Management of Biological Invasions (2025) Volume 16, Issue 1: 187–210

Special Issue: Advances in the study of the management of biological invasions in inland waters and the legacy of Gordon Howard Copp (1956−2023)
Guest editors: Lorenzo Vilizzi and Calum MacNeil

Risk Assessment

Identifying higher risk invaders to the Columbia Glaciated Freshwater Ecoregion using a new screening tool: the Non-Indigenous Species Screening Tool (NISST)

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Co-Editors' Note: This paper was contributed as part of the Special Issue "Advances in the study of the management of biological invasions in inland waters and the legacy of Gordon Howard Copp (1956–2023)". This collaborative effort has attracted some of the most prominent invasion biologists who have contributed a diverse collection of high-profile papers addressing current knowledge gaps, research advances, and future opportunities in the management of biological invasions.

Citation: Wilcox MA, Johnson D, Dyke K, Gunsch D, Lyons DA, DiBacco C, Therriault TW (2025) Identifying higher risk invaders to the Columbia Glaciated Freshwater Ecoregion using a new screening tool: the Non-Indigenous Species Screening Tool (NISST). *Management of Biological Invasions* 16(1): 187–210, https://doi.org/10.3391/mbi.2025.16.1.12

Received: 29 February 2024

Accepted: 26 June 2024

Published: 15 January 2025

Handling editor: Lorenzo Vilizzi

Abstract

To inform non-indigenous species management and policy decisions it is often necessary to have a prioritized list of species and screening tools frequently are used for this purpose. However, despite numerous tools available that typically evaluate aspects of the introduction, establishment, and impacts of potential invasive species, there are still gaps in the criteria used meaning that not all tools are fit-for-purpose. Further, incorporating uncertainty in a way useful to managers has proven problematic. This paper introduces the Non-Indigenous Species Screening Tool, which was developed to fill such gaps and address common limitations in previous tools for screening potentially invasive species. Using a series of questions organized into three separate modules examining steps in the invasion process combined with both ecological impacts and socioeconomic impacts, this tool provides a semiquantitative valuation of risk which explicitly incorporates uncertainty into the score. Further, recognizing the increasing importance of considering climate change when assessing invasion risk, this tool also incorporates a modifier for this. We applied this tool to both existing non-indigenous species and potential ones (N = 44 species) across different taxa (plant, invertebrate, and fish) for the Columbia Glaciated Freshwater Ecoregion using four assessors. The question scores across all species and assessors showed strong correlation and the tool was able to differentiate low to high-risk species across taxa for species that were both present and not yet present. This suggests this tool is not taxa specific and can easily be applied for a variety of purposes.

Key words: risk screening, prioritization method, Columbia Basin, biosecurity, uncertainty

Introduction

The Pacific Northwest is one region of North America that is experiencing rapid changes due to the introduction of non-indigenous species (NIS) and human-induced pressures including climate change (Langdon and Lawler 2015). This is especially true for the Columbia Glaciated Freshwater Ecoregion of the World (FEOW 120) encompassing southeastern British

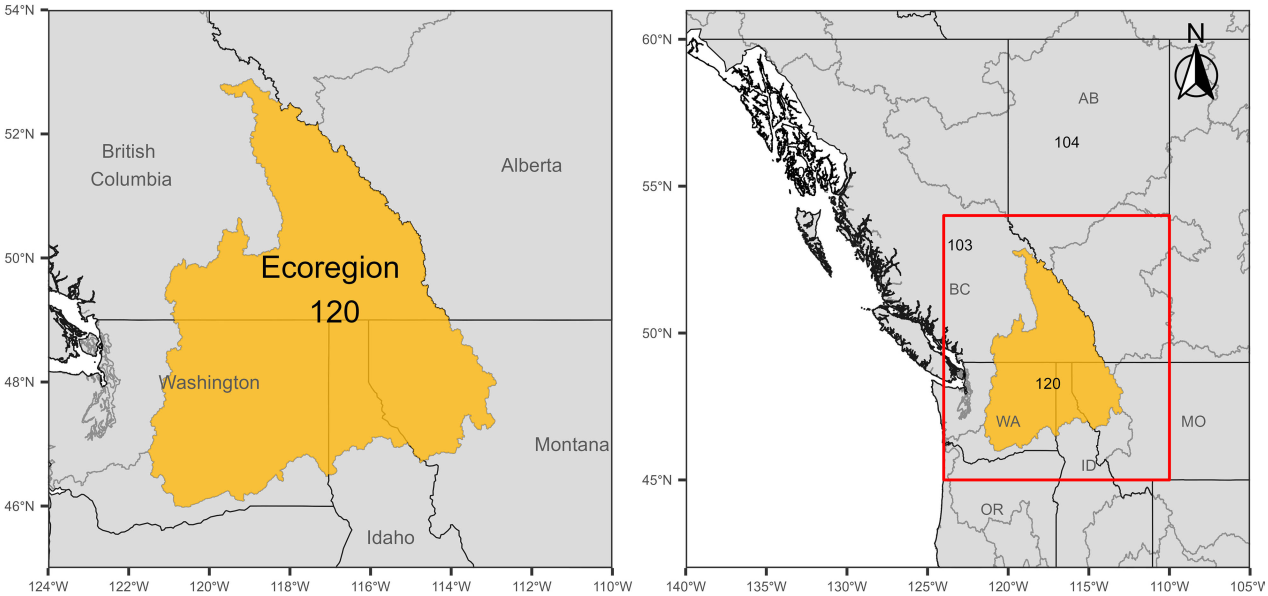

Figure 1. Map Columbia Glaciated Freshwater Ecoregion of the World (FEOW 120) encompassing southeastern British Columbia, northern Montana and Idaho, and northwest Washington (left) and general location of FEOW 120 within the Pacific Northwest of North America (right).

