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Science Advisory Report 2025/057

NATIONAL SCREENING-LEVEL RISK ASSESSMENT (SLRA) OF GOLDFISH, PRUSSIAN CARP, CHAIN PICKEREL, AND BLACK CRAPPIE IN CANADA

Figure 1. (A) Goldfish (photo: R.P. Jacobs and E.B. O'Donnell), (B) Prussian Carp (photo: George Chernilevsky), (C) Chain Pickerel (photo: Conservation Commission of Missouri), (D) Black Crappie (photo: R.P. Jacobs and E.B. O'Donnell).

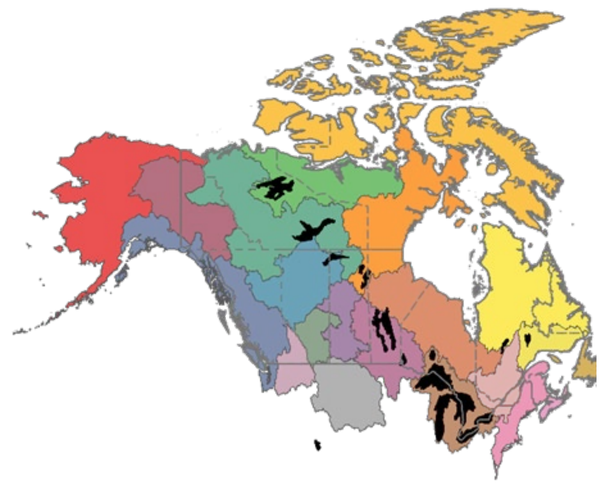

Figure 2. Freshwater ecoregions in Canada (after Abell et al. 2008).

CONTEXT

Aquatic invasive species (AIS) are species introduced or spread to ecosystems beyond their natural range that threaten freshwater 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*). Using an adaption of the Canadian Marine Invasive Screening Tool (CMIST), a screening-level risk assessment (SLRA) was performed to estimate the level of invasion risk (high, moderate, or low) of these four species across freshwater ecoregions in Canada. SLRAs help decision-makers identify species that pose substantial threats to native species/ecosystems, and facilitate the development of policy and management procedures for the purpose of preventing/mitigating the impacts of biological invasions. Additionally, SLRAs help prioritize species and areas that might require comprehensive (detailed-level) risk assessments (DLRA) and/or identify knowledge gaps where further research is needed. Results from this SLRA will help prioritize efforts and resources to control and/or mitigate spread, inform public education and outreach, and inform socio-economic screening-level risk assessments of the four fish assessed. Recommendations stemming from this science advice could be used to inform management and policy on mitigating freshwater fish invasions across Canada.

This Science Advisory Report is from the March 27-29, and May 29-30, 2023 National peer review meetings on Screening Level Risk Assessment (AIS) for Chain Pickerel (*Esox niger*), Goldfish (*Carassius auratus*), Prussian Carp (*Carassius gibelio*), and Black Crappie (*Pomoxis nigromaculatus*). Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- 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.

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 well-being (Ogden *et al.* 2019; Jones *et al.* 2017). 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). Pathways of particular concern for freshwater fish include (but are not limited to) live food and aquarium trades (Crossman and

Cudmore 1999; Chan *et al.* 2022), recreational fishing (Drake and Mandrak 2014a, 2014b), compassionate/spiritual release (Campbell *et al.* 2021), and unaided dispersal through 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 have 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**.**

Recently, the potential ecological impacts of four freshwater fishes were identified as being of particular concern across Canada: Goldfish (*Carassius auratus)*, Prussian Carp (*Carassius gibelio)*, Chain Pickerel (*Esox niger),* and Black Crappie (*Pomoxis nigromaculatus)*. The latter two species are native in certain regions of Canada, while Goldfish and Prussian Carp are strictly non-indigenous. All four species presently have at least one established non-indigenous population in Canada (often more) and are undergoing range expansion. Currently, 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 control or the prevention of new introductions. Consequently, the Aquatic Invasive Species National Core Program requested screening-level risk assessments (SLRAs) for Goldfish, Prussian Carp, Black Crappie, and Chain Pickerel to identify regions at risk of invasion.

SLRAs are tools used to estimate the invasion risk of potentially invasive 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.* 2016). Through 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.* 2016; Mandrak *et al.* 2012).

The objectives of this Science Advisory Report were to

1. perform SLRAs for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie in Canadian freshwater ecoregions, considering their likelihood of introduction, potential ecological impacts, and changes in invasion risk under a current and projected climate scenario, and
2. determine how results across freshwater ecoregions influence conclusions at the national level.

Recommendations stemming from this science advice could be used to inform management and policy on mitigating freshwater fish invasions across Canada.

ASSESSMENT

Canadian Marine Invasive Screening Tool and modifications

A modified version the Canadian Marine Invasive Screening Tool (CMIST; DFO 2014; Drolet *et al.* 2016), a score-based SLRA that includes a series of 17 questions (each of which is also scored for certainty), was used to estimate the invasion risk of Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie in Canada. SLRAs were completed under historical (1981-2000) and a ‘worst-case’ projected climate matching scenario (period 2081-2100, projected SSP5-8.5

high emissions climate scenario), for each fish species in each Canadian freshwater ecoregion (21 ecoregions) as defined by Abell *et al.* (2008) (available at https://www.feow.org/), which uses cluster analyses of distinct fish community assemblages within freshwater communities to categorize watersheds into ecoregions across the globe. As only questions four (How much of the assessment area offers suitable environmental conditions for the species to survive?) and five (Are the species' reproductive requirements available in the assessment area?) were considered to be directly affected by changes in climate, only these two questions were rescored under the projected climate scenario. Afterwards these new scores were combined with the remaining unchanged scores, to provide an assessment of risk under the projected climate scenario.

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. A brief description of the scoring considerations for each question and detailed guidance on how each question and associated certainty was scored can be found in Hill *et al.* (2024). Due to lack of information (and certainty) pertaining to species' impacts on socio-economics, CMIST question 16 was excluded from this SLRA.

CMIST questions are designed to broadly evaluate the likelihood of introduction (present status and potential of introduction, survival, establishment, and spread) and the potential ecological impacts of an AIS in a defined assessment area (Drolet *et al.* 2016). For each fish species in each ecoregion, 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. 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 Hill *et al.* (2024).

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). 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 to 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.

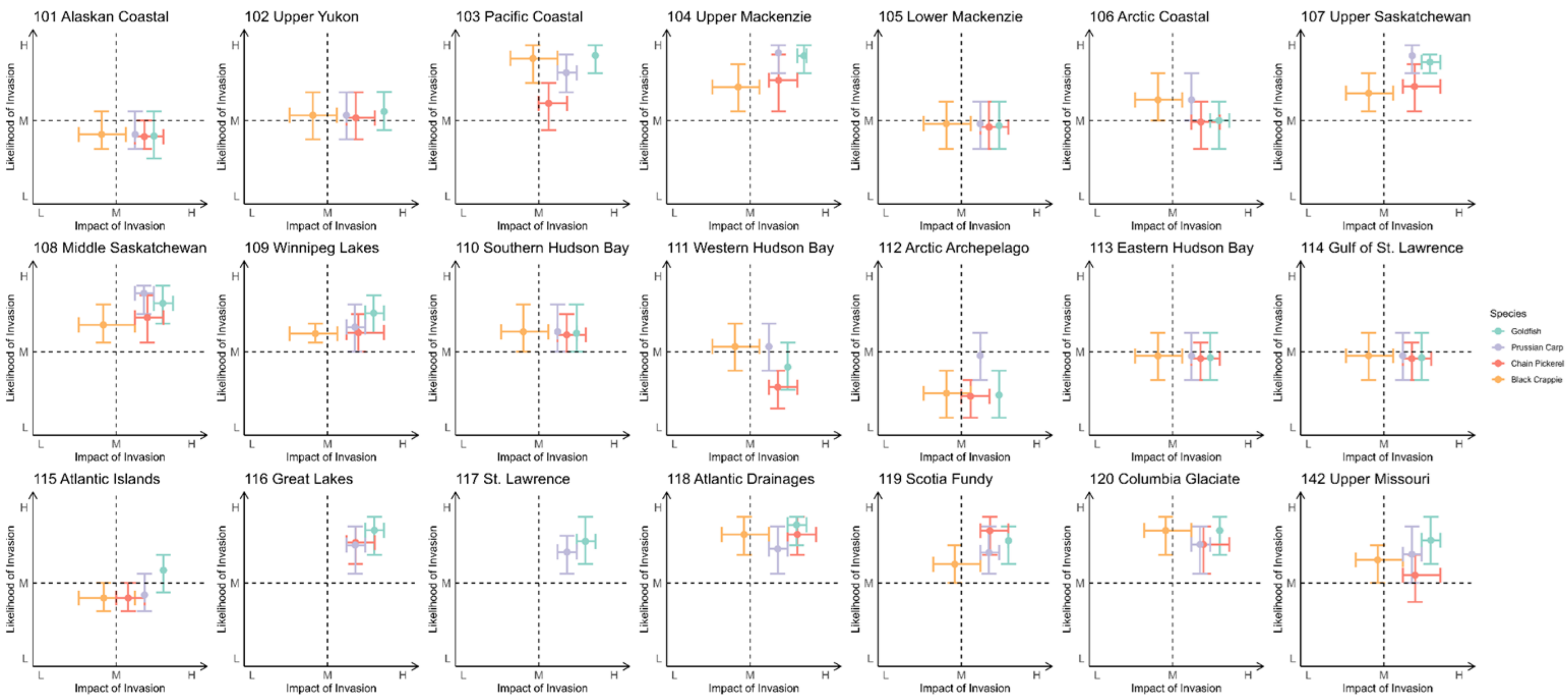

Figure 3. Likelihood and impact scores (low (L), moderate (M), and high (H)) for each numbered ecoregion (panels) for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie. 95% confidence intervals are represented by error bars which indicate overall certainty for each axis. Here certainty describes confidence in data quality and not ecological variation.

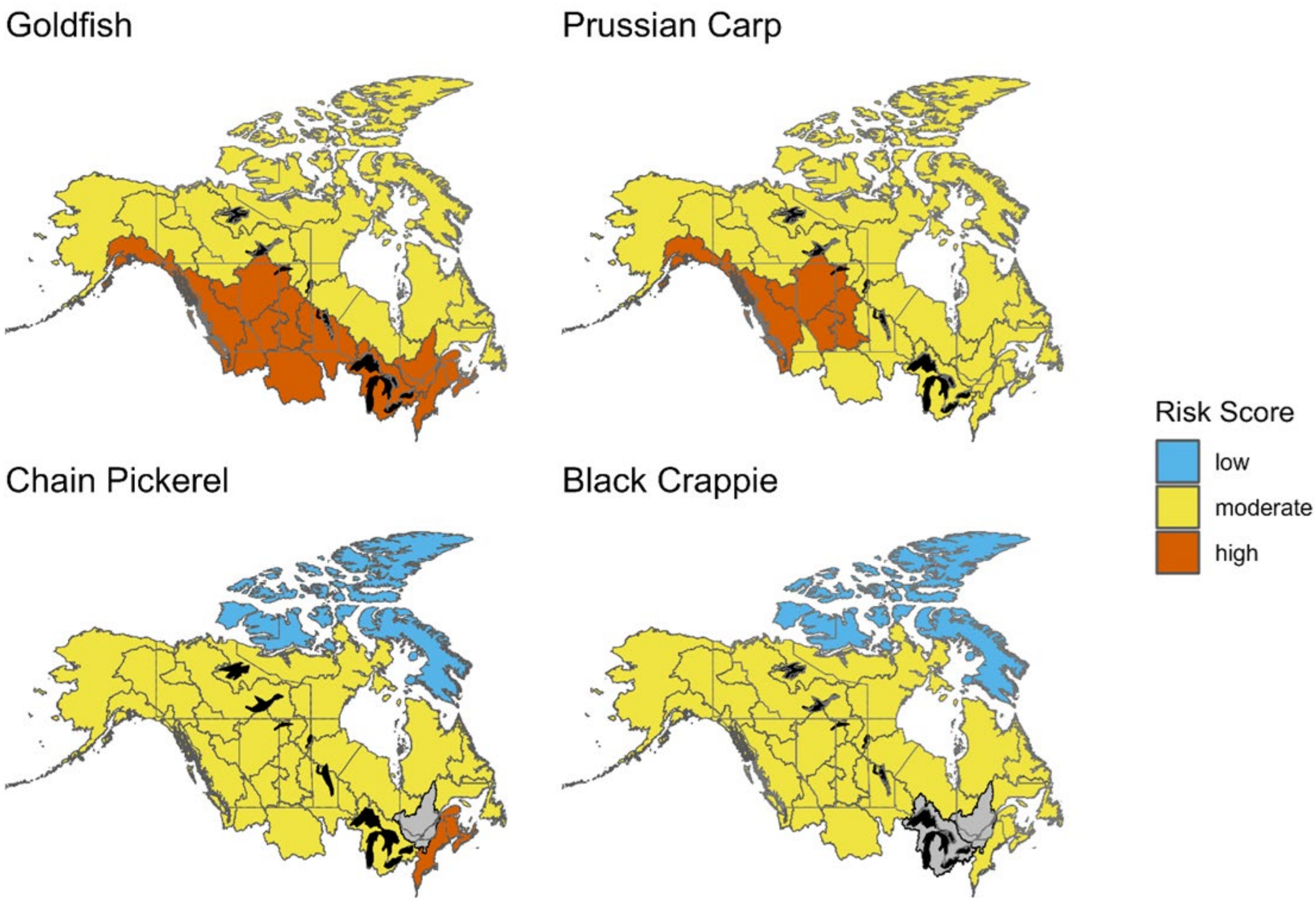

Figure 4. Heatmaps showing the final screening-level assessments of invasion risk for Goldfish, Prussian Carp, Chain Pickerel, and Black Crappie across Canadian ecoregions. Ecoregions in grey represent native range of the species that were not scored.

Table 1. 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. See Hill et al. (2025) for more details.

Questions	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Established ? (Q1)	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)	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)

Questions	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Suitable environmental conditions (Q4) and reproductive requirements (Q5)	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)
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)**	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)

Table 2. Summary of answers to impact of invasion questions (questions 9 to 17) for each species. Fishes were not scored in their native ecoregions. See Hill et al. (2025) for more details.

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).	Declines of multiple native fish and benthic invertebrate species, commercial carp, plankton. Decline due to sexual parasitism (gynogenetic reproduction).	Decreases in fish richness, diversity and reduced fish abundance and fish size Declines of native fish species, including preventing salmon stocking.	No impacts on population growth reported in the literature–- potentially suppresses Yellow Perch and Walleye.
Impacts on community (Q10)	Altered competition dynamics in fish communities and community composition of aquatic plants.	Altered community composition of native fishes, invertebrates and mussel populations, including reproductive interference through gynogenetic reproduction.	Decreased watershed biodiversity of fish, fish abundance and size, including preventing salmon stocking.	Modified fish community structure.
Impacts on habitat (Q11)	Reduction of aquatic vegetation and increased turbidity. Amplification of cyanobacteria and subsequent algal blooms.	Habitat degradation and alteration, increases turbidity, creates eutrophic conditions.	No evidence.	No evidence.
Impacts on ecosystem function (Q12)	Declines of multiple species (salamanders, aquatic vegetation, invertebrates, multiple native fish species, phytoplankton).	Alters ecosystem trophic functioning and dynamics. Decline in spawning sites and lake quality, increases turbidity.	Reduced fish and freshwater mussel abundance, reduced fish size distribution and ecosystem richness.	No evidence.
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	Carp Edema Virus impacts carp species only. No native carps in any ecoregions. Disease reported in WOAH only.	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

Question	Goldfish	Prussian Carp	Chain Pickerel	Black Crappie
Hybridization with native fish species (Q14)	No	No	Yes Redfin Pickerel which is native to 116 (and 117) Grass Pickerel which is native to 116 (and 117) Northern Pike is not native in ecoregions 103, 112, 115, and 119 only Chain Pickerel was not evaluated in its native ecoregion of 117.	No White Crappie which is native to ecoregion 116 Black Crappie was not evaluated in its native ecoregion of 116.
Impacts on at-risk or depleted species (Q15)	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	Europe	USA	USA, Mexico, Panama

Levels of Invasion Risk

Goldfish and Prussian Carp

The high risk of Goldfish in the southern ecoregions of Canada (Figures 1 and 2) reflects its current establishment, which increases the anticipated frequency of secondary introduction events, and the number of individuals expected to arrive with each secondary introduction event in current and adjacent ecoregions. 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 and subsequent spread into connecting watersheds in both Alberta and Saskatchewan (Elgin *et al.* 2014; Docherty *et al.* 2017; Ruppert *et al.* 2017; Hamilton 2021). Taxonomic confusion has complicated the understanding of invasion histories of both Goldfish and Prussian carp because Prussian Carp regularly hybridizes with other carp species (Vetemaa *et al.* 2005; Rylkova *et al.* 2010; Fuad *et al.* 2021) and are often morphologically indistinguishable from Goldfish (Elgin *et al.* 2014; Ribeiro *et al.* 2015).

Expected frequency (and associated propagule pressure) of arrival was high for both carp species (Figure 1, Table 1), where the aquarium and water garden trades are likely 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; Tweedley *et al.* 2017) likely drives spread of Goldfish. 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 neighbouring British Columbia. Anthropogenic dispersal of Prussian Carp also scored high, as original management strategies encouraged a catch, kill, and eat policy, ultimately leading to an increase in recreational fisher-driven translocations (Table 1).

Impacts of invasion were high for both carps (Figure 1, Table 2), which have the capacity to engineer the ecosystems they inhabit (Richardson *et al.* 1995; Morgan and Beatty 2004; Razlutskij *et al.* 2021). 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 *et al.* 1995; Razlutskij *et al.* 2021). 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; Monello and Wright 2001; Richardson *et al.* 1995, Halačka *et al.* 2003; Ruppert *et al.* 2017; Carosi *et al.* 2017, 2019). Goldfish may carry Epizootic Ulcerative Syndrome (EUS) and Infectious Pancreatic Necrosis (IPN) (both Canadian Food Inspection Agency reportable diseases and with EUS listed by the World Organization for Animal Health), which could negatively affect native fish communities. Both species have wide ranges of tolerance to multiple environmental parameters (Magurran 1984, 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; Morgan and Beatty 2004). This permits a tolerance to disturbance (Robison and Buchanan 1988; 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). Additionally, Prussian Carp is also able to reproduce asexually by using sperm from other cyprinid males to activate egg development and produce genetic clones (Paschos *et al.* 2004; Leonardos *et al.* 2007), consequently parasitizing other cyprinid fish through reproductive interference. Goldfish is identified in COSEWIC calculators as a threat to

Lake Chub and Lake Chubsucker (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 invasion impacts in these carp species and the relatively short invasion history of Prussian Carp in North America, its limited distribution and difficultly in taxonomic identification, it is possible that risks associated with Prussian Carp invasion are higher than what is presented here.

Chain Pickerel and Black Crappie

Final assessments of risk indicated ecoregions 118 and 119 were at high risk of invasion by Chain Pickerel, whereas all remaining ecoregions were moderate risk. All ecoregions had moderate risk of invasion from Black Crappie. For both species, the risk of invasion in the Arctic Archipelago (112) was low (Figures 1 and 2). 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), with historical translocations associated with sportfishing (Williamson, 1832 cited in Whittier *et al.* 1997). In Atlantic Canada, Chain Pickerel has now invaded approximately 380 lakes/rivers in New Brunswick and Nova Scotia (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; USGS 2022). Repeated historical stocking events (Mosindy 1995; Kerr 2006), illegal releases, and natural dispersal (Krishka *et al.* 1996 cited in Kerr and Grant 2000) have resulted in non-native Black Crappie populations in southern Manitoba, southern British Columbia (Scott and Crossman 1998; Whitney 2003; Holm *et al.* 2021), and New Brunswick (McAlpine *et al.* 2020; Powell 2022).

The expected frequency of arrival (and associated propagule pressure) is moderate-high for Black Crappie and Chain Pickerel (Figure 1, Table 1), but overall, our understanding of the frequency of arrival (and in what numbers) that both fishes enter each ecoregion, and what happens once they 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. Consequently, the fisher translocation and/or live-bait pathways are considered important vectors for the invasion/spread of Chain Pickerel and Black Crappie (Courtenay *et al.* 1984; 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). Although anglers are generally in favor of management strategies preventing introductions and/or spread of AIS, 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 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 lower than Goldfish and Prussian Carp (Figure 1, Table 2) 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). 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), but there is no evidence that its behaviour has direct impacts 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), 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 can limit 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 2001). 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 (Schiavone 1983). No clear evidence is available in the literature on the impacts of Black Crappie on the population growth of other species, although some studies speculate on the cumulative effects of multiple stressors (fishing pressure, climate change, diet competition and direct predation of fry) in relation to Walleye, Yellow Perch, and Black Crappie populations where all three species coexist (Schiavone 1983, 1985; Mosindy *et al.* 1984; Krishksa *et al.* 1996 as cited in Kerr and Grant 2000; Broda *et al.* 2022). 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. Eastern Canada lacks predator species (e.g., Northern Pike) with gape sizes large enough to consume adult Chain Pickerel or Black Crappie. 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.

Climate Change

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. 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. While climate change may influence multiple biotic and abiotic ecosystem factors (e.g., habitat availability, species interactions, dissolved oxygen, 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; 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.

Limitations

The majority of SLRA tools 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. 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. SLRAs are also not designed to evaluate cumulative effects or magnitude of impacts of an AIS and do 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 (Blackburn *et al.* 2011, Lockwood *et al.* 2016). Although each question in the CMIST tool is given equal weight in its contribution to the 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 detailed-level risk assessments (Copp *et al.* 2005, Copp *et al.* 2016; Vilizzi *et al.* 2022).

Sources of Uncertainty

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 in this work. The variety of ecoregions and associated habitats in each province also complicated expert opinion in our regional discussions, as regional expertise was often focussed more on specific species and less on habitat characteristics. Data/knowledge gaps in the literature, databases, and/or expert opinion also affected risk assessment outcomes. A lack of information on parasites/viruses/pathogens associated with the four fishes, as well as those documenting 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. 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. Furthermore, 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; Brand *et al.* 2021). Habitat changes can create unpredictable consequences or opportunities, inducing feeding strategy and/or trophic dynamics modifications (Broderson *et al.* 2015; 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.

CONCLUSIONS

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 linked to the presence of established AIS populations within an ecoregion (or adjacent ecoregions), because they increased future introduction potential. These two 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 on population growth and communities of other species. Although 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. Consequently, heatmaps of risk should be used in conjunction with biplots in order to understand the range in scoring and the certainty associated certainty associated with the likelihood and impact of invasion scores for each fish species per 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 high risk for invasion.

OTHER CONSIDERATIONS

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 among many other fish species in aquaponic systems. 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.

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