran, M.C., Hofelich Mohr, A., Lindsay, T., Fulton, D.C., Phelps, N.B.D. 2022. Patterns of live baitfish use and release among recreational anglers in a regulated landscape. North American Journal of Fisheries Management, 42: 295-306. https://doi.org/10.1002/nafm.10747.

McNeil, O.C. 1992. A review of the life history, habitat requirements and past introductions of Black Crappie. Report prepared for the Ontario Ministry of Natural Resources, Midhurst District. Owen Sound, Ontario. 36 pp.

Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O. 2016. Estimating the volume and age of water stored in global lakes using a geostatistical approach. Nature Communications, 7: 1–11. https://doi.org/10.1038/ncomms13603.

Meyer, A.H., Schmidt, B.R., Grossenbacher, K. 1998. Analysis of three amphibian populations with quarter–century long time–series. Proceedings of the Royal Society of London. Series B: Biological Sciences, 265(1395): 523-528.

Meyers, C.D., Muncy, R.J. 1962. Summer food and growth of chain pickerel, *Esox niger*, in brackish waters of the Severn River, Maryland. Chesapeake Science, 3: 125-128.

Mezhzherin, S.V., Kokodii, S.V., Kulish, A.V., Verlati, D.B., Fedorenko, L.V. 2012. Hybridization of crucian carp Carassius carassius (Linnaeus, 1758) in Ukrainian reservoirs and the genetic structure of hybrids. Cytology and Genetics, 46: 28–35. https://doi.org/10.3103/S0095452712010069

MFFP, 2023. Liste des espèces susceptibles d'être désignées comme menacées ou vulnérables. Gouvernement du Québec. [Online], https://www.quebec.ca/agriculture-environnement-et-ressources-naturelles/faune/gestion-faune-habitats-fauniques/especes-fauniques-menacees-vulnerables/liste. Accessed July 21, 2022.

Miller, S.J., Fox, D.D., Bull, L.A., McCall, T.D. 1990. Population Dynamics of Black Crappie in Lake Okeechobee, Florida, following suspension of commercial harvest. North American Journal of Fisheries Management, 10: 98-105. https://doi.org/10.1577/1548-8675(1990)010<0098:PDOBCI>2.3.CO;2.

Mills, E.L., Leach, J.H., Carlton, J.T., Secor, C.L. 1993. Exotic Species in the Great Lakes: A History of Biotic Crises and Anthropogenic Introductions. Journal of Great Lakes Research, 19: 1-54. https://doi.org/10.1016/S0380-1330(93)71197-1.

Mirza, R.S., Chivers, D.P. 2001. Chemical alarm signals enhance survival of brook charr (*Salvelinus fontinalis*) during encounters with predatory chain pickerel (*Esox niger*). Ethology, 107 (11): 989-1005.

Mitchell, S.C., LeBlanc, J.E., Heggelin, A. J. 2012. Impact of introduced Chain Pickerel (*Esox niger*) on lake fish communities in Nova Scotia, Canada. Nova Scotia Department of Fisheries and Aquaculture, Halifax, Nova Scotia, Canada. 18 pp.

Monello, R.J., Wright, R.G. 1999. Amphibian habitat preferences among artificial ponds in the Palouse region of northern Idaho. Journal of Herpetology. 33: 298-303.

Monello, R.J., Wright, R.G. 2001. Predation by Goldfish (*Carassius auratus*) on eggs and larvae of the Eastern Long-Toed Salamander (*Ambystoma macrodactylum columbianum*). Journal of Herpetology, 35(2): 350–353.

Mooney, H.A., Cleland, E.E. 2001. The evolutionary impact of invasive species. Proceedings of the National Academy of Sciences USA, 98: 5446–5451.

Morgan, D., Beatty. S. 2004. Fish fauna of the Vasse River and the colonisation by feral Goldfish (*Carassius auratus*). Centre for Fish and Fisheries Research, Murdoch University. 35 pp.

Morrison, B.P., Moore, D.J. 2017. First occurrence of a juvenile Chain Pickerel (*Esox niger*) in Ontario waters of Lake Ontario. The Canadian Field-Naturalist, 131(4): 331-334.

Mosindy, T. 1995. Black crappie introductions in the Lake of the Woods area. In P. MacMahon (Eds.), Fish: To Stock or Not to Stock, Northwest Region Science and Technology Workshop Proceedings WP-003, Ontario Ministry of Natural Resources, Thunder Bay, ON. p. 17-18

Mosindy, T. 1997. Habitat requirements of walleye populations. In Proceedings of the Non-Salmonid Rehabilitation Workshop, Ontario Ministry of Natural Resources, Barrie, ON. p. 83-84.

Moyle, P.B. 2002. Inland Fishes of California: revised and expanded. University of California Press, Oakland, CA. 502 pp.

Mugerwa, M. 2022. Invasive goldfish proliferating in Saskatoon storm ponds. CBC News. Published August 23, 2022. [Online]. https://www.cbc.ca/news/canada/saskatchewan/invasive-goldfish-swimming-into-saskatoon-storm-ponds-1.6559934. Accessed Oct 27, 2023.

Mulligan, H., Schall, B.J., Davis, T., Coulter, A.A. 2023. Opportunities for regional collaboration and prevention: Assessing the risk of the live bait trade as a pathway of invasive species. Biological Conservation, 287: 110342. https://doi.org/10.1016/j.biocon.2023.110342.

Natural Earth 2021. [Online], https://www.naturalearthdata.com/.

Nico, L.G., Schofield, P.J., Larson, J., Makled, T.H., Fusaro, A., Morningstar, C. 2022. *Carassius auratus* (Linnaeus, 1758). USGS Geological Survey, Non-indigenous Aquatic Species Database, Gainsville, FL. [Online], https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=508. Accessed May 26, 2022.

Nilsson, G.E. 2001. Surviving anoxia with the brain turned on. Physiology, 16: 217–221. https://doi.org/10.1152/physiologyonline.2001.16.5.217.

Nova Scotia Live Fish Possession Regulations, N.S. Reg. 212/2012. 2012. [Online} https://www.novascotia.ca/JUST/REGULATIONS/regs/fcrlivefish.htm. Accessed January 20, 2023.

Ogden, N.H., Wilson, J.R.U., Richardson, D.M., Hui, C., Davies, S.J., Kumschick, S., Le Roux, J.J., Measey, J., Saul, W.C., Pulliam, J.R.C. 2019. Emerging infectious diseases and biological invasions: a call for a One Health collaboration in science and management. Royal Society Open Science, 6: 181577. https://doi.org/10.1098/rsos.181577.

Olden, J.D., Whattam, E., Wood, S.A. 2021. Online auction marketplaces as a global pathway for aquatic invasive species. Hydrobiologia, 848: 1967–1979. https://doi.org/10.1007/s10750-020-04407-7

O'Sullivan, A.M., Samways, K.M., Perreault, A., Hernandez, C. Gautreau, M.D., Curry, R.A., Bernatchez, L. 2020. Space invaders: Searching for invasive Smallmouth Bass (*Micropterus dolomieu*) in a renowned Atlantic Salmon (*Salmo salar*) river. Ecology and Evolution, 10: 2588–2596. https://doi.org/10.1002/ece3.6088.

Page, L.M., Burr, B.M. 2011. Peterson field guide to freshwater fishes of North America north of Mexico. 2nd ed. Boston, Houghton Mifflin Harcourt. 597pp

Papoušek, I., Vetešník, L., Halačka, K., Lusková, V., Humpl, M., Mendel. J. 2008. Identification of natural hybrids of gibel carp *Carassius auratus gibelio* (Bloch) and crucian carp *Carassius carassius* (L.) from lower Dyje River floodplain (Czech Republic). Journal of Fish Biology, 72 : 1230–1235. https://doi.org/10.1111/j.1095-8649.2007.01783.x.

Parsons, B.G., Reed, J.R. 1998. Angler exploitation of bluegill and Black Crappie in four west-central Minnesota lakes. St. Paul: Minnesota Department of Natural Resources Investigational Report, 468: 1-35.

Paschos I., Nathanailides C., Tsoumani M., Perdicaris C., Gouva E., Leonardos I. 2004. Intra- and inter-specific mating options for gynogenetic reproduction of *Carassius gibelio* (Bloch, 1783) in Lake Pamvotis (NW Greece). Belgian Journal of Zoology, 134: 55–60.

Paulovits, G., Ferincz, Á., Staszny, Á., Weiperth, A., Tátrai, I., Korponai, J., Mátyás, K., Kováts, N. 2014. Long-term changes in the fish assemblage structure of a shallow eutrophic reservoir (Lake Hídvégi, Hungary), with special reference to the exotic *Carassius gibelio*. International Review of Hydrobiology, 99: 373-381. https://doi.org/10.1002/iroh.201301662.

Pebesma, E., 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal, 10(1): 439-446. https://doi.org/10.32614/RJ-2018-009

Pebesma, E., Bivand, R. 2023. Spatial Data Science: With Applications in R. Chapman and Hall/CRC. https://doi.org/10.1201/9780429459016

Pelham, M.E., Pierce, C.L., Larscheid, J.G. 2001. Diet dynamics of the juvenile piscivorous fish community in Spirit Lake, Iowa, USA, 1997–1998. Ecology of Freshwater Fish,10(4): 198-211.

Perdikaris, C., Ergolavou, A., Gouva, E., Nathanailides, C., Chantzaropoulos, A., Paschos, I. 2012. *Carassius gibelio* in Greece: the dominant naturalised invader of freshwaters. Reviews in Fish Biology and Fisheries, 22: 17–27. https://doi.org/10.1007/s11160-011-9216-8.

Peterson, A.T., Vieglais, D.A. 2001. Predicting species invasions using ecological niche modeling: new approaches from bioinformatics attack a pressing problem. BioScience, 51: 363–371.

Pheloung, P.C. 1996. Climate: a system to predict the distribution of an organism based on climate preferences. South Perth: Agriculture Western Australia.

Post, J.R., van Poorten, B.T., Rhodes, T., Askey, P. Paul, A. 2006. Fish entrainment into irrigation canals: an analytical approach and application to the Bow River, Alberta, Canada. North American Journal of Fisheries Management, 26: 875-887.

Potts, L.P., Castaneda, R.A., Grant, P., Reid, S.M., Lepitzki, D.A.W., Mandrak, N.E., May-McNally, S.L., Robert, K., and Drake, D.A.R. *2023 in press*. IUCN threats calculator results for COSEWIC-assessed aquatic species in Canada, 2013–2021. Canadian Manuscript Report of Fisheries and Aquatic Sciences.

Powell, J.R. 2022. A biological synopsis of Black Crappie (*Pomoxis nigromaculatus*). Prepared for Fisheries and Oceans Canada. 64pp.

Pullan, S., Smith, P. J. 1987. Identification of hybrids between koi (*Cyprinus carpio*) and goldfish (*Carassius auratus*). New Zealand Journal of Marine and Freshwater Research, 21(1): 41-46.

QGIS Development Team, 1991. QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

Quebec Fishery Regulations, 1990, SOR/90-214. 1990. [Online]. https://laws-lois.justice.gc.ca/eng/regulations/SOR-90-214/index.html. Accessed December 10, 2022.

Quinn, S., Paukert, C. 2009. Centrarchid Fisheries. In S.J. Cooke, D.P. Philipp (Eds.), Centrarchid Fishes: diversity, biology, and conservation. Blackwell Publishing Ltd. 312-339.

R Core Team 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Raney, E. C. 1942. The summer food and habits of the chain pickerel (*Esox niger*) of a small New York pond. The Journal of Wildlife Management, 6(1): 58-66.

Razlutskij, V., Mei, X., Maisak, N., Sysova, E., Lukashanets, D., Makaranka, A., Jeppesen, E., Zhang, X. 2021. Omnivorous Carp (*Carassius gibelio*) increase eutrophication in part by preventing development of large-bodied zooplankton and submerged macrophytes. Water, 13(11): 12 pp. https://doi.org/10.3390/w13111497.

Ribeiro, F., Rylková, K., Moreno-Valcárcel, R., Carrapato, C., Kalous, L. 2015. Prussian carp *Carassius gibelio*: a silent invader arriving to the Iberian Peninsula. Aquatic Ecology, 49: 99-104.

Ricciardi, A. 2007. Are modern biological invasions an unprecedented form of global change? Conservation Biology, 21: 329–336. https://doi.org/10.1111/j.1523-1739.2006.00615.x.

Ricciardi, A., Iacarella, J.C., Aldridge, D.C., Blackburn, T.M., Carlton, J.T., Catford, J.A., Dick, J.T.A., Hulme, P.E., Jeschke, J.M., Liebhold, A.M., Lockwood, J.L., MacIsaac, H.J., Meyerson, L.A., Pyšek, P., Richardson, D.M., Ruiz, G.M., Simberloff, D., Vilà, M., Wardle, D.A. 2021. Four priority areas to advance invasion science in the face of rapid environmental change. Environmental Reviews 29(2): 119–141. https://doi.org/10.1139/er-2020-0088

Ricciardi, A., MacIsaac, H. J. 2022. Vector control reduces the rate of species invasion in the world's largest freshwater ecosystem. Conservation Letters, 15: e12866. https://doi.org/10.1111/conl.12866.

Richardson, M.J., Whoriskey, F.G., Roy, L.H. 1995. Turbidity generation and biological impacts of an exotic fish *Carassius auratus*, introduced into shallow seasonally anoxic ponds. Journal of Fish Biology, 47(4): 576-585.

Richardson, M.J., Whoriskey, F.G. 1992. Factors influencing the production of turbidity by goldfish (*Carassius auratus*). Canadian Journal of Zoology, 70(8): 1585-1589.

Richardson, M.J. 1991. Biological impacts and turbidity generation by an introduced exotic fish (*Carassius auratus*). MSc Thesis, McGill University. 60pp.

Rixon, C.A., Duggan, I.C., Bergeron, N., Ricciardi, A., MacIsaac, H.J. 2005. Invasion risks posed by the aquarium trade and live fish markets on the Laurentian Great Lakes. Biodiversity and Conservation, 14(6): 1365-1381. https://doi.org/10.1007/s10531-004-9663-9.

Robison, H.W., Buchanan, T.M. 1988. Fishes of Arkansas. The University of Arkansas Press, Fayetteville, AR.

Ruppert, J.L.W., Docherty, C., Neufeld, K., Hamilton, K., McPherson, L., Poesch, M.S. 2017. Native freshwater species get out of the way: Prussian Carp (*Carassius gibelio*) impacts both fish and benthic invertebrate communities in North America. Royal Society Open Science, 4: 170400. http://dx.doi.org/10.1098/rsos.170400.

Rylkova, K., Kalous, L., Bohlen, J., Lamatsch, D.K. Petrtyl, M. 2012. Phylogeny and biogeographic history of the cyprinid fish genus *Carassius* (Teleostei: Cyprinidae) with focus on natural and anthropogenic arrivals in Europe. Aquaculture, 380-383: 13-20.

Rylkova, K., Kalous, L., Slechtova, V., Bohlen, J. 2010. Many branches, one root: first evidence for a monophyly of the morphologically highly diverse goldfish (*Carassius auratus*). Aquaculture, 302(9): 36–41.

Saint Lawrence Seaway Development Corporation. 2008. Seaway Regulations and Rules: Ballast Water. Code of Federal Regulations 33-CFR Part 401.

Salgado, J., Vélez, M.I., Caceres-Torres, L.C., Villegas-Ibagon, J.A., Bernal-Gonzalez, L.C., Lopera-Congote, L., Martinez-Medina, N.M., González-Arango, C. 2019. Long-term habitat degradation drives neotropical macrophyte species loss while assisting the spread of invasive plant species. Frontiers in Ecology and Evolution, 7: 3389. https://doi.org/10.3389/fevo.2019.00140.

Sanderson, B.L., Barnas, K.A., Rub, A.M.W. 2009. Non-indigenous Species of the Pacific Northwest: An Overlooked Risk to Endangered Salmon? BioScience, 59(3): 245–256. https://doi.org/10.1525/bio.2009.59.3.9.

Savini, D., Occhipinti-Ambrogi, A., Marchini, A., Tricarico, E., Gherardi, F., Olenin, S., Gollasch, S. 2010. The top 27 animal alien species introduced into Europe for aquaculture and related activities. Journal of Applied Ichthyology, 26 (Suppl. 2): 1-7.

Savidov, N.A., Hutchings, E.. Rakocy, J.E. 2007. Fish and plant production in a recirculating aquaponic system: a new approach to sustainable agriculture in Canada. Acta Horticulturae, 742: 209-221. https://doi.org/10.17660/ActaHortic.2007.742.28

Schiavone, A., Jr. 1985. Response of walleye populations to the introduction of the black crappie in the Indian River Lakes. New York Fish and Game Journal, 32(2): 114-140.

Schiavone, A., Jr. 1983. The Black Lake fish community, 1931 to 1979. New York Fish and Game Journal, 30(1): 78-90.

Schindler, D.W. 1997. Widespread effects of climatic warming on freshwater ecosystems in North America. Hydrological Processes, 11(8): 1043-1067.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences, 58(1): 18-29.

Schofield, P.J., Brown, M.E., Fuller, P.L. 2006. Salinity tolerance of Goldfish (*Carassius auratus* L.), a non-native fish in the United States. Florida Scientist, 69(4): 258–268. http://www.jstor.org/stable/24321452.

Schramm, H.L., Jr., Shireman, J.V., Hammond, D.E., Powell, D.M.1985. Effect of commercial harvest of sport fish on the Black Crappie population in Lake Okeechobee, Florida. North American Journal of Fisheries Management. 5 (2B): 217-226 https://doi.org/10.1577/1548-8659(1985)5%3C217:EOCHOS%3E2.0.CO;2.

Scott, W.B., Crossman, E.J. 1959. The Freshwater Fishes of New Brunswick : a checklist with distributional notes. Contributions of the Royal Ontario Museum Division of Zoology and Palaeontology No. 51. Toronto, Canada. 62 pp.

Scott, W.B., Crossman, E.J. 1998. Freshwater fishes of Canada. Revised Edition. Galt House Publishing, Oakville, Ontario. 966 pp.

Seebens, H., Blackburn, T.M., Dyer, E.E., Genovesi, P., Hulme, P.E., Jeschke, J.M., Pagad, S., Pyšek, P., Winter, M., Arianoutsou, M., Bacher, S., Blasius, B., Brundu, G., Capinha, C., Celesti-Grapow, L., Dawson, W., Dullinger, S., Fuentes, N., Jager, H., Essl, F. 2017. No saturation in the accumulation of alien species worldwide. Nature Communications, 8: 14435. https://doi.org/10.1038/ncomms14435.

Serns, S.L., McKnight, T.C. 1977. The occurrence of northern pike X grass pickerel hybrids and an exceptionally large grass pickerel in a northern Wisconsin stream. Copeia, 4: 780-781.

Shoubridge, E.A., Hochachka, P.W. 1980. Ethanol: novel end product of vertebrate anaerobic metabolism. Science, 209: 308–309.

Sikora, L.W., VanDeHey, J.A., Sass, G.G., Matzke, G., Preul, M. 2021. Fish community changes associated with bullhead removals in four northern Wisconsin lakes. North American Journal of Fisheries Management, 41: 71-81.

Slavík, O., Bartoš, L. 2004. What are the reasons for the Prussian carp expansion in the upper Elbe River, Czech Republic? Journal of Fish Biology, 65 (Suppl. A): 240-253. https://doi.org/10.1111/j.0022-1112.2004.00560.x.

Smartt, J. 2007. A possible genetic basis for species replacement: preliminary results of interspecific hybridisation between native crucian carp *Carassius Carassius* (L.) and introduced goldfish *Carassius auratus* (L.). Aquatic Invasions, 2(1): 59-62. http://dx.doi.org/10.3391/ai.2007.2.1.7.

Smith, E.R.C., Bennion, H., Sayer, C.D., Aldridge, D.C., Owen, M. 2020. Recreational angling as a pathway for invasive non-native species spread: awareness of biosecurity and the risk of long distance movement into Great Britain. Biological Invasions, 22: 1135–1159. https://doi.org/10.1007/s10530-019-02169-5.

Smith, S.M., Maceina, M.J., Dunham, R.A. 1994. Natural hybridization between black crappie and white crappie in Weiss Lake, Alabama. Transactions of the American Fisheries Society, 123(1): 71-79. https://doi.org/10.1577/1548-8659(1994)123<0071:NHBBCA>2.3.CO;2.

South, A, 2017. Rnaturalearth: World Map Data from Natural Earth. R package version 0.1.0. https://CRAN.R-project.org/package=rnaturalearth.

Southwick, R., Norman, M.D. 1991. Impact of Salinity Changes on Fish Populations in Back Bay, Virginia, 1950-1989.

Statistic Canada. 2022. Annual Demographic Estimates: Canada, Provinces and Territories 2022. Catalogue no. 91-215-X, 69 pp.

Strahler, A.N. 1952. Dynamic basis of geomorphology. Bulletin of the Geological Society of America, 63: 923–938.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Transactions American Geophysical Union, 38(6): 913–920.

Strauss, S.Y., Lau, J.A., Carroll, S.P. 2006. Evolutionary responses of natives to introduced species: what do introductions tell us about natural communities?. Ecology Letters, 9: 357-374. https://doi.org/10.1111/j.1461-0248.2005.00874.x.

Takada, M., Tachihara, K., Kon, T., Yamamoto, G., Iguchi, K., Miya, M., Nishida, M. 2010. Biogeography and evolution of the *Carassius auratus*-complex in East Asia. BMC Evolutionary Biology, 10: 7. https://doi.org/10.1186/1471-2148-10-7.

Tang, R.W.K., Doka, S.E., Gertzen, E.L., Neigum, L.M. 2020. Dissolved oxygen tolerance guilds of adult and juvenile Great Lakes fish species. Canadian Manuscript Report of Fisheries and Aquatic Sciences. 3193: 69 pp.

Tarkan, A.S., Gaygusuz, Ö., Gürsoy Gaygusuz, Ç., Saç, G., Copp, G.H. 2012. Circumstantial evidence of gibel carp, *Carassius gibelio*, reproductive competition exerted on native fish species in a mesotrophic reservoir. Fisheries Management and Ecology, 19: 167-177. https://doi.org/10.1111/j.1365-2400.2011.00839.x.

Taylor, A., Sigona, A., Kelly, M. 2023. Modeling spatial distributions of Amah Mutsun priority cultural plants to support Indigenous cultural revitalization. Ecosphere. 14(1): 1–16. https://doi.org/10.1002/ecs2.4374.

Taylor, J., Mahon, R. 1977. Hybridization of *Cyprinus carpio* and *Carassius auratus*, the first two exotic species in the lower Laurentian Great Lakes. Environmental Biology of Fishes, 1: 205-208.

Taylor, S. 2019. How a Canadian cannabis producer is using fish poop to reduce its water consumption. Global News. Published February 4, 2019. [Online]. https://globalnews.ca/news/4924450/aquaponics-cannabis-fish-waste-green-relief/ Accessed Oct 27, 2023.

Tennekes, M. 2018. tmap: Thematic Maps in R. Journal of Statistical Software. 84 (6): 1-39.

Therriault, T.W., Weise, A.M., Gillespie, G.E. and T.J. Morris. 2011. Risk assessment for New Zealand mud snail (*Potamopyrgus antipodarum*) in Canada. DFO Canadian Science Advisory Secretariat Research Document. 2010/108. 93 pp.

Therriault, T.W., Weise, A.M., Higgins, S.N., Guo, Y., Duhaime, J. 2013. Risk assessment for three Dreissenid mussels (Dreissena polymorpha, Dreissena rostriformis bugensis, and Mytilopsis leucophaeata) in Canadian freshwater ecosystems. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/174 v + 88 p.

Theoharides, K.A., Dukes, J.S. 2007. Plant invasion across space and time: factors affecting nonindigenous species success during four stages of invasion. New Phytologist, 176: 256-273. https://doi.org/10.1111/j.1469-8137.2007.02207.x

Travnichek, V.H., Maceina, M.J., Smith, S.M., Dunham, R.A. 1996. Natural hybridization between black and white crappies (*Pomoxis*) in 10 Alabama reservoirs. American Midland Naturalist, 135: 310-316.

Trujillo-González, A., Becker, J.A., Hutson, K.S. 2018. Parasite dispersal from the ornamental goldfish trade. Advances in Parasitology, 100: 239-281. https://doi.org/10.1016/bs.apar.2018.03.001.

Tsipas, G., Tsiamis, G., Vidalis, K., Bourtzis, K. 2009. Genetic differentiation among Greek Lake populations of *C. gibelio* and *C. carpio carpio*. Genetica, 136: 491–500. https://doi.org/10.1007/s10709-008-9331-1.

Tucker, W.H. 1973. Food habits, growth and length-weight relationships of young-of-the-year black crappie and largemouth bass in ponds. Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners, 26: 565-577.

United States Fish and Wildlife Service (USFWS). 2019. Prussian Carp (*Carassius gibelio*) Ecological Risk Screening Summary. https://www.fws.gov/sites/default/files/documents/Ecological-Risk-Screening-Summary-Prussian-Carp.pdf

United States Geological Survey (USGS) 2022. Nonindigenous Aquatic Species Database, Gainesville, FL. [Online], http://nas.er.usgs.gov. Accessed July 12, 2022.

Vagnon, C., Rohr, R.P., Bersier, L.-F., Cattanéo, F., Guillard, J., Frossard, V. 2022. Combining food web theory and population dynamics to assess the impact of invasive species. Frontiers in Ecology and Evolution, 10: 3389. https://doi.org/10.3389/fevo.2022.913954.

Valéry, L., Fritz, H., Lefeuvre, J., Simberloff, D. 2009. Invasive species can also be native. Trends in Ecology and Evolution, 24: 585. https://doi.org/10.1016/j.tree.2009.07.003.

Van der Veer, G., Nentwig, W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. Ecology of Freshwater Fish, 24: 646-656. https://doi.org/10.1111/eff.12181.

VandenBroeck, J. 1997. Assessment of an adult black crappie transfer. In P. MacMahon (Ed.), Fish: To Stock or Not to Stock, Northwest Region Science and Technology Workshop Proceedings WP-003, Ontario Ministry of Natural Resources, Thunder Bay, ON. 19 pp.

Vetemaa, M., Eschbaum, R., Albert, A., Saat, T. 2005. Distribution, sex ratio and growth of *Carassius gibelio* (Bloch) in coastal and inland waters of Estonia (north-eastern Baltic Sea). Journal of Applied Ichthyology. 21: 287-291. https://doi.org/10.1111/j.1439-0426.2005.00680.x.

Vilizzi, L., Hill, J.E., Piria, M., Copp, G.H. 2022. A protocol for screening potentially invasive non-native species using Weed Risk Assessment-type decision-support tools. Science of The Total Environment, 832: 54966. https://doi: 10.1016/j.scitotenv.2022.154966. Epub 2022 Apr 1.

Warner, K. 1972. Further studies of fish predation in salmon stocks in Maine lakes. Progressive Fish Culturalist, 34: 217-221.

Warner, K. 1972. Further studies of fish predation in salmon stocks in Maine lakes. Progressive Fish Culturalist. 34: 217-221.

Warner, K., Auclair, R.P., DeRoche, S.E, Havey, K.A., Ritzi, C.F. 1968. Fish predation on newly stocked landlocked salmon. Journal of Wildlife Management, 32 (4): 712-717.

Warren, M.L., 2009. Centrarchid identification and natural history. In: Cooke, S.J., Philipp, D.P. (Eds.) Centrarchid Fishes: diversity, biology, and conservation. Blackwell Publishing Ltd. pp. 375-534.

Welcomme, R.L. 1988. International Introductions of Inland Aquatic Species. https://www.fao.org/3/X5628E/X5628E00.htm.

Whittier, T.R., Halliwell, D.B., Paulsen, S.G. 1997. Cyprinid distributions in Northeast USA lakes: evidence of regional-scale minnow biodiversity losses. Canadian Journal of Fisheries and Aquatic Sciences, 54(7): 1593-1607. https://doi.org/10.1139/f97-066.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wilcox, M.A., Weise, A.M., Guerin, A.J., Chu, J.W.F., Therriault, T.W. 2024. National Aquatic Invasive Species (AIS) Risk Assessment for Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*Dreissena rostriformis bugensis*), April 2022. DFO Can. Sci. Advis. Sec. Res. Doc. 2024/008. ix + 91 p.

WOAH. 2019. Infection with Spring Viraemia of Carp virus. In WOAH Aquatic Manual 2019. Chapter 2.3.9. p.1-19. https://www.woah.org/fileadmin/Home/eng/Health_standards/aahm/current/2.3.09_SVC.pdf

WOAH. 2021. Infection with Viral Haemorrhagic Septicaemia virus. In Manual of Diagnostic Tests for Aquatic Animals. Chapter 2.3.10. p. 377-401. https://www.woah.org/fileadmin/Home/eng/Health_standards/aahm/current/2.3.10_VHS.pdf

WOAH. 2022a. Infection with *Aphanomyces invadans* (Epizootic Ulcerative Syndrome). In WOAH Aquatic Manual 2022. Chapter 2.3.1. p. 1-18. https://www.woah.org/fileadmin/Home/eng/Health_standards/aahm/current/2.3.01_EUS.pdf

WOAH. 2022b. Infection with Koi Herpes Virus. In WOAH Aquatic Manual 2022. Chapter 2.3.6. p. 1-18. https://www.woah.org/fileadmin/Home/eng/Health_standards/aahm/current/2.3.06_KHV.pdf

WOAH. 2022c. Infection with Carp Edema Virus (CEV). https://www.woah.org/app/uploads/2023/03/a-woah-cev-disease-card-nov-2022.pdf. [Online]. Accessed May 5, 2023.

Wouters, J., Janson, S., Lusková, V., Olsén, K.H. 2012. Molecular identification of hybrids of the invasive gibel carp *Carassius auratus gibelio* and crucian carp *Carassius carassius* in Swedish waters. Journal of Fish Biology, 80(7): 2595-2604. https://doi.org/10.1111/j.1095-8649.2012.03312.x.

WWF/TNC 2019. Freshwater Ecoregions of the World [Online]. Available from https://www.feow.org/.

Wydoski, R.S., Whitney, R.R. 2003. Inland fishes of Washington 2nd edition. American Fisheries Society in Association with University of Washington Press, Seattle. 322 pp.

Yu, D.R., Pulyayevskaya, M.V., Zuev, I.V., Makhutova, O.N., Degermendxhi, A.G. 2011. Growth, diet and fatty acid composition of Gibel carp *Carassius gibelio* in Lake Shira, a brackish water body in Southern Siberia. Journal of Siberian Federal University. Biology, 4(1): 86-103.

Zhou, L., Wang, Y., Gui, J.F. 2000. Genetic evidence for gonochoristic reproduction in gynogenetic silver crucian carp (*C. auratus gibelio* Bloch) as revealed by RAPD assays. Journal of Molecular Evolution, 51: 498–506. https://doi.org/10.1007/s002390010113.

APPENDIX 1

GENERAL GUIDANCE ON SCORING AND CERTAINTY

Scores

Scores for each question were calculated per freshwater ecoregion (Abell *et al.* 2008; available at https://feow.org/) based on the CMIST guidance from Drolet *et al.* (2016) and the associated manual available at https://www.bio.gc.ca/science/monitoring-monitorage/cmist/usage-en.php. They range from 1 to 3, with 1 representing the least risky score, and 3 representing the highest risk score.

Terminology modifications: Uncertainty to Certainty

Guidance around uncertainty scores in the CMIST are explained in Drolet et al. (2016) and range from 1 to 3, with 1 representing high uncertainty, and 3 representing low uncertainty. To simplify comprehension in this document we will refer to certainty (rather than uncertainty). Consequently:

- Low certainty = high uncertainty (score 1): little to no reliable information is available AND the user has no experience with the species.

- Moderate certainty = moderate uncertainty (score 2): some reliable information is available; if information is incomplete it is supplemented with information on or experience with a similar species in a similar environment.

- High certainty = low uncertainty (score 3): considerable amount of reliable information is available OR the user has first-hand experience with the species and the assessment area.

Scoring per question

Some CMIST questions were broken down into separately scored variables (where each variable was scored separately for likelihood/impact of invasion and associated certainty scores), to incorporate various concepts influencing the evaluation of risk. Guidance on determining the final risk score for each question can be found in detail below, under the guidelines for each question.

Panels of subject matter experts

Expert opinion was gathered from panels of subject matter experts (SMEs) with local knowledge/experience, across seven DFO regions (Gulf, Maritimes, Newfoundland and Labrador, Quebec, Ontario and Prairie, Pacific, Arctic). SMEs were comprised of federal and provincial researchers and biologists, as well as academic researchers, who were invited to answer the CMIST questions which were subject to the most regional variability (i.e. 1, 2, 3, 6, 7, 8, 15). SME knowledge contributed to region-specific information and filled knowledge/data gaps on some species and/or ecoregions. Questions and pertinent background information per species (gathered via literature reviews to support the CMIST assessments) were sent out to panel participants prior to discussion. Panel discussions took place virtually and panel members discussed the background information, personal observations, and then each expert provided a likelihood (Q1-3, Q6-8) or impact of invasion (Q15) score along with associated certainty for these questions. Final expert opinion scores were determined via panel consensus. Expert opinion scores were incorporated into the scoring rubric for this SLRA as described in Table 2 and Appendix 1.

As ecoregions regularly overlapped multiple provincial and territorial boundaries, and SME knowledge was often applicable to general areas within their regions of expertise (e.g., southern Alberta), SME knowledge was applied to ecoregions where the SME was confident in their knowledge and to ecoregions that overlapped with their regions of expertise. For example, the Ontario & Prairie (O&P) DFO region includes four provinces and 10 ecoregions and not all SMEs had the same expertise in all ecoregions. Consequently, final ecoregion risk scores were based on the opinion of the SME with the most experience in the ecoregion that primarily overlapped with their area of focus. For example, in the O&P DFO region, the SME from Alberta determined the risk scores for ecoregions 104 and 107, where the SME from Manitoba determined the risk scores for ecoregions 109 and 142. In cases where an ecoregion spanned multiple provinces, only the opinion of the SME working in the province that encompassed the majority of the ecoregion was considered.

Finding SMEs for ecoregions in the Nunavut, Northwest Territories (NT), Labrador and Nunavik was more complicated, with no availability for panel discussions and minimal information on AIS. Some information was provided for question 1 from biologists working in these regions, however, little else was available. Due to the knowledge gaps in northern ecoregions, and broadscale climate similarities among these regions, they were grouped and scored by SMEs as a single region ("Arctic") and SME knowledge was then applied to all Arctic ecoregions.

QUESTION 1 – IS THE SPECIES ESTABLISHED IN THE ASSESSMENT AREA?

CMIST: This question is meant to differentiate species that are not present in the assessment area (1) from species that are established in the assessment area (3). Species that are present in the assessment area but not established would score 2.

Considered only the Canadian portion of the ecoregion. Fishes were not scored in their native ecoregions. Two species (Chain Pickerel and Black Crappie) are considered native in some ecoregions (Black Crappie = 116 and 117, Chain Pickerel = 117) but invasive in other ecoregions. Species were considered native to an ecoregion based on consensus in the literature. Scores were as follows:

Risk score

- Score 3: if multiple sources of reported establishment are available for an ecoregion. Must include (1) published literature on establishment, (2) expert opinion confirming establishment and (3) observations of presence over multiple years from other independent sources (e.g., research grade iNaturalist (2022), EDDMapS (2022), GBIF.org (2023), and/or USGS (2022) - (see maps provided in Appendix 1, Figure 1 below).

- Score 2: if establishment is confirmed by only 2 out of 3 sources mentioned above (published literature and/or expert opinion and/or multiple observations over multiple years in online databases).

- Score 1: if present in the American portion but not observed in the Canadian portion OR if never observed in the ecoregion.

Certainty

- Score 3: if there are reports from published literature.

- Score 2: if there are records from data platforms only and/or expert opinion only.

- Score 1: if there is no information.
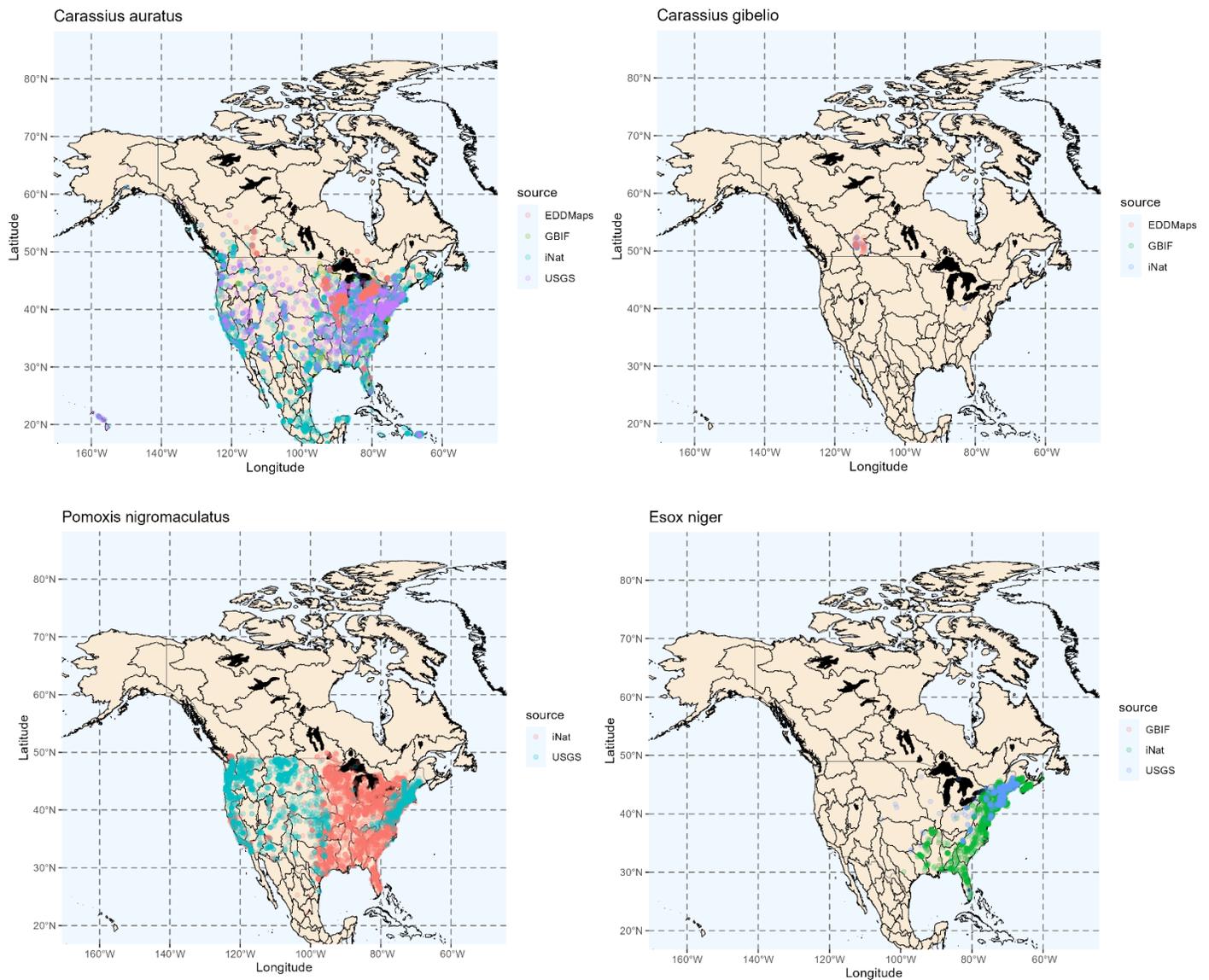
Appendix 1 Figure 1. Current distribution of Goldfish, Prussian Carp, Chain Pickerel and Black Crappie across North America. Data was pulled from [GBIF](), [iNaturalist](), [EDDmaps]() and [USGS]() data platforms. Some data platforms lacked reports for some species (USGS for Prussian Carp, EDDMaps for Black Crappie and Chain Pickerel and GBIF for Black Crappie).

QUESTION 2 – HOW FREQUENTLY AND IN WHAT NUMBERS IS THE SPECIES EXPECTED TO ARRIVE INTO THE ASSESSMENT AREA?

CMIST: Consider initial arrival into the assessment area by primary vectors only and not secondary spread (anthropogenic or natural) within the assessment area by already established species.

Consider all primary anthropogenic and natural vectors for transport into the assessment area (e.g., ballast water, hull fouling, aquaculture, rafting, natural dispersal from outside the assessment area).

Risk score

Scoring incorporated risks associated with the aquarium trade, expert opinion on unauthorized activities/releases, freshwater connectivity and expert opinion on spread/dispersal from adjacent ecoregions. Aquarium trade risks were calculated by using the number of households releasing aquarium organisms per year (Chan *et al.* 2022); expert opinion on unauthorized activities/releases considered bait risk from legal and illegal bait practices and unauthorized introductions associated with sport/recreational fishing; freshwater connectivity between ecoregions was calculated using Hydro Atlas Rivers (https://www.hydrosheds.org/products/hydrorivers) in QGIS; and expert opinion on spread/dispersal from an adjacent ecoregion considered presence/absence in adjacent ecoregions (or the American portion of an ecoregion), mountain ranges and natural and anthropogenic barriers).

Note: Aquaculture risk was not considered because none of the species studied are found in aquaculture in Canada.

Variable 1 – Aquarium trade risks

Based on the gridded heatmap Figure 11E in Chan *et al.* (2022) (reproduced below in Appendix 1, Figure 2), score according to the number of households releasing aquarium organisms per year. Scores were as follows:

- Score 3: for 475 to 7026 households

- Score 2: for 34 to 474 households

- Score 1: for 0 to 33 households

- Score 0: if the fish species is not in the aquarium trade

To ensure a precautionary approach, scores were based on the maximum number of households releasing aquarium organisms in an ecoregion (e.g., if even one square in the ecoregion is the deepest red (475-7026 households), you would score a 3.
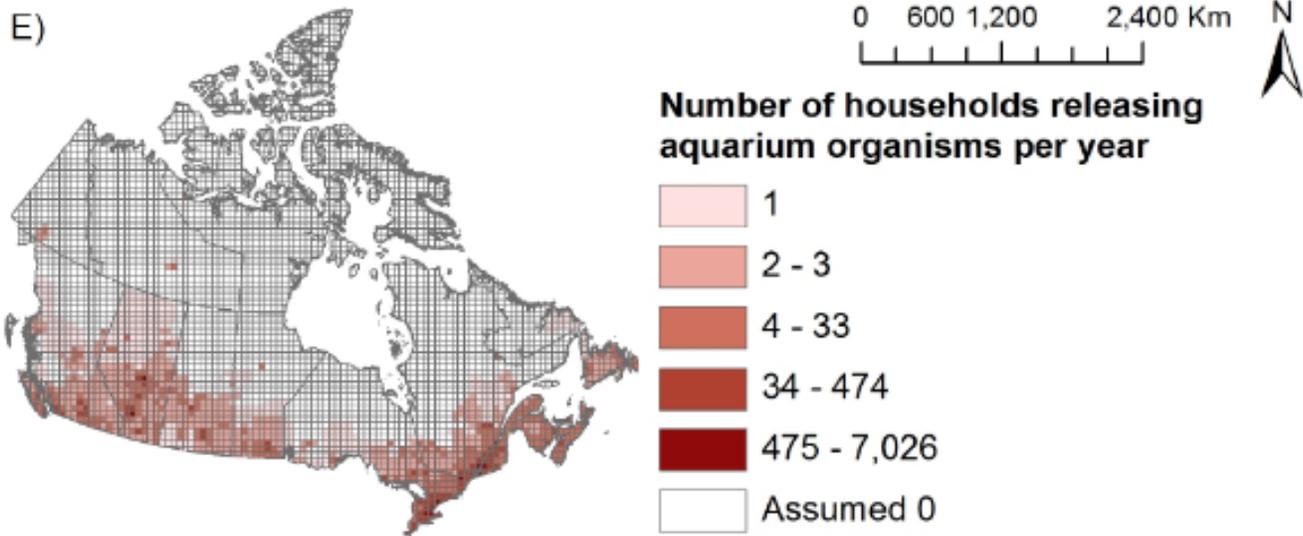
Appendix 1 Figure 2. Reproduced from Chan et al. 2022 (Figure 11E). The expected numbers and spatial distributions of households releasing aquarium organisms (i.e. releasers) per year in Canada generated through sensitivity analysis, where the proportion of households owning aquaria, p(Aq) = 10.6%, and the proportion of households owning aquaria that are releasers, p(Rel|Aq) = 2.0%. Values < 0.5 were assumed zero. Each grid represents a 50 km x 50 km spatial coverage. To facilitate scoring, use the image found in the original publication.

Variable 2 – Expert opinion on unauthorized activities/releases

Panels of experts provided information on bait risk from legal and illegal bait practices and unauthorized introductions associated with sport/recreational fishing (but not spiritual release) within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 1: Infrequently in low numbers.
- Score 2: Frequently in low numbers OR infrequently in high numbers.
- Score 3: Frequently in high numbers.

Variable 3 – Freshwater connectivity

Using the HydroRiver.gbd file from Atlas Hydro Rivers (Lehner and Grill 2013), shapefiles were created in QGIS for rivers of Strahler (1952, 1957) orders 1, 2 and 3. From the shapefile River_order_1, using the ID number (Main_riv), the number of rivers and lake connections linked to adjoining ecoregions was counted. The same process was used for the shapefiles River_order_2 and 3, maintaining their link with River order 1 and was scored as follows:

- Score 3: if there were ≥ 2 rivers of Strahler orders 1, 2 and 3 that link the ecoregion to another.
- Score 2: if only one river of Strahler order 1, 2 or 3 crossed into an adjacent ecoregion.
- Score 1: if there were no rivers of any Strahler order crossing into adjacent ecoregions.

Variable 4 – Expert opinion on spread/dispersal (new introductions via anthropogenic vectors and/or natural dispersal)

Panels of experts considered presence/absence in adjacent ecoregions (or the American portion of an ecoregion), connectivity, mountain ranges and natural and anthropogenic barriers)

within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 3: Frequently in high numbers.

- Score 2: Frequently in low numbers OR infrequently in high numbers.

- Score 1: Infrequently in low numbers.

Final Risk Scores

To ensure a pre-cautionary approach, use the maximum score found amongst variables.

Certainty

Variable 1 – Aquarium trade risk

Aquarium trade risk was determined using a gridded heatmap from Figure 11e in Chan *et al.* 2022 (reproduced above in Appendix 1, Figure 1) representing the number of households releasing aquarium organisms per year, based on recent spatially explicit estimates of propagule pressure. Because this data was interpolated over a range of modeled values, it was given a certainty score of 2 for all ecoregions.

Variable 2 – Expert opinion on unauthorized activities/releases

- Score 3: if expert panel has first-hand experience with the species and the assessment area.

- Score 2: if expert panel has experience with similar species in a similar environment.

- Score 1: if expert panel has no experience with the species and/or ecoregion.

Variable 3 – Freshwater connectivity

River order shapefiles were determined using metrics pulled from Atlas Hydro Rivers. This data layer is based on recent historical and best available data and was therefore given a certainty score of 3 for all ecoregions.

Variable 4 – Expert opinion on spread/dispersal from adjacent ecoregions

- Score 3: if expert panel has first-hand experience with the species and the assessment area.

- Score 2: if expert panel has experience with similar species in a similar environment.

- Score 1: if expert panel has no experience with the species and/or ecoregion.

Final Certainty Scores

As this question considers multiple variables with different measures of certainty and to ensure a precautionary approach in our final scoring, use the **certainty** score corresponding with the variable which had highest risk score.

Here are some simplified example scores, where two variables are considered. In the table below:

Example 1 – Risk score Variables 1 (V1) and 2 (V2) have different scores, with V2 being the highest risk score (2), and different certainty scores = Final certainty score is 1.

Example 2 – Risk score Variables 1 (V1) and 2 (V2) are the same (2) but have different certainty scores = Final certainty score is 3.

Example 3 – Risk score Variables 1 (V1) and 2 (V2) have different scores, with V2 being the highest risk score (3), but certainty scores are the same = Final certainty score is 2.

Appendix 1 Table 1. Final certainty scoring method example for questions 2, 8 and 15.

Examples	Variables	Risk score	Certainty Score	Final certainty score
Example 1	V1	1	3	1
Example 1	V2	2	1	
Example 2	V1	2	2	3
Example 2	V2	2	3	
Example 3	V1	1	2	2
Example 3	V2	3	2	

QUESTION 3: HOW MUCH OF THE ASSESSMENT AREA OFFERS SUITABLE HABITAT FOR THE SPECIES?

CMIST: First consider the species' broad habitat zone (e.g., intertidal, subtidal, benthic, pelagic), and then consider the proportion of that zone within the assessment area that offers suitable habitat for the species.

Consider suitable anthropogenic habitat (e.g., docks, aquaculture sites) as well as natural habitat.

Risk score

Given the mismatch between the data required to answer this question (depth, habitat type, substrate, weed beds, flow etc.) and what was available across Canadian ecoregions, only SME opinion was considered here. Panels of SMEs scored this question based on their knowledge and experience of physical habitat within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 3: if most of the assessment area is a suitable habitat for the species.
- Score 2: if moderate proportion of the assessment area is a suitable habitat for the species.
- Score 1: if a negligible proportion of the assessment area is a suitable habitat for the species.

Certainty

- Score 3: if expert panel has first-hand experience with the species and the assessment area.
- Score 2: if expert panel has experience with similar species in a similar environment.
- Score 1: if expert panel has no experience with the species and/or assessment area.

QUESTION 4: HOW MUCH OF THE ASSESSMENT AREA OFFERS SUITABLE ENVIRONMENTAL CONDITIONS FOR THE SPECIES TO SURVIVE?

CMIST: Consider environmental conditions (e.g., temperature, salinity, turbidity) in its suitable habitat.

Consider the most tolerant life stage at any time of year. Consider survival only, not reproduction. 1-Negligeable proportion of the assessment area, 2-Moderate proportion of the assessment area, 3-Most of the assessment area

Risk score

Evaluating how much of the assessment area offers suitable environmental conditions for each species to survive in each ecoregion is best completed using climate matching analyses. Here this was achieved following the apporach of Hubbard *et al.* (2023) based on the methods of Campbell *et al.* (2022). Species source data were gathered using occurrence data from Global Biodiversity Information Facility (GBIF) for global occurrences (species-specific references in Appendix 1, Table 1) and Anas and Mandrak (2021) for North American occurrence records. Our methods in this analysis differed from Campbell et al. (2022) in that here we included GBIF records not designated as part of the species' native range, thus incorporating species' invasive ranges. GBIF records were removed if they were missing coordinates, were flagged for a geospatial issue, or one or more of the following issues: coordinate precision invalid, geodetic datum invalid, continent coordinate mismatch, individual count invalid, or occurrence status inferred from basis of record (which refer to museum specimens and not presence/absence data). GBIF records were also removed if uncertainty in longitude and latitude precision was greater than 10 km, to align with climate data resolution (Marcer *et al.* 2022). Point source data were examined against species range information (Froese and Pauly 2022), perceived outliers were removed if they were outside the range description and in unlikely locations such as in marine environments (Howeth *et al.* 2016). Some of these records came from iNaturalist research-grade observations database (iNaturalist Users 2023), which has been increasingly used in Species Distribution Modelling (e.g., Taylor *et al.* 2023). To combine point source records (GBIF) with watershed occurrence records (Anas and Mandrak 2021), all records were overlayed with the HydroBASINS global watersheds level 5 database (Lehner and Grill 2013) and climate data were extracted from the watershed polygons with occurrences.

The R package Euclimatch was used for climate matching (Hubbard *et al.* 2023), which implements the CLIMATCH algorithm (Crombie *et al.* 2008; Pheloung 1996), a Euclidian distance metric. Climate match was modelled between the freshwater ecoregions within Canada as recipients (*n* = 21; Abell *et al.* 2008), and the species occurrence records as sources of the four freshwater fishes. Climate match was expressed as the percentage of grid cells with a Climate 6 score or greater within the recipient ecoregion (Bomford *et al.* 2010; Howeth *et al.* 2016). Climate match was calculated using a set of eight temperature and eight precipitation based bioclimatic variables for example mean annual temperature and mean annual precipitation (Bomford *et al.* 2010). Climate matching was conducted using climate data from Worldclim v2.1 for the historical climate period, which provides mean values over the 1981-2000 period (Fick and Hijmans 2017) and a climate change projection, which was the mean values over the period 2081-2100 for the fossil-fuel-driven growth shared socio-economic pathway SSP5-8.5 scenario, at a resolution of 10 arc minutes (Campbell *et al.* 2022). For the climate change projection we generated an ensemble (i.e., the mean across multiple projections) from six global climate models (BCC-CSM2-MR, CanESM5, CNRM-ESM2-1, IPSL-CM6A-LR, MIROC-ES2L, MRI-ESM2-0) from the Coupled Model Intercomparison Project (CMIP6) accessed via www.worldclim.org. All climate matching analyses were conducted using R statistical software (R Core Team 2022) and maps were made using the 'tmap' package

(Tennekes, 2018). Results used for the scoring are presented in Appendix 1, Table 2, and in Appendix 1, Figure 2. Risk scores are based on the climate matching thresholds in Howeth et al. (2016) where successful AIS establishment in the Great Lakes requires a climate match of ≥ 71.7%. While this threshold may be different across ecoregions, there is a lack of available data with which to calibrate this across Canadian ecoregions and consequently 71.7% was used as a proxy for successful AIS establishment in all ecoregions.

Scores were as follows:

- Score 3: if the climate match (%) was ≥ 71.7%.

- Score 2: if the climate match (%) was between 40 and 71.6%.

- Score 1: if the climate match (%) was between 0 and 39%.

Certainty

As climate matching is based on long-term historical datasets available at WorldClim (www.worldclim.org), considered as best available data. All ecoregions consequently scored 3 (high certainty).

Appendix 1 Table 2. The climate match (CM, %) and area (km^2) by ecoregion in Canada, under historical (1981-2000) and projected climatic conditions (2090 SSP5-8.5), for Goldfish, Prussian Carp, Chain Pickerel and Black Crappie.

ID	Area (km^2)	Goldfish Historical CM (%)	Goldfish Projected CM (%)	Prussian Carp Historical CM (%)	Prussian Carp Projected CM (%)	Chain Pickerel Historical CM (%)	Chain Pickerel Projected CM (%)	Black Crappie Historical CM (%)	Black Crappie Projected CM (%)
101	990 699.7	95.5	100.0	100.0	100.0	92.8	97.4	95.9	100.0
102	572 690.0	99.8	100.0	100.0	100.0	98.6	99.8	99.8	100.0
103	927 260.6	98.5	94.7	84.3	82.6	69.3	63.4	90.5	90.0
104	630 669.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
105	1 089 035.8	99.8	100.0	100.0	100.0	95.0	100.0	99.9	100.0
106	580 809.8	65.1	100.0	100.0	100.0	48.1	99.9	73.4	100.0
107	223 720.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
108	317 721.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
109	643 607.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
110	997 304.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
111	891 808.8	63.2	100.0	100.0	100.0	30.0	99.9	79.7	100.0
112	1 347 214.9	12.4	87.6	97.4	99.8	9.7	84.5	14.7	88.9
113	1 093 120.3	100.0	100.0	100.0	100.0	99.9	99.9	100.0	100.0
114	263 985.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
115	129 059.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
116	767 004.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
117	387 065.0	100.0	100.0	99.7	100.0	100.0	100.0	100.0	100.0
118	360 067.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
119	57 256.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
120	256 937.3	100.0	100.0	100.0	99.7	91.9	75.7	100.0	100.0
142	679 471.2	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
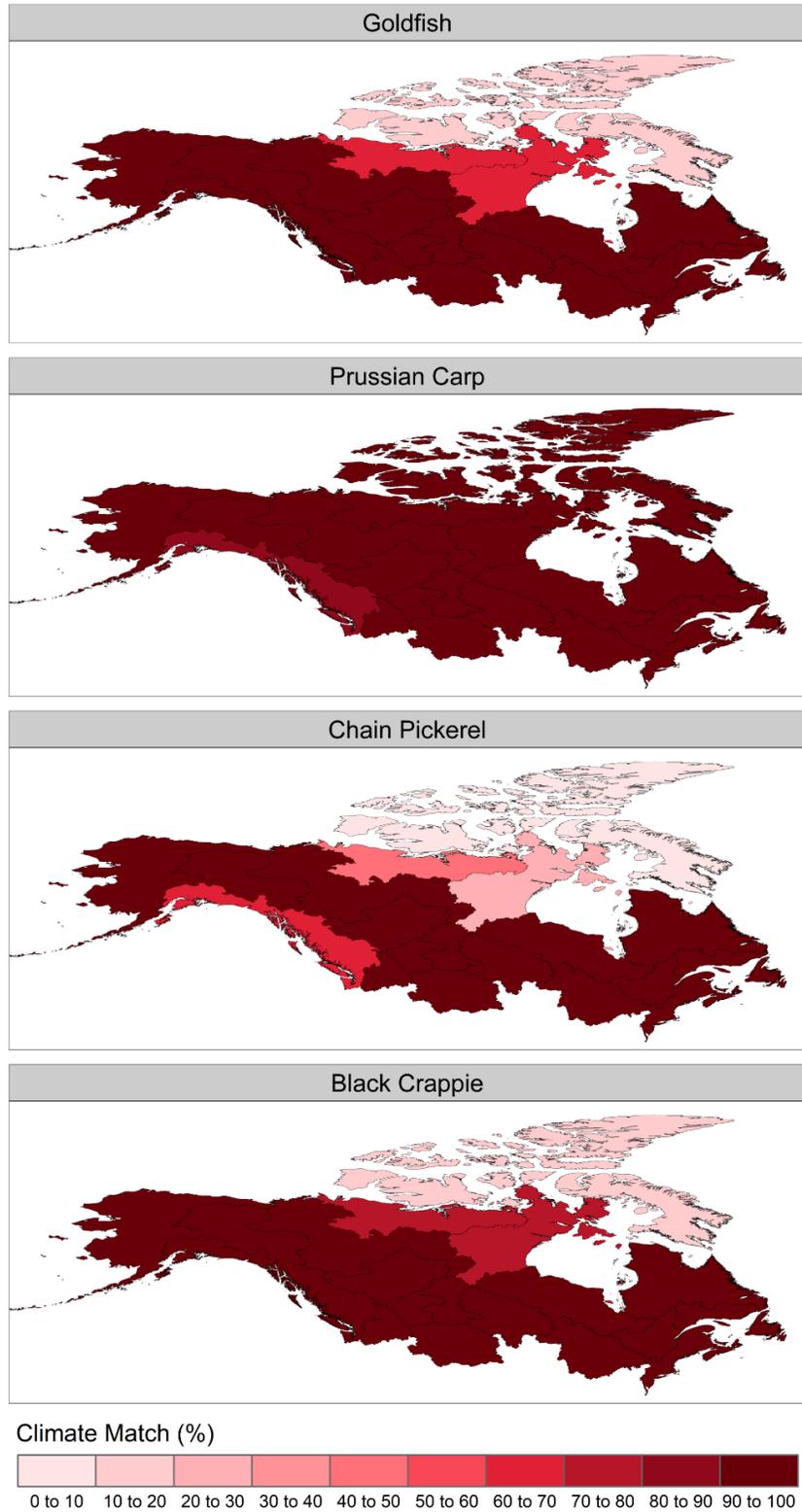
Appendix 1 Figure 3. Climate match (%) of Goldfish, Prussian Carp, Chain Pickerel and Black Crappie to the freshwater ecoregions of Canada under historical climatic conditions (1981-2000).

QUESTION 5: ARE THE SPECIES' REPRODUCTIVE REQUIREMENTS AVAILABLE IN THE ASSESSMENT AREA?

CMIST: Consider any constraints to the species' life cycle (e.g., temperature, salinity, habitat) that may affect its ability to reproduce in its suitable habitat.

Risk score

Climate matching as completed above for Question 4, evaluates how similar each Canadian ecoregion is to the climate in other global ecoregions where the species in already established (both native and invaded ranges). As such, this necessairly incorporates a measure of suitablility for reproduction, as succesful reproduction is implicit in establishment. Consequently the scores from Question 4 were also used here.

Same scoring as question 4.

Certainty

Same scoring as question 4.

QUESTION 6: TO WHAT EXTENT COULD NATURAL CONTROL AGENTS SLOW THE SPECIES' POPULATION GROWTH IN THE ASSESSMENT AREA?

CMIST: Consider presence and incidence of known natural control agents (e.g., predators, competitors, disease, disturbance) in the species' suitable habitat and to what extent they could slow the species' population growth.

This question is meant to differentiate species with known, effective natural control agents in the assessment area (likely to restrict population growth = 1) from those with no known, effective natural control agents in the assessment area (unlikely to slow population growth = 3). Species with known—but not necessarily effective—natural control agents in the assessment area would likely score a 2.

Risk score

Scoring incorporated risks associated with resistance to invasion and expert opinion on the likelihood of natural control agents within ecoregions.

Variable 1 – Resistance to invasion

Here resistance of an ecoregion to invasion was evaluated using Figure 4B from Chu *et al.* (2015) (reproduced below in (Appendix 1 Figure 4). Here we chose the colour (s) and the associated score (s) (considering only BIO-STR combinations) found in the majority of the ecoregion. If the ecoregion has an approximately equal amount of two colours, we chose the most conservative risk (i.e. the highest score) among the colours.

- Score 3 if there is low resistance (low biodiversity and high stress)

- Score 2 if there is moderate resistance (high biodiversity and high stress OR low biodiversity and low stress)

- Score 1 if there is high resistance (high biodiversity and low stress)
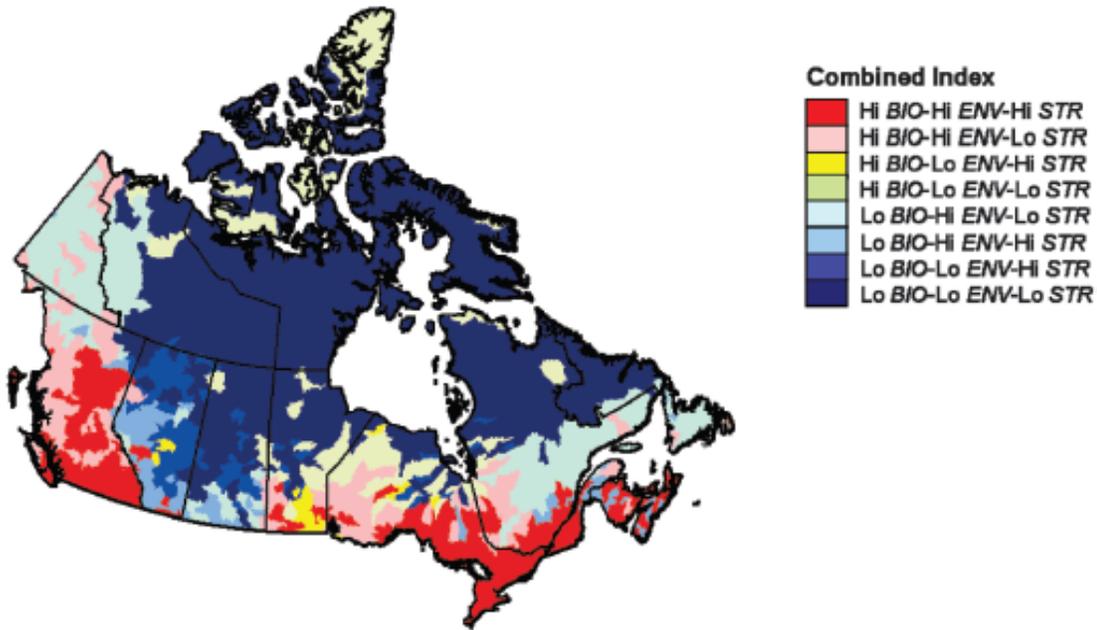
Appendix 1 Figure 4. Reproduced from Chu et al. 2015 (Figure 4B). Eight-category combined index of freshwater fish biodiversity (BIO), environmental conditions (ENV), and anthropogenic stress (STR) indices for 953 tertiary watersheds in Canada for recent time periods. Information on recent environmental conditions was collected between 1981 and 2010, anthropogenic stress information was collected between 2006 and 2008 and freshwater fish biodiversity was collected from the database in Chu et al. (2003). HI and Lo represent biodiversity index based on presence (HI) or absence (Lo) of COSEWIC listed species.

Variable 2 – Expert opinion on likelihood of natural control agents

Panels of experts scored this question based on their knowledge and experience of the likelihood of natural control agents within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 3: If natural control agents are unlikely to restrict population growth
- Score 2: If natural control agents could slow population growth
- Score 1: If natural control agents are likely to severely restrict population growth

Final Risk Scores

To ensure a precautionary approach use the maximum score among resistance and expert opinion.

Certainty

Because expert opinion risk scores on natural control agents in the assessment area incorporates an understanding of biodiversity within an ecoregion, certainty should be scored as follows:

- Score 3: if scores between resistance and expert opinion were the same
- Score 2: if scores between resistance and expert opinion differed by 1
- Score 1: if scores between resistance and expert opinion differed by 2.

QUESTION 7: WHAT IS THE RANGE OF THE SPECIES' POTENTIAL NATURAL DISPERSAL IN THE ASSESSMENT AREA?

CMIST: Consider the natural dispersal vectors (e.g., currents, rafting, migration) for all life stages. Consider any constraints on natural dispersal vectors in the assessment area.

Risk score

Scoring incorporated risks associated with freshwater connectivity and expert opinion on natural dispersal constraints linked to barriers within ecoregions. Freshwater connectivity between and ecoregions was calculated using Hydro Atlas Rivers (https://www.hydrosheds.org/products/hydrorivers) in QGIS and expert opinion on dispersal constraints considered how natural and artificial barriers might limit natural dispersal within ecoregions.

Variable 1 – Freshwater connectivity

The scores from CMIST Question 2 Variable 3 were used here because freshwater connectivity, evaluated as the number of rivers connected between ecoregions, also provides a general indication of whether an ecoregion has a high, moderate or low number of rivers and thus connectivity which may influence natural dispersal within an ecoregion.

Variable 2 – Expert opinion on natural dispersal constraints linked to natural/artificial barriers

Panels of experts scored this question based on their knowledge and experience of constraints on natural dispersal within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 3: few constraints to natural dispersal

- Score 2: moderate constraint to natural dispersal

- Score 1: severe constraints to natural dispersal

Final Risk Scores

To ensure a precautionary approach use the maximum risk score among connectivity and expert opinion.

Certainty

Because expert opinion risk scores on natural dispersal in the assessment area incorporates an understanding of connectivity within an ecoregion, certainty should be scored as follows:

- Score 3: if scores between freshwater connectivity and expert opinion were the same.

- Score 2: if scores between freshwater connectivity and expert opinion differed by 1.

- Score 1: if scores between freshwater connectivity and expert opinion differed by 2.

QUESTION 8: WHAT IS THE RANGE OF THE SPECIES' POTENTIAL DISPERSAL IN THE ASSESSMENT AREA FROM ANTHROPOGENIC MECHANISMS?

CMIST: Consider anthropogenic dispersal vectors (e.g., ballast, hull fouling, aquaculture) for all life stages

This question considers spread risk via anthropogenic mechanisms within an ecoregion. It is meant to differentiate species which are likely to have negligible contact with anthropogenic vectors of dispersal in the assessment area (1) from those that are likely to have contact with anthropogenic vectors which could disperse them over large distances (3), species that have contact with anthropogenic vectors which could disperse them over short distances would score a 2. Consider anthropogenic dispersal vectors for all life stages.

Risk score

Scoring incorporated risks determined via expert opinion on unauthorized activities/releases and anthropogenic dispersal constraints linked to natural/artificial barriers withing ecoregions. Expert opinion associated with unauthorized activities/releases considered bait risk from legal and illegal bait practices and unauthorized introductions associated with sport/recreational fishing; and expert opinion on dispersal constraints considered how natural and artificial barriers might limit anthropogenic dispersal within ecoregions.

Variable 1 – Expert opinion on unauthorized activities/releases

Panels of experts provided information on bait risk from legal and illegal bait practices and unauthorized introductions associated with sport/recreational fishing within their provinces. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 1: Infrequently in low numbers.
- Score 2: Frequently in low numbers OR infrequently in high numbers.
- Score 3: Frequently in high numbers.

Variable 2 – Expert opinion on anthropogenic dispersal constraints linked to natural/artificial barriers

Panels of experts scored this question based on their knowledge and experience on constraints to anthropogenic dispersal within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 3: few constraints to anthropogenic dispersal
- Score 2: moderate constraint to anthropogenic dispersal
- Score 1: severe constraints to anthropogenic dispersal

Final Risk Scores

To ensure a precautionary approach use the maximum risk score found amongst the two variables.

Certainty

Variable 1 – Expert opinion on unauthorized activities/releases

Use the same scores as CMIST Question 2, certainty variable 2, where:

- Score 3: if expert panel has first-hand experience with the species and the assessment area.

- Score 2: if expert panel has experience with similar species in a similar environment.

- Score 1: if expert panel has no experience with the species and/or assessment area.

Variable 2 – Expert opinion on natural/artificial barriers

- Score 3: if expert panel has first-hand experience with the species and the assessment area.

- Score 2: if expert panel has experience with similar species in a similar environment.

- Score 1: if expert panel has no experience with the species and/or assessment area.

Final Certainty Scores

As this question considers multiple variables with different measures of certainty and to ensure a precautionary approach in our final scoring, use the **certainty** score corresponding with the variable which had highest risk score.

Here are some simplified example scores, where two variables are considered. In the table below:

Example 1 - Risk score Variables 1 (V1) and 2 (V2) have different scores, with V2 being the highest risk score (2), and different certainty scores = Final certainty score is 1.

Example 2 – Risk score Variables 1 (V1) and 2 (V2) are the same (2) but have different certainty scores = Final certainty score is 3.

Example 3 – Risk score Variables 1 (V1) and 2 (V2) have different scores, with V2 being the highest risk score (3), but certainty scores are the same = Final certainty score is 2.

Appendix 1 Table 3. Final certainty scoring method example for questions 2, 8 and 15.

Examples	Variables	Risk score	Certainty Score	Final certainty score
Example 1	V1	1	3	1
Example 1	V2	2	1	
Example 2	V1	2	2	3
Example 2	V2	2	3	
Example 3	V1	1	2	2
Example 3	V2	3	2	

QUESTION 9: WHAT LEVEL OF IMPACT COULD THE SPECIES HAVE ON POPULATION GROWTH OF OTHER SPECIES IN THE ASSESSMENT AREA?

Only consider impacts in the species' suitable habitat. Consider positive and negative impacts (i.e., population increase or decrease). Consider impacts to indigenous and non-indigenous populations. Consider ecological impacts on aquaculture and commercially fished species, not economic impacts on the industry itself.

Risk Score

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 4), scoring was as follows:

- Score 3: if there are multiple species-specific impacts on the population growth of multiple species.

- Score 2: if there is 1 species-specific impact on the population growth of 1 species.

- Score 1: if there are no species-specific impacts reported on the population growth of any species.

Certainty

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 4), scoring was as follows:

- Score 3: if there are ≥ 3 studies showing impacts on population growth of other species.

- Score 2: if there are 2 studies showing impacts on population growth of other species.

- Score 1: if there is 1 study or no information showing impacts on population growth of other species.

Scoring of the impact of invasion questions were based primarily on the quantity of published studies demonstrating impacts of invasive fishes on native species or ecosystems. However, to be conservative in the impact of invasion scoring, opposing outcomes (i.e. studies which showed no or opposite impacts) were not considered, as these do not invalidate the impacts seen elsewhere.

Appendix 1 Table 4. Impacts of Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel on native species population growth.

Species	Population growth
Goldfish	Reduction in salamander (Monello and Wright 1999) aquatic vegetation (Richardson *et al.* 1995) and invertebrate populations (Richardson and Whoriskey 1992); native fish population decline (Deacon *et al.* 1964; Carosi *et al.* 2017, 2019); increase phytoplankton growth of *Microcystis aeruginosa* (Kolmakov and Gladyshev 2003)
Prussian Carp	Reduction in fish and benthic invertebrate populations (Tarkan *et al.* 2012; Ruppert *et al.* 2017), decline in native fish species in Czech Republic (Halačka *et al.* 2003; Lusk *et al.* 2010) and reduction in plankton populations (Hrbáček *et al.* 1961); sexual parasitism (Lusk *et al.* 2010); detrimental to commercial carp production (Halačka *et al.* 2003).

Species	Population growth
Black Crappie	No impacts on population growth reported from the literature. Not included: Walleye and Yellow Perch (Schiavone 1983,1985)[1]; Walleye (Krishksa *et al.* 1996 and Mosindy *et al*. 1984 cited in Kerr and Grant 2000)[2]; Broda *et al.* 2022[3].
Chain Pickerel	Decrease of fish richness, diversity and reduced fish and freshwater mussel abundance and fish size (Bradford *et al.* 2004; Mitchell *et al.* 2012, COSEWIC 2013); chemical cues which may change other fish species behaviour (Mirza and Chivers 2000); prevented salmon stocking (Warner *et al.* 1968; Warner 1972).

[1] Schiavone (1983), (1985): Competition for food, loss of Yellow Perch forage, and direct predation of fry and fingerlings combined with angling exploitation of walleye and perch may lead to declines in perch and walleye abundance in lakes where black crappie are introduced. Declines here are associated with multiple cumulative effects and not directly to the introduction of black crappie.

[2] Mosindy *et al.* (1984) and Krishksa *et al.* (1996) as cited in Kerr and Grant (2000) infer that a reduction in Yellow Perch forage due to potential competition with introduced black crappie may have reduced Yellow Perch abundance (a preferred prey of walleye) and ultimately suppressed walleye recruitment. Links between black crappie and both Yellow Perch and walleye in these studies are theoretical and no evidence is provided.

[3] Broda *et al.* (2022): Identify declines of walleye abundance in electrofishing transects and increases in black crappie catches in fyke nets. Cautions against making any causal inferences, as walleye population is likely driven by fishing-pressure, climate change, and lack of regulations for panfish angling. Declines here are associated with multiple cumulative effects and not directly to the introduction of black crappie.

QUESTION 10: WHAT LEVEL OF IMPACT COULD THE SPECIES HAVE ON COMMUNITIES IN THE ASSESSMENT AREA?

Only consider impacts in the species' suitable habitat. Consider positive and negative impacts. Consider impacts to indigenous and non-indigenous populations.

Risk Score

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 5):

- Score 3: if there are multiple species-specific impacts which altered diversity or community structure.
- Score 2: if there is 1 species-specific impact which altered diversity or community structure.
- Score 1: if there are no species-specific impacts reported to alter diversity or community structure.

Certainty

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 5):

- Score 3: if there are ≥ 3 studies showing altered diversity or community structure.
- Score 2: if there are 2 studies showing altered diversity or diversity or community structure.
- Score 1: if there is 1 study or no information showing altered diversity or community structure.

Scoring of the impact of invasion questions were based primarily on the quantity of published studies demonstrating impacts of invasive fishes on native species or ecosystems. However, to be conservative in the impact of invasion scoring, opposing outcomes (i.e. studies which showed no or opposite impacts) were not considered, as these do not invalidate the impacts seen elsewhere.

Appendix 1 Table 5. Impacts of Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel on diversity or community structure.

Species	Impact on diversity or community structure
Goldfish	Fish competition (Deacon *et al.* 1964; Busst and Britton 2015; Carosi *et al.* 2017, 2019) and alteration of aquatic plant community structure (Richardson *et al.* 1995).
Prussian Carp	Decrease in fish and invertebrate populations (Ruppert *et al.* 2017; Tarkan *et al.* 2012), declines in native mussel populations (Perdikaris *et al.* 2012), gynogenetic reproduction and sexual interference (Paschos *et al.* 2004).
Black Crappie	Modified fish community structure (Schiavone 1983).
Chain Pickerel	Decreasing watershed biodiversity (Mitchell *et al.* 2012; Warner 1972), reduced fish abundance and fish size (Mitchell *et al.* 2012); Prevented salmon stocking (Warner 1972).

QUESTION 11: WHAT LEVEL OF IMPACT COULD THE SPECIES HAVE ON HABITAT IN THE ASSESSMENT AREA?

Only consider impacts in the species' suitable. Consider habitat engineering (e.g., reef-building organisms) and habitat destruction (e.g., bioturbating organisms).

Risk Score

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 6):

- Score 3: if there are multiple species-specific impacts on habitat.

- Score 2: if there is at least 1 species-specific impact on habitat.

- Score 1: if there are no species-specific impacts reported on habitat.

Certainty

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 6):

- Score 3: if ≥ 3 studies show habitat impacts.

- Score 2: if there are 2 studies showing habitat impacts or the potential of habitat impact is high.

- Score 1: if there is 1 study or no evidence that habitat is altered by this species.

Scoring of the impact of invasion questions were based primarily on the quantity of published studies demonstrating impacts of invasive fishes on native species or ecosystems. However, to be conservative in the impact of invasion scoring, opposing outcomes (i.e., studies which showed no or opposite impacts) were not considered, as these do not invalidate the impacts seen elsewhere.

Appendix 1 Table 6. Impacts of Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel impacts on habitat.

Species	Impact on habitat
Goldfish	Reduction of aquatic vegetation and increased turbidity (Richardson 1991; Richardson and Whoriskey 1992; Richardson *et al.*1995), amplification of cyanobacteria and subsequent algal blooms (Kolmakov and Gladyshev 2003; Morgan and Beatty 2007).
Prussian Carp	Habitat degradation and alteration (Crivelli 1995), reduction of aquatic vegetation and increased turbidity (Richardson and Whoriskey 1992; Richardson *et al.* 1995).
Black Crappie	No habitat impacts reported in the literature
Chain Pickerel	No habitat impacts reported in the literature

QUESTION 12: WHAT LEVEL OF IMPACT COULD THE SPECIES HAVE ON ECOSYSTEM FUNCTION IN THE ASSESSMENT AREA?

Only consider impacts in the species' suitable habitat. Consider changes (positive or negative) to the physical, chemical, and biological processes that would normally maintain the ecosystem.

Risk Score

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 7):

- Score 3: if there are multiple species-specific impacts on ecosystem function.

- Score 2: if there is 1 species-specific impact on ecosystem function.

- Score 1: if there are no species-specific impacts reported on ecosystem function.

Certainty

Using publications on field studies in the primary scientific literature (see Appendix 1, Table 7):

- Score 3: if ≥ 3 studies show that the AIS has impacted ecosystem function.

- Score 2: if there are 2 studies showing that the AIS has impacted ecosystem function.

- Score 1: if there is 1 study or no information showing that the AIS has impacted ecosystem function.

Scoring of the impact of invasion questions were based primarily on the quantity of published studies demonstrating impacts of invasive fishes on native species or ecosystems. However, to be conservative in the impact of invasion scoring, opposing outcomes (i.e., studies which showed no or opposite impacts) were not considered, as these do not invalidate the impacts seen elsewhere.

Appendix 1 Table 7. Impacts of Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel on ecosystem function.

Species	Impact on ecosystem function
Goldfish	Salamander decline (Monello and Wright 1999); decrease in aquatic vegetation cover, habitat and potential spawning sites (Richardson *et al.* 1995); decline in invertebrate populations (Richardson and Whoriskey 1992); decline in native fish populations (Deacon *et al.* 1964; Carosi *et al.* 2017, 2019); increases in phytoplankton *Microcystis aeruginosa* and algal blooms (Kolmakov and Gladyshev 2003; Morgan and Beatty 2007).
Prussian Carp	Changes in ecosystem function (Paulovits 1998; Perdikaris 2012; Tarkan *et al.* 2012); trophic level disturbance (Paschos *et al.* 2004); habitat degradation and alteration (Crivelli 1995); reduction of aquatic vegetation and increased turbidity (Richardson and Whoriskey 1992; Richardson *et al.* 1995).
Black Crappie	No impacts on ecosystem function reported in the literature.
Chain Pickerel	Reduction of fish community richness and diversity, fish population abundance and size distribution (Warner 1972; Mitchell *et al.* 2012).

QUESTION 13: WHAT LEVEL OF IMPACT COULD THE SPECIES' ASSOCIATED DISEASES, PARASITES, OR TRAVELERS HAVE ON OTHER SPECIES IN THE ASSESSMENT AREA?

CMIST: Only consider impacts in the species' suitable habitat.

There are large knowledge gaps in the literature concerning parasites/viruses/pathogens associated with AIS and answering this question would require targeted research. Consequently here, we consider only parasites/viruses/pathogens identified as of concern by either the World Organization for Animal Health (WOAH; https://www.woah.org/en/home/) and the Canadian Food Inspection Agency (CFIA; https://www.canada.ca/en/public-health/services/infectious-diseases.html) according to the following rubric:

Risk Score

Using publications in the primary scientific literature (see Appendix 1, Table 8):

- Score 3: if the AIS carries parasites/viruses/pathogens (as reported in the scientific literature) that are listed on the WOAH and/or CFIA websites **AND** there are other native species that may be impacted in the assessment area.

- Score 2: if the AIS carries parasites/viruses/pathogens (as reported in the scientific literature) that are listed on the WOAH and/or CFIA websites **BUT** native species are unlikely to be impacted in the assessment area should the AIS arrive.

- Score 1: if there is no evidence that the AIS carry parasites/viruses/pathogens listed on the WHOA and/or CFIA websites.

Certainty

Using publications in the primary scientific literature (see Appendix 1, Table 8):

- Score 3: if at least 1 publication shows evidence that the AIS **is** a carrier of WOAH/CFIA parasite/virus/pathogen.

- Score 1: if at least 1 publication is showing evidence that the AIS is not a carrier of WOAH/CFIA parasite/virus/pathogen OR there is no evidence.

Appendix 1 Table 8. Parasites/viruses/pathogens associated with Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel which may impact other native species in Canadian ecoregions.

Species	WOAH	CFIA	Species these diseases can affect
Goldfish	Epizootic Ulcerative Syndrome (WOAH 2022a), Spring Viremia of Carp (WOAH 2019), Koi Herpes Virus (potential, but not considered a susceptible host) (WOAH 2022b).	Infectious Pancreatic Necrosis (CFIA 2020a), Spring Viremia of Carp (CFIA 2020b), Epizootic Ulcerative Syndrome (CFIA 2022), Koi Herpes Virus (CFIA 2013).	Epizootic Ulcerative Syndrome, Infectious Pancreatic Necrosis and Spring Viremia of Carp affects many fish species. At least one native species which can be affected is likely to be in each ecoregion.
Prussian Carp	Carp Edema Virus (WOAH 2022c)	N/A	Impacts carp species only. No native carps in any Canadian ecoregion.
Black Crappie	Viral Haemorrhagic Septicaemia Virus (WOAH 2021)	Viral Haemorrhagic Septicaemia Virus (CFIA 2020c)	Viral Haemorrhagic Septicaemia Virus affects many fish species. At least one native species which can be affected is likely to be in each ecoregion.
Chain Pickerel	N/A	N/A	N/A

QUESTION 14: WHAT LEVEL OF GENETIC IMPACT COULD THE SPECIES HAVE ON OTHER SPECIES IN THE ASSESSMENT AREA?

CMIST: Only consider impacts in the species' suitable habitat. Consider only indigenous species in the assessment area.

Consider hybridization (among species hybridization and supplementation of genetic material between strains or varieties of a species) as well as other genetic impacts.

Risk Score

Using publications in the primary scientific literature (see Appendix 1, Table 9):

- Score 3: if there is evidence of hybridization AND native congeners are present in the ecoregion.

- Score 2: if there is no evidence of hybridization AND native congeners are present in the ecoregion.

- Score 1: if there are no native congeners present in the ecoregion.

Certainty

Score certainty based on the scores (above) as follows:

- If scored 1 above: Score certainty 3 because no hybridization can take place without native congener in the ecoregion (certainty is high).

- If score 2 above: Score certainty 1 because there are native congeners in the ecoregion but there is no evidence that hybridization occurs (certainty is moderate).

- If score 3 above: Score certainty 3 (certainty is high).

Appendix 1 Table 9. Evidence of goldfish, Prussian Carp, Black Crappie or Chain Pickerel hybridization with native fish species.

Species	Evidence species has hybridized with another fish species.	References	Native congeners present in ecoregion?
Goldfish	• Common Carp (*Cyprinus carpio*) • Koi (*C. carpio carpio*) • Prussian Carp (*C. gibelio*)	Taylor and Mahon 1977 Hume *et al.* 1983 Pullan and Smith 1987 Kramer *et al.* 2020 Hänfling *et al.* 2005 Smartt 2007 Kucinski *et al.* 2015 Mezhzherin *et al.* 2019	No
Prussian Carp	• Crucian Carp (*Carassius carassius*), • Common Carp (*Cyprinus carpio*) • Goldfish (*Carassius auratus*)	Hänfling *et al.* 2005 Papoušek *et al.* 2008 Mezhzherin *et al.* 2012	No
Black Crappie	• White Crappie *(Pomoxis annularis)*	Smith *et al.* 1994 Travnichek *et al.* 1996	No White Crappie is native to ecoregion 116 (Scott and Crossman, 1998) Black Crappie was not evaluated in its native ecoregion of 116.
Chain Pickerel	• Redfin Pickerel (*E. americanus americanus*) • Grass Pickerel (*Esox americanus vermiculatus*) • Northern Pike (*E. lucius*)	Embody 1918 Raney 1955 McCarraher 1960 Crossman and Buss 1965 Scott and Crossman 1998 Serns and McKnight 1977	Yes Redfin Pickerel is native to ecoregion 116 (and 117; Scott and Crossman 1998) Grass Pickerel is native to ecoregion 116 (and 117; Scott and Crossman 1998; Crossman and Holm 2005) Northern Pike is native to all Canadian ecoregions except: 103, 112, 115, and 119 (Harvey 2009) Chain Pickerel was not evaluated in its native ecoregion of 117.

QUESTION 15: WHAT LEVEL OF IMPACT COULD THE SPECIES HAVE ON AT-RISK OR DEPLETED SPECIES IN THE ASSESSMENT AREA?

Consider all possible impacts on species in the assessment area that are depleted, of extra value, or recognized as being at risk.

Risk Score

Scoring incorporated expert opinion on the impacts AIS may have on species at risk within their region of expertise and AIS associated threats identified in published COSEWIC reports for SARA listed species.

Variable 1 – Expert opinion on impacts on species at risk

Panels of experts scored this question based on their knowledge and experience of potential impacts on species at risk within their region of expertise. Scores were determined via discussion and subsequent consensus using the following rubric:

- Score 3: if high impact in many areas.

- Score 2: if high impact in few areas OR moderate impact in many areas

- Score 1: Low impact or no impact

Variable 2 – SARA listed species threat calculators

Threat calculators based on IUCN spreadsheets have been mandatory in published COSWEIC reports for SARA listed species since 2012. A summary of all threats reported in these threat calculators has been completed by Potts *et al.* (2023 *in prep*), from which we were able to flag all instances where our AIS of interest were identified as posing a threat to any SARA listed species across Canada (see Appendix 1, Table 11).

- Score 3: if threat calculator reported impacts on SAR or their habitat as high or very high. If a range is reported, use highest impact level.

- Score 2: if threat calculator reported impacts on SAR or their habitat as moderate. If a range is reported, use highest impact level.

- Score 1: if threat calculator reported impacts on SAR or their habitat as low.

If more than one species was reported to be at risk in the same ecoregion, the highest risk among those species was chosen in order to be conservative in our threat estimation. All other ecoregions where no threats are reported in the threats calculator were scored 1.

Final Risk Scores

Use the maximum risk score found amongst variables.

Certainty

Variable 1 – Expert opinion on impacts on species at risk

- Score 3: if expert panel has first-hand experience with the species and the assessment area.

- Score 2: if expert panel has experience with similar species in a similar environment.

- Score 1: if expert panel has no experience with the species and/or ecoregion.

Variable 2 – SARA listed species threat calculators

- Score 3: if threats are reported in calculators (as summarized by Potts et al. 2023 *in prep*). Confidence is high because threats calculators are based are based on best available information, follow the IUCN template and are provided in published COSEWIC reports.

- Score 2: if no threats are reported in calculators. Here confidence is moderate because we cannot confirm the absence of threat.

Final Certainty Scores

As this question considers multiple variables with different measures of certainty and to ensure a precautionary approach in our final scoring, use the **certainty** score corresponding with the variable which had highest risk score.

Here are some simplified example scores, where two variables are considered. In the table below:

Example 1 – Risk score Variables 1 (V1) and 2 (V2) have different scores, with V2 being the highest risk score (2), and different certainty scores = Final certainty score is 1.

Example 2 – Risk score Variables 1 (V1) and 2 (V2) are the same (2), but have different certainty scores = Final certainty score is 3.

Example 3 – Risk score Variables 1 (V1) and 2 (V2) have different scores, with V2 being the highest risk score (3), but certainty scores are the same = Final certainty score is 2.

Appendix 1 Table 10. Final certainty scoring method example for questions 2, 8 and 15.

Examples	Variables	Risk score	Certainty Score	Final certainty score
Example 1	V1	1	3	1
Example 1	V2	2	1	
Example 2	V1	2	2	3
Example 2	V2	2	3	
Example 3	V1	1	2	2
Example 3	V2	3	2	

Appendix 1 Table 11. Threat calculator information extracted from the summary completed by Potts et al. (2023 in prep.) on the threats associated with Goldfish, Prussian Carp, Black Crappie and Chain Pickerel on SARA listed species across Canadian ecoregions.

Impacted Species	Provinces	Ecoregion	Threat Species	Impact	Full comment from threats calculator inventory
Lake Chub (Atlin Warm Springs populations)	British Columbia	102	Goldfish	High-Low	Cherry Shrimp have been released in the spring and there is concern for introductions of goldfish or other warm water non-indigenous species.
Lake Chub (Liard Hot Springs populations)	British Columbia	104	Goldfish	High-Low	There is concern for introductions of goldfish or other warm water non-indigenous species.
Lake Chubsucker	Ontario	116	Goldfish	Low	Common Carp/Goldfish. Found throughout Canadian range. Primary consequence is modification of habitat features required by Lake Chubsucker for feeding, cover, reproduction.
Lake Chubsucker	Ontario	116	Black Crappie	Moderate-Low	Considers illegal stocking. Includes native predatory sportfish such as Black Crappie, Largemouth Bass, Northern Pike. Historical composition of Lake Chubsucker fish communities poorly understood. Illegal stocking of Northern Pike has been confirmed from Old Ausable Channel; consequences unclear. Black Crappie is native to this Ontario ecoregion (116), and so it was not scored here.

Impacted Species	Provinces	Ecoregion	Threat Species	Impact	Full comment from threats calculator inventory
Western Silvery Minnow (WSM)	Alberta	142	Black Crappie	Moderate-Low	Lake Whitefish and Black Crappie are also present in Fresno reservoir and could expand into the Alberta portion of the Milk River. While the impacts of these species are currently likely minimal, stabilization of the flow regime (from the construction of a dam, say) may favor these species over WSM and exacerbate the effects.
Yellow Lampmussel	New Brunswick, Nova Scotia	118,119	Chain Pickerel	Negligible	Chain Pickerel, Muskellunge, Smallmouth Bass impact questionable in next 10 years in both Saint John River and Sydney River.
Rainbow Smelt (Lake Utopia large-bodied population)	New Brunswick	118	Chain Pickerel	Low	Chain Pickerel (confirmed) and Largemouth Bass (not confirmed) have been reported in Lake Utopia which both would prey on juvenile Smelt. There is uncertainty in the severity of the impact.
Rainbow Smelt (Lake Utopia small-bodied population)	New Brunswick	118	Chain Pickerel	Very High	Chain Pickerel (confirmed) and Largemouth Bass (not confirmed) have been reported in Lake Utopia which both would prey on juvenile Smelt. There is uncertainty in the severity of the impact.

DO NOT SCORE QUESTION 16

Question 16 was considered to be out of scope for a DFO Science assessment of risk, as it evaluates the impacts of AIS on aquaculture and commercially fished species, which are principally related to economic health. Question 16 was consequently removed from the analyses.

QUESTION 17: IS THE SPECIES KNOWN OR GENERALLY CONSIDERED TO BE INVASIVE ANYWHERE IN THE WORLD?

CMIST: This question is meant to differentiate species that are not invasive and not likely to be invasive based on their life history traits, from those that are known or generally considered to be invasive.

Risk Score

- Score 3: if the species are known to be invasive elsewhere in the world.

- Score 2: if the species are not generally considered to be invasive, but has traits related to invasiveness.

- Score 1: if the species is not invasive and not likely to be invasive based on their life history traits.

Certainty

- Score 3 if there are ≥ 2 studies which show that the species is invasive elsewhere in the world

- Score 2: if there is 1 study which shows that the species is invasive elsewhere in the world

- Score 1: if there no evidence that the species is invasive elsewhere in the world

Appendix 1 Table 12. Literature stating where Goldfish, Prussian Carp, Black Crappie and Chain Pickerel are considered invasive across the globe.

Species	References
Goldfish	USA (Courtenay 1993, Courtenay *et al.* 1984; Courtenay and Stauffer 1984); Europe (Lorenzoni *et al.* 2007; Lorenzoni *et al.* 2010) , Australia (Haynes *et al.* 2012), elsewhere in the world (Bonham and Siriwardena 2022; GBIF 2022).
Prussian Carp	Europe (Vetemaa *et al.* 2005; Komiyama *et al.* 2009; Savini *et al.* 2010; Takada *et al.* 2010; Rylkova *et al.* 2012; Britton 2022, GBIF 2022).
Black Crappie	USA (Sanderson *et al.* 2009; Fuller *et al.* 2023), Mexico and Panama (Welcomme 1988).
Chain Pickerel	United States (Coffie 1998; Scott and Crossman 1998).