Columbia, northern Montana and Idaho, and eastern Washington (Figure 1). Salmonid fish have been important in this area for both ecosystem function and human use (McPhail and Lindsey 1986), though their continued presence is increasingly threatened by both NIS (intentional and unintentional introductions) and climate change. Intentionally released NIS include: common carp (*Cyprinus carpio* Linnaeus, 1758), eastern brook trout (*Salvelinus fontinalis* Mitchill, 1814), largemouth bass (*Micropterus salmoides* Lacepède, 1802), and smallmouth bass (*Micropterus dolomieui* Lacepède, 1802) to promote recreational opportunities; the mosquitofish (*Gambusia affinis* S.F. Baird & Girard, 1853) for biocontrol, and several crayfish species through organisms in trade (Pimentel et al. 2005; Simberloff et al. 2005; Chan et al. 2019; Brown and Therriault 2022). Unintentional introductions have occurred due to angling, water sports, and recreational vessel fouling (Johnson et al. 2009; Bollens et al. 2012; Stanford et al. 2023). Once introduced, natural spread via interconnected waterways or biotic transport (e.g., migratory bird fouling) is probable, along with human-induced spread via numerous activities. Studies have shown that predation by NIS accounts for a large portion of juvenile salmon declines (Tovey et al. 2008; Sanderson et al. 2009). For example, an estimated 250,000 to 2,000,000 salmon smolts are consumed annually by walleye (*Sander vitreus* Mitchill, 1818) in the Columbia River alone (Rieman et al. 1991; Tinus and Beamesderfer 1994), and stocked eastern brook trout have led to decreases in native bull trout (*Salvelinus confluentus* Suckley, 1859) and cutthroat trout (*Oncorhynchus clarkii* Richardson, 1836) populations by direct competition, hybridization, and displacement (Gunckel et al. 2002; Dunham et al. 2004; Peterson et al. 2004; Sanderson et al. 2009).

There are a number of NIS that pose either existing or potential threats to FEOW 120, especially to salmonids and their habitats. For example, zebra mussel (*Dreissena polymorpha* Pallas, 1771), a well-known invader that has spread across North America via recreational boats, reduces phytoplankton productivity leading to food-web impacts and population declines in zooplankton and fish, as well as causing harmful algal blooms (Higgins and Zanden 2010; Fera et al. 2017; Bahlai et al. 2021). Species like bass and pike have been introduced for angling but smallmouth bass are increasingly outcompeting native northern pikeminnow (*Ptychocheilus oregonensis* Richardson, 1836) due to their rapid maturity and high predation rates (Fritts and Pearsons 2006), whereas Northern pike (*Esox lucius* Linnaeus, 1758) are a concern since their invasion in Alaska quickly led to decreased salmon productivity (Sepulveda et al. 2013; Jalbert et al. 2021). American shad (*Alosa sapidissma* Wilson, 1811) are an increasing problem in the Columbia River as juvenile feeding decreases the availability of planktivorous prey for juvenile salmonids and act as prey that encourages the proliferation of salmon predators (Petersen et al. 2003; Haskell et al. 2006). Invasive plant species also can have significant impacts by altering salmonid habitat, demonstrated by species such as purple loosestrife (*Lythrum salicaria* Linnaeus), which can form dense stands leading to subsequent decomposition, potentially shifting the timing of nutrient availability and impacting organisms that rely on winter/spring food web peaks (Blossey et al. 2001). Similarly, Eurasian water milfoil (*Myriophyllum spicatum* Linnaeus) forms dense, decomposing mats which decrease dissolved oxygen, significantly impacting ecosystem structure and function (Unmuth et al. 2000; Cronin et al. 2006). Other aquatic macrophytes such as reed canary grass (*Phalaris arundinacea* Linnaeus) can alter flow and lead to increased sedimentation and overcrowding of native plant species, thereby reducing salmonid spawning habitats (Kettenring et al. 2019; Stevens 2020).

Impacts such as these are likely to be compounded when multiple NIS invade a system and are exacerbated by climate change. Understanding the impacts and processes associated with the invasion of NIS is necessary to inform management. Given the numerous pathways for introduction and the potentially high impacts that NIS could impart, prioritizing which species pose a greater risk to native species and ecosystems using approaches like invasive species Watch Lists (Wilcox et al. 2024) is necessary to support management that aids in maintaining the native biodiversity of the region, especially for iconic salmonid species.

Applying screening tools is one way to systematically identify higher risk species and prioritize current and potential NIS for the purpose of facilitating and improving management decisions. Rapidly screening a large number of species allows limited resources to be directed towards those NIS posing the greatest risk. Although screening tools vary in their specific formulations and questions, they are generally developed around factors related to invasion risk (Kumschick and Richardson 2013) and are typically either decision trees (Reichard and Hamilton 1997; Kolar and Lodge 2002; Caley and Kuhnert 2006) or scoring systems (Pheloung et al. 1999; Daehler et al. 2004; Copp et al. 2009, 2016; Drolet et al. 2016; Vilizzi et al. 2022, 2024). For most applications where ranking is important, such as creating a prioritized list of NIS for potential management intervention or policy development, semiquantitative scoring systems are frequently used. In a review of a number of screening tools, Srébalienė et al. (2019) showed that each varied in the degree to which they incorporated many of the expected components of risk, including elements related to invasion success and different types of impacts. Specifically, socioeconomic impacts were underrepresented in most tools and only about half (8 of 15) contained any considerations of how climate change might change the risk. Thus, assessors need to ensure any tool selected is fit-for-purpose and contains the appropriate components and criteria to characterize risk based on their stated objectives. Further, Roy et al. (2018) highlights the need to ensure minimum standards for risk assessments are met as many current tools were developed before this framework was established. By applying the concepts in this framework, it ensures decision makers have a better understanding of the strengths and weaknesses of an assessment, including such things as uncertainty. The integration of uncertainty directly into the scores of screening tools is rare (but see Hayes et al. 2005; Drolet et al. 2016), though it has proven useful to mangers to fully understand the potential risk of a species.

Given the limitations of existing tools in conjunction with the need to ensure minimum standards are met and the large number of potential NIS that could invade FEOW 120 belonging to different taxa, we felt there was a need to develop a new tool that incorporated all of these components. Thus, we developed the Non-Indigenous Species Screening Tool (NISST) to address these limitations with guided questions that are general enough to apply to different taxa, risk assessment areas, and objectives. Its modules have been developed around the invasion process and ecological and socioeconomic impacts, it can be applied quickly and consistently, and is easily modified if needed. Further, it allows assessors the ability to explicitly include climate change effects which is essential for areas like FEOW 120 facing the dual threats of NIS and climate change. The resulting risk scores, which incorporate the assessor's uncertainty via a novel Monte Carlo procedure, combined with information collected during assessments, can be used to inform management decisions. We evaluated NISST using a variety of species belonging to different taxa, invasion histories, and level of documented impacts for FEOW 120, an area chosen as representative of the Pacific Northwest, to demonstrate the utility of this new tool.

Methods

A New Screening Tool

The NISST is a conceptual expansion of the Canadian Marine Invasive Screening Tool (CMIST: Drolet et al. 2016) and includes considerations and criteria from other score-based screening tools such as the Aquatic Species Invasiveness Screening Kit (AS-ISK: Copp et al. 2016) and those used to rank Australian marine pests (Hayes et al. 2005). It consists of 26 questions organized into three modules: A – Invasion Potential; B – Ecological Impact; C – Socioeconomic Impact (Table 1; see below). This new tool addresses some operational limitations noted in previous applications of CMIST (see Drolet et al. 2017; Therriault et al. 2018; Brown and Therriault 2022) and reviews of other screening tools (Srébalienė et al. 2019) such as the inclusion of a socioeconomic assessment module, the option for specifically addressing how climate change could alter the risk score throughout, and the modification of scoring rubrics to facilitate more consistent, easier and quicker scoring by assessors. Related files such as scoring sheets, guidance, and code can be accessed online (https://github.com/MarkAlanWilcox/Non-Indigenous-Species-Screening-Tool-NISST).

Scoring and uncertainty

One of the more novel components of this new tool is the method by which questions are scored and uncertainty incorporated into the score. In NISST, uncertainty is incorporated similar to the CMIST approach (Drolet et al. 2016) using a Monte Carlo method. However, there are several key differences. First, in CMIST, assessors are asked to score each question on a 3-point scale and provide a confidence level, also on a 3-point scale. From the 9 possible combinations, 9 *a priori* distributions are used to adjust the overall scoring of questions. In NISST, assessors instead generate a question-specific probability distribution around the potential outcomes for each question that is indicative of the assessor’s confidence in their answers and more accurately describes the assessor’s true uncertainty than the *a priori* distributions used in CMIST (see example Supplementary material Table S1). The tighter the distribution around a specific outcome, the greater the assessor’s certainty in that outcome. In both tools, the uncertainty is typically related to the strength or availability of information from the literature and other sources. Second, Monte Carlo techniques used in CMIST simulate an entire assessment (1000 iterations) using the generic *a priori* distributions such that the final adjusted score represents the mean value of those simulations, while the uncertainty represents the 95% confidence interval for those simulations. However, NISST uses Monte Carlo techniques to calculate the score and characterize the uncertainty at the question level rather than at the assessment level. Simulations are conducted for each question, such that the score recorded for each question is derived as the

Table 1. The Non-indigenous Species Screening Tool (NISST) questions and descriptions of possible scores organized into the Invasion Potential module (A), Ecological Impact module (B), and Socioeconomic Impact module (C).

A: Invasion Potential module	**Scoring Rubric**				
A1: What is the likelihood of introduction or reintroduction in the area of interest?					
A1.1: What is the average annual entrainment potential from all potential vectors?	1: 10s individuals	2: 100s individuals	3: 1000s individuals	4: 10000s individuals	5: >100000 individuals
A1.2: How many vectors are available that could entrain this species into the area of interest?	0: < 3 potential vectors		1: ≥ 3 potential vectors		
A1.3: Do you expect the number of vectors or propagule pressure to change under a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase		
A1 score = Sum of A1.1 and A1.2 to a maximum of 5	**A1 Climate score = Sum of A1 score and A1.3 to a maximum of 5 and minimum of 1**				
A2: What is the dispersal potential within the area of interest?					
A2.1: What is the average or typical yearly dispersal range of spread through either natural or anthropogenic sources within the assessment area?	1: Unlikely to be dispersed	2: 100s of meters	3: 1–9 kms	4: 10s of kms	5: >100 km
A2.2: Do you expect the dispersal potential to change under a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase		
A2 score = A2.1	**A2 Climate score = Sum of A2 score and A2.2 to a maximum of 5 and minimum of 1**				
A3: What proportion of the assessment area is available for establishment by the species interest? Score this question as the minimum score of 3.1 and 3.2					
A3.1: How much of the assessment area offers suitable environmental conditions which are not outside the extreme tolerances of the species of interest?	1: < 10%	2: 10-< 25%	3: 25-< 50%	4: 50-< 75%	5: > 75%
A3.2: How much of the assessment area offers suitable habitat types?	1: < 10%	2: 10-< 25%	3: 25-< 50%	4: 50-< 75%	5: > 75%
A3.3: Do you expect the percentage of assessment area that offers suitable environmental conditions or habitat types to change under a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase		
A3 score = Minimum score for A3.1 and A3.2	**A3 Climate score = Sum of A3 score and A3.3 to a maximum of 5 and minimum of 1**				
A4: Does the species exhibit life history and developmental traits that facilitate invasion?					
A4.1: What is the per capita offspring the species can produce per year?	1: 1–10	2: 10–100	3: 100–1000	4: 1000–10000	5: >10000
A4.2: What is the developmental rate of the species? (Consider how long before asexual reproduction might occur)	0: If > 1 year		1: If ≤ 1 year		
A4.3: Do you expect the life history characteristics and developmental traits to change under a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase		
A4 score = Sum of A4.1 and A4.2 to a maximum of 5	**A4 Climate score = Sum of A4 score and A4.3 to a maximum of 5 and minimum of 1**				
Invasion Potential score = Average of A1, A2, A3, A4 scores	**Invasion Potential Climate modified score = Average of A1, A2, A3, A4 Climate scores**				

B: Ecological Impact module	**Scoring Rubric**		
B1: Evidence of population levels impacts to native species			
B1.1: Evidence the species could cause a considerable reduction in the size of any single population of a native species due to predation/herbivory/parasitism	1: Low to no impact	2: Moderate impacts	3: High impacts
B1.2: Evidence the species could cause a considerable reduction in the size of any single population of a native species due to competition	1: Low to no impact	2: Moderate impacts	3: High impacts
B1.3: Evidence the species is known to carry diseases or parasites that could infect a native species (either is known to already infect the species in a different region, or a species that is taxonomically similar)	1: Low to no impact	2: Moderate impacts	3: High impacts
B1.4: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
B1 score = Sum of B1.1, B1.2, and B1.3	**B1 Climate score = Sum of B1 score and B1.4 to a maximum of 9 and a minimum of 3**		
B2: Evidence of community level impacts to native species			
B2.1: Evidence the species could cause a considerable reduction in the population size of more than one native species	1: Low to no impact	2: Moderate impacts	3: High impacts
B2.2: Evidence the species could cause considerable impacts to multiple functional groups	1: Low to no impact	2: Moderate impacts	3: High impacts
B2.3: Evidence the species could cause a considerable decrease in productivity of native communities	1: Low to no impact	2: Moderate impacts	3: High impacts
B2.4: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
B2 score = Sum of B2.1, B2.2, and B2.3 scores	**B2 Climate score = Sum of B2 score and B2.4 to a maximum of 9 and a minimum of 3**		
B3: Evidence of ecosystem level impacts			
B3.1: Evidence the species could cause a considerable change in the availability of nutrients and essential elements (e.g., N, O, P, S, etc.)	1: Low to no impact	2: Moderate impacts	3: High impacts
B3.2: Evidence the species could damage, degrade, or modify the physical (abiotic) environment	1: Low to no impact	2: Moderate impacts	3: High impacts

Table 1. (continued).

B3.3: Evidence that species could cause impacts to species that create biogenic habitat	1: Low to no impact	2: Moderate impacts	3: High impacts
B3.4: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
B3 score = Sum of B3.1, B3.2, and B3.3 scores	**B3 Climate score = Sum of B3 score and B3.4 to a maximum of 9 and a minimum of 3**		
B4: Evidence of impacts to conservation units			
B4.1: Evidence the species could represent a threat to species of high conservation value (consider most impacted)	1: Low to no impact	2: Moderate impacts	3: High impacts
B4.2: Evidence the species could represent a threat to areas of high conservation value	1: Low to no impact	2: Moderate impacts	3: High impacts
B4.3: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
B4 score = Sum of B4.1 and B4.2 scores	**B4 Climate score = Sum of B4 score and B4.3 to a maximum of 6 and minimum of 2**		
Ecological Impact score = Sum of B1, B2, B3, and B4 scores divided 11 (the number of non-climate sub-questions)	**Ecological Impact Climate score = Sum of B1, B2, B3, and B4 Climate scores divided 11 (the number of non-climate sub-questions)**		
C: Socioeconomic Impact module	**Scoring Rubric**		
C1: Evidence of economic costs			
C1.1: Evidence the species could cause increased economic costs to industry	1: Low to no impact	2: Moderate impacts	3: High impacts
C1.2: Evidence the species could cause increased economic costs to individuals	1: Low to no impact	2: Moderate impacts	3: High impacts
C1.3: Evidence the species could cause increased economic costs to government	1: Low to no impact	2: Moderate impacts	3: High impacts
C1.4: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
C1 score = Sum of C1.1, C1.2, and C1.3 scores	**C1 Climate score = Sum of C1 score and C1.4 to a maximum of 9 and minimum of 3**		
C2: Human Health			
C2.1: Evidence the species could cause impacts to physical human health	1: Low to no impacts to health	2: Moderate impacts to human health	3: Severe or lethal impacts
C2.2: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
C2 score = C2.1 score	**C2 Climate score = Sum of C2 score and C2.2 to a maximum of 3 and minimum of 1**		
C3: Evidence of impacts to available natural resources			
C3.1: Evidence the species could impact accessibility of food and drinking water resources	1: Low to no impact	2: Moderate impacts	3: High impacts
C3.2: Evidence that the species could impact accessibility of non-food resources (e.g., wood, medicines, ornamental species, etc.)	1: Low to no impact	2: Moderate impacts	3: High impacts
C3.3: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
C3 score = Sum of C3.1 and C3.2 scores	**C3 Climate score = Sum of C3 score and C3.3 to a maximum of 6 and minimum of 2**		
C4: Impacts to species or areas of cultural or social importance			
C4.1: Evidence the species could impact a species of cultural or social importance	1: Low to no impact	2: Moderate impacts	3: High impacts
C4.2: Evidence the species could impact an area of culture or social importance	1: Low to no impact	2: Moderate impacts	3: High impacts
C4.3: Do you expect the magnitude of impacts to differ in a future climate?	-1: Decrease	0: Remain at similar levels	1: Increase
C4 score = Sum of C4.1 and C4.2 scores	**C4 Climate score = Sum of C4 score and C4.3 to a maximum of 6 and minimum of 2**		
Socioeconomic Impact module score = Sum of C1, C2, C3, C4 scores divided by 8 (the number of non-climate sub-questions)	**Socioeconomic Impact Climate score = Sum of C1, C2, C3, C4 Climate scores divided by 8 (the number of non-climate sub-questions)**		
Total Risk Score = Invasion Potential score * (Ecological Impact score + Socioeconomic Impact score)	**Total Climate score = Invasion Potential Climate score * (Ecological Impact Climate score + Socioeconomic Impact Climate score)**		

mean score of the simulated outcomes (based on 1000 iterations from the assessor generated probability distribution) and the confidence interval represents the standard deviation of the simulated outcomes. The error can then be propagated through the assessment to provide uncertainty for both individual modules and the final risk scores.

Module structure

The Invasion Potential module (A) has been designed around the introduction and establishment phases in the invasion process. It uses information on propagule pressure to characterize the likelihood of introduction (question A1), dispersal potential (question A2), environmental and habitat suitability (question A3), and life history and developmental traits that may facilitate invasion success (question A4). Based on challenges identified in past screenings, the scoring rubrics for questions within this module were expanded to a five-point scale with discrete bounds (generally orders of magnitude) based on quantifiable values that can be extracted or estimated from the primary literature. Questions pertaining to available area are scored using percentage bounds while questions pertaining to distance or numbers of individuals are scored using a logarithmic scale for each bin. In question A1, to account for species whose propagule pressure (scored through sub-question A1.1) is the result of multiple vectors, which may pose an increased risk of introduction, an additional modifier (sub-question A1.2) is applied to the score derived from the Monte Carlo procedure up to the maximum question score (5). Similarly for question A4, to account for species that can either reproduce asexually or reach sexual maturity within a year which may facilitate rapid establishment, an additional modifier (sub-question A4.2) was applied to the score derived from the Monte Carlo procedure, also up to the maximum question score (5). For question A3, the suitable habitat is determined through areas that meet environmental tolerances of the species (sub-question A3.1) and contain suitable habitat types (sub-question A3.2). The final scoring for question A3 represents the lowest of the two scores (following the Monte Carlo procedure) given that the species must have both suitable habitat types and have environmental parameters within the species tolerances in order to invade (i.e., one of the two metrics will be limiting). The module score for Invasion Potential is then calculated as the average of questions A1 through A4 for an overall score between 1 and 5 and the associated error for the module was calculated from individual question errors generated via the Monte Carlo procedure using propagation of error rules.

Recognizing that impacts differ between ecological and socioeconomic endpoints, NISST scores impacts in two separate modules with similar structure and scoring. Questions are scored using a three-point scale that rates the impacts as low (1: negligible to low impacts), moderate (2), and high (3: severe and possibly irreversible impacts) for each type of impact. In general, higher risk species will have more impacts. The Ecological Impact module (B) asks questions pertaining to impacts expected at the population level (sub-questions B1.1–B1.3; predation, competition, disease and parasitism), the community level (sub-questions B2.1–B2.3; impacts to multiple species, functional groups, or impacts to productivity), and the ecosystem level (sub-questions B3.1–B3.3; nutrients, modification of abiotic environment, impacts to biogenic habitat), as well as impacts to threatened species and areas (sub-questions B4.1 and B4.2). The Socioeconomic Impact module (C) asks questions regarding economic impacts to industries, individuals, and governments (sub-questions C1.1–C1.3), human health impacts (sub-question C2.1), accessibility to natural resources (sub-questions C3.1 and C3.2), and impacts to socially or culturally important species and areas (sub-questions C4.1 and C4.2). Each module score is calculated as the average score across all sub-questions within that module, resulting in a score between 1 and 3 per module. The associated error for the module is calculated from individual question errors generated via the Monte Carlo procedure using propagation of error rules.

Module scores and errors were then averaged for each species across all assessors, using propagation of error rules for the latter. A total risk score was calculated as the product of the Invasion Potential score and the sum of the two impact module scores as risk is generally related to the probability of an event occurring (here, an invasion) multiplied by the consequences of that event (here, impacts due to an invasion) and the product results in higher risk scores for species which score higher for both invasion and impacts. Biplots depicting invasion module scores plotted against different impact scores were used to visualize the contribution of each component of risk, along with the associated error metric. The Monte Carlo simulations were conducted in R using the *sample()* function in the base package (R Core Team 2021) to obtain question scores and uncertainty. Module and final scores as well as all outputs were produced in R.

Climate change

Assessors also have the option to include climate change effects using an additional climate modifier sub-question within each question for each module (16 questions). Factors such as breeding seasons, growth rates, survival, and settlement rates of invading species are often highly dependent on environmental factors such as temperature, salinity, or physical factors such as suitable substrate availability, all of which are expected to shift based on future climate projections that may facilitate or inhibit invasions and their impacts. To account for these potential changes in the tool, the assessor indicates whether the scoring of any sub-questions would likely decrease (−1), remain the same (0), or increase (1) due to factors associated with climate change (Table 1). The climate modified question scores are then calculated by adding the climate modifier score to the total question score generated from the Monte Carlo procedure after other modifiers have been applied. However, the final value cannot exceed the maximum or minimum question score (e.g., if the maximum score across four sub-questions was 9, then the climate modifier could not exceed 9). Climate module scores and final climate scores are then calculated the same way the non-climate modified scores are calculated. Outputs for climate modified scores can be represented graphically as vector plots showing the change in scores compared to non-climate modified scores.

Study region, species selection and data collection

The FEOW is a global biogeographical classification system that uses multiple variables to identify distinct assemblages of fish distributions largely contained within watershed regions (Abell et al. 2008). The Columbia Glaciated FEOW 120 contains the headwaters of the Columbia River basin and a large network of connected waterways. It is a naturally diverse area encompassing many of British Columbia's 14 biogeoclimatic zones (McPhail and Lindsey 1986) with a variety of aquatic habitats and human land use. Thus, it is representative of the Pacific Northwest and serves as an indicator for the range of different environments in this region susceptible to invasion and contains both ecologically and culturally significant areas making it a good choice to evaluate NISST. Sockeye salmon (*Oncorhynchus nerka* Walbaum, 1792), chinook salmon (*O. tshawytscha* Walbaum, 1792), cutthroat trout, and rainbow trout inhabit many of the rivers, streams and lakes in this ecoregion (McPhail and Lindsey 1986) and many of these populations are at-risk (COSEWIC 2023), therefore identifying NIS that could impact these species is critical.

For this analysis, current and potential invasive species for FEOW 120 were identified from multiple sources including various invasive species watch lists such as the current list of priority invasive species in British Columbia (BC Inter-Ministry Invasive Species Working Group 2023) and the United States Department of Agriculture invasive species lists from the Pacific Northwest region (Alaska, Washington, Oregon, and California) (National Invasive Species Information Center). From these, a subset of species (33 in total; see Table 2) was chosen to test the robustness of the tool. These species represent a variety of taxonomic groups (e.g., plants, invertebrates, fish), possible invasion vectors, invasion status within the ecoregion (i.e., currently present, not yet present). Although we believed this subset represented different levels of risk among species, an additional 11 species which were expected to have poor habitat match and lower impacts were added to determine if the tool is capable of distinguishing species unlikely to invade or to have negligible impacts (i.e., lower risk ones). All information for both the risk assessment area and species to be assessed was gathered into a common database for standardization and transparency and included sources from the primary literature, reference texts, online databases, and other grey literature such as news articles. Information for each species was entered into a single datasheet which was then referred to by each assessor when completing the assessments. This documentation provided material used in the justification for scoring, allowing for easier interpretation of the results and comparison among

Table 2. List of non-indigenous aquatic species screened using the Non-indigenous Species Screening Tool for the Columbia Glaciated Freshwater Ecoregion (FEOW 120).

Scientific name	Common name	Vectors of introduction	Presence/ Absence
Ambloplites rupestris Rafinesque, 1817	Rock bass	Intentional, bait	Present
Ameiurus nebulosus Lesueur, 1819	Brown bullhead	Intentional stocking, natural spread via water	Present
Bythotrephes cederstroemi Schoedler, 1877	Spiny waterflea	Boating and angling contamination, biotic (fish/birds)	Absent
Cabomba caroliniana A. Gray, 1837	Cabomba fanwort	Aquarium, boating, biotic (birds/animals)	Absent
Carassius auratus Linnaeus, 1758	Goldfish	Aquarium trade, bait, natural spread via water	Present
Carassius gibelio Bloch, 1782	Prussian carp	Aquarium trade, natural spread via water	Absent
Cipangopaludina chinensis J.E. Gray, 1833	Chinese mystery snail	Aquarium trade, boating	Absent
Corbicula fluminea O.F. Müller, 1774	Asian clam	Bait, aquarium trade, fish stocking, ballast, biotic	Present
Crossocheilus oblongus Kuhl & van Hasselt, 1823	Siamese algae eaters	Aquarium	Absent
Cyprinus carpio Linnaeus, 1758	Common carp	Aquaculture escape, aquarium/pet release/escape	Present
Dreissena rostriformis bugensis Andrusov, 1897	Quagga mussel	Boat fouling, biotic (macrophytes, birds), aquarium	Absent
Egeria densa Planch.	Brazilian elodea	Aquarium, boating, biotic (birds)	Absent
Esox lucius Linnaeus, 1758	Northern Pike	Intentional introduction, natural spread via water	Present
Gambusia affinis Baird & Girard, 1853	Western mosquitofish	Aquarium, intentional stocking (bio control agent)	Absent
Hippopotamus amphibius Linnaeus, 1758	Hippopotomus	Intentional release, natural spread via waterways	Absent
Hydrocharis morsus-ranae Linnaeus	Common frogbit	Ornamental, biotic (birds), boating	Absent
Hypostomus Plecostomus Linnaeus, 1758	Pleco	Aquarium	Absent
Lepomis gibbosus Linnaeus, 1758	Pumpkinseed Sunfish	Intentional, bait, water	Absent
Lithobates catesbeianus Shaw, 1802	American bullfrog	Intentional introduction, bait, aquarium/pet release	Present
Lythrum salicaria Linnaeus	Purple loosestrife	Ornamental, ballast, water, biotic, soil, equipment	Present
Micropterus salmoides Lacepède, 1802	Large-mouth bass	Intentional, water	Present
Microsorum pteropus Blume & Fraser-Jenk	Java fern	Aquarium	Absent
Misgurnus anguillicaudatus Cantor, 1842	Oriental weatherfish	Bait, aquarium trade	Absent
Myriophyllum spicatum Linnaeus	Eurasian water milfoil	Aquarium trade, boating	Present
Mysis relicta Lovén, 1862	Mysis shrimp	Intentional	Present
Nasturtium officinale W.T. Aiton	Common watercress	Aquarium, biotic, natural spread via water	Present
Neocaridina davidi Bouvier, 1904	Cherry shrimp	Aquarium	Present
Osphronemus goramy Lacépède, 1801	Giant gourami	Aquarium, intentional stocking as food item	Absent
Paracheirodon innesi G.S. Myersm, 1936	Neon tetra	Aquarium	Absent
Phalaris arundinacea Linnaeus	Reed canary grass	Ornamental, intentional, natural spread, biofouling	Present
Pistia stratiotes Linnaeus	Water lettuce	Aquaculture and ornamental, natural spread	Absent
Phragmites australis australis (Cav.) Trin. Ex	European common reed	Seeds (wind, contaminant in mud on machinery)	Present
Pontederia crassipes (Mart.) Solms	Water hyacinth	Ornamental, natural spread via water, biotic (birds)	Absent
Procambarus virginalis Lyko, 2017	Marbled crayfish	Aquarium, biotic	Absent
Pomacea maculata Perry, 1810	Apple snail	Aquarium	Absent
Potamogeton crispus Linnaeus	Curled pondweed	Contaminated soil or equipment, wind	Present
Puntius titteya Deraniyagala, 1929	Cherry barb	Aquarium	Absent
Sewellia lineolata Valenciennes, 1846	Hillstream loach	Aquarium	Absent
Stratiotes aloides Linnaeus	Water soldier	Ornamental, aquarium	Absent
Tanichthys albonubes Linnaeus, 1932	White-cloud mountain minnow	Aquarium	Absent
Tinca tinca Linnaeus, 1758	Tench	Ornamental, intentional, bait	Present
Trachemys scripta elegans Seidel, 2002	Red-eared slider turtle	Aquarium/pet release/escape	Present
Tylomelania sp. Sarasin & Sarasin, 1897	Rabbit snails	Aquarium	Absent
Xenopus laevis Daudin, 1802	African clawed frog	Aquarium, natural spread via water	Absent

assessments. Analyses of inter-assessor scores were conducted for total scores and by question for each module through visual inspection of biplots and correlation coefficients derived from Pearson's moment correlation analysis.

Results

Comparisons of question scores by species between each of the four assessors exhibited general agreement within each of the three modules

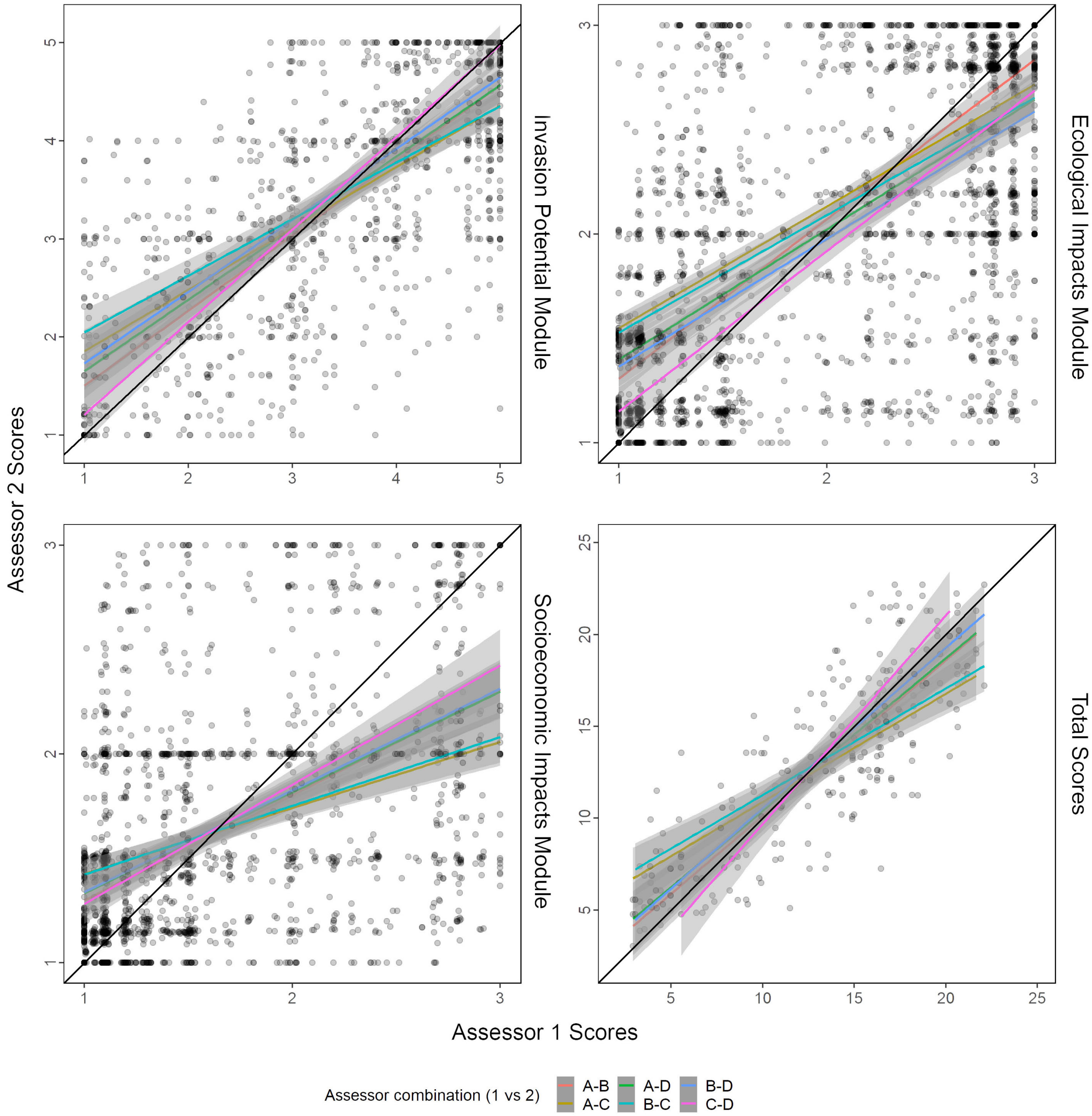

Figure 2. Inter-assessor variability in question scores for non-indigenous aquatic species across each of the three NISST modules and for total assessment scores of each species. For module comparisons, each point represents the evaluation of one question for one species by two assessors. Each line represents the correlation between combinations of the four independent assessors. Bounds represent the 95% confidence interval for the correlation.

(Figure 2). Correlation coefficients of inter-assessor comparisons were significant for all comparisons and greatest for questions within the Invasion Potential module (between 0.621 and 0.780) and Ecological Impact module (between 0.617 and 0.762). Slightly greater variation between assessor scores were exhibited for the Socioeconomic Impact module (correlation coefficient between 0.402 and 0.534). Comparisons of total scores between assessors showed high agreement with correlation coefficients ranging from 0.811 to 0.875.

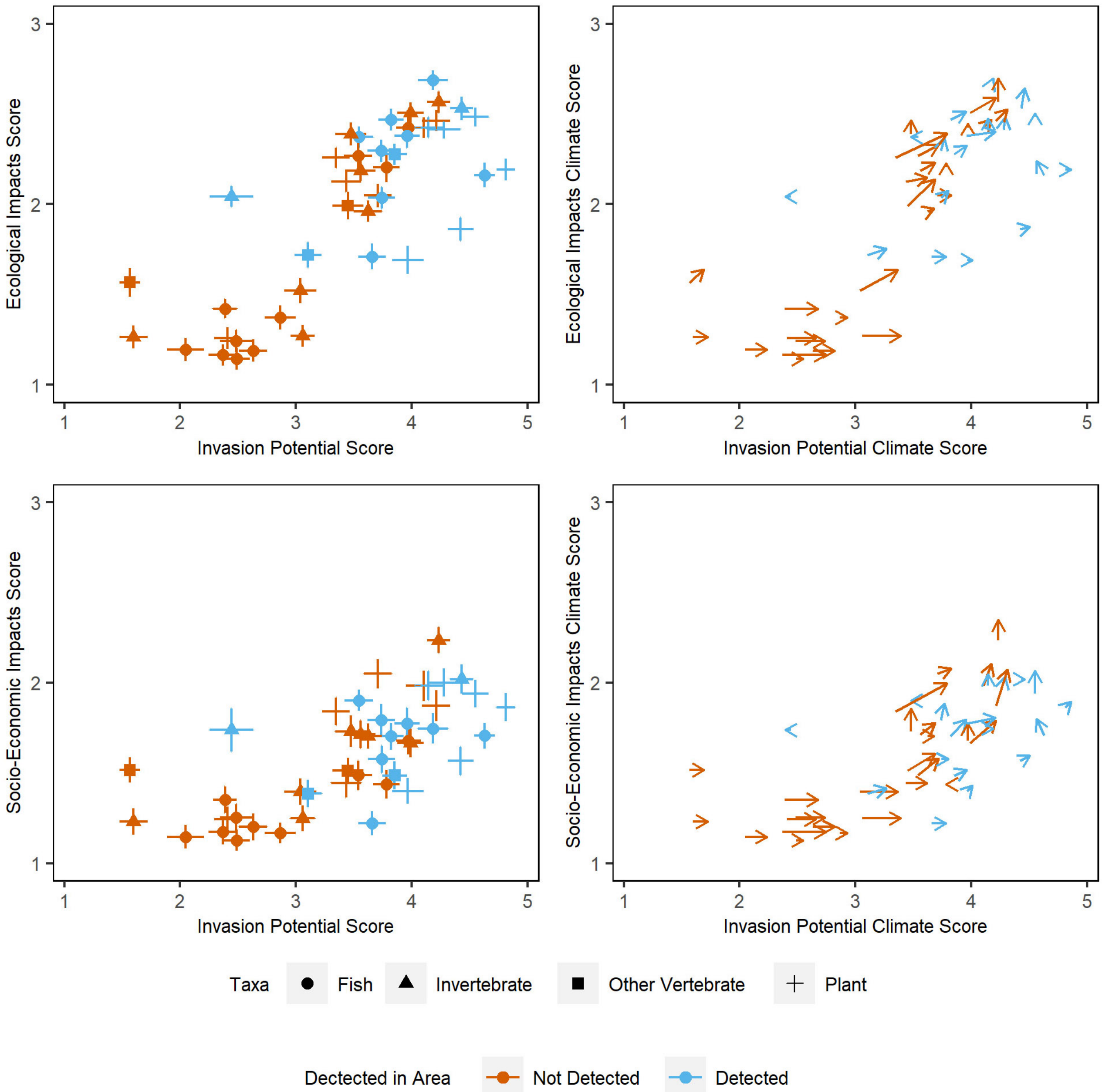

Figure 3. Biplots showing impact (ecological in the top panel and socioeconomic in the bottom panel) plotted against invasion potential for each species screened using NISST categorized by taxonomic groups (Left). Error bars represent the propagated error based on standard deviations from the Monte Carlo simulations. Vector plots showing the change in scores when using the climate modifier questions, where the base of the arrow depicts the unmodified score and the tip of the arrow depicts the climate modified score (Right). The length of the line depicts magnitude and the direction indicates the relative contributions of impacts and invasion potential to the modified scores.

The range of scores obtained for species that were presently introduced to the area and those that are not yet known from the area were comparable across modules (Figure 3) and total risk scores (Figure 4). Scores for the Invasion Potential and Socioeconomic Impact modules were on average higher for species that are currently introduced compared to those that have yet to invade, while scores for the Ecological Impact module were similar between these two groups (Figure 3). Ranges of scores across taxa were also similar across modules. Scores for other vertebrates were typically lower than the other assessed species, while plants on average

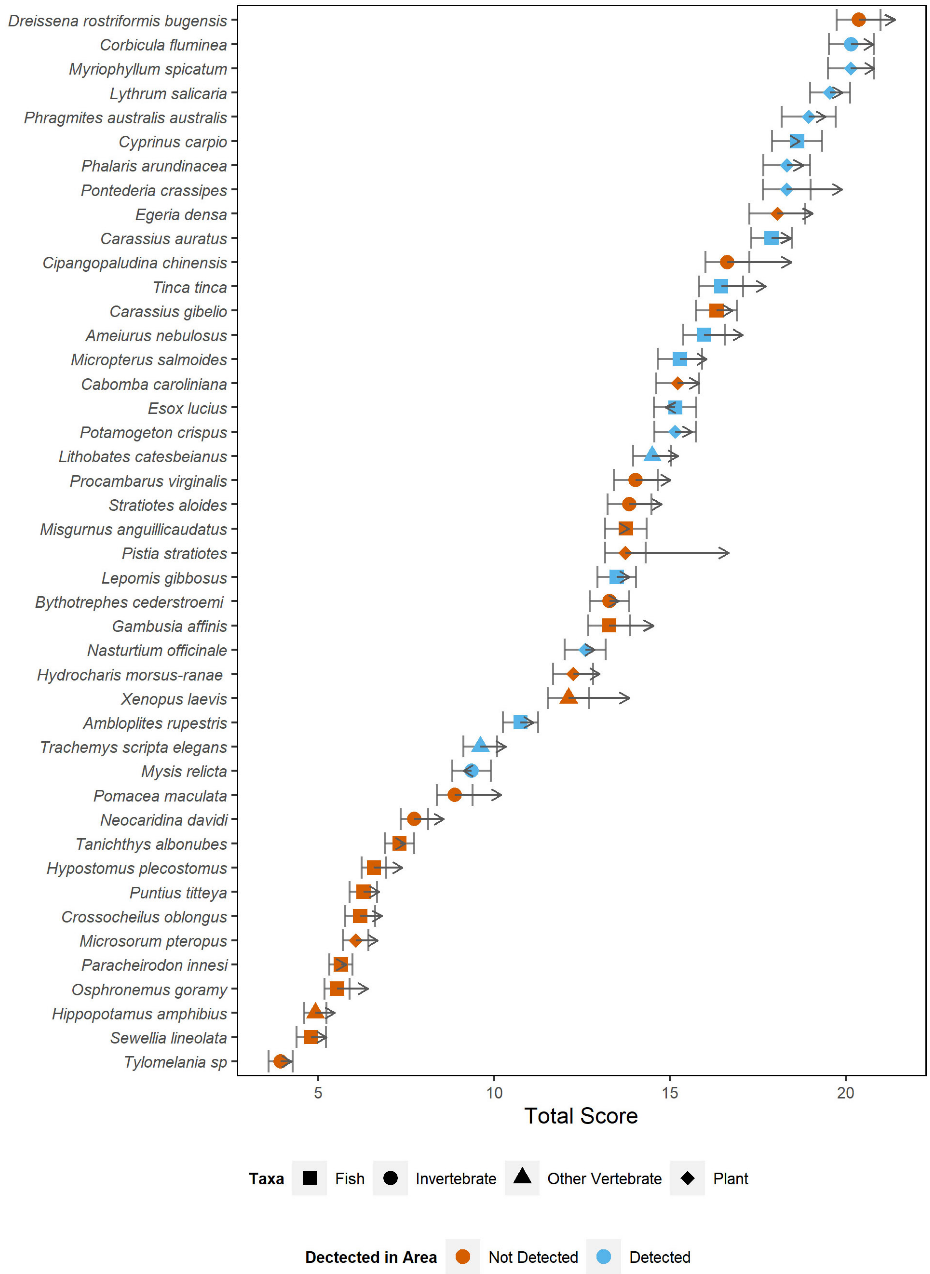

Figure 4. Ranked NISST scores for non-indigenous aquatic species for the Columbia Glaciated Freshwater Ecoregion (120). Error bars represent propagated error based on standard deviations from the Monte Carlo simulation. Arrows depict the climate modified scores.

scored higher than other taxonomic groups (6 of the top 10 species for total risk score). The inclusion of climate change to the scores for each module typically increased the score (Figures 3 and 4) although the magnitude varied by species. For some species such as water hyacinth (*Pontederia crassipes* (Mart.) Solms), African clawed frog (*Xenopus laevis* Daudin, 1802) and water lettuce (*Pistia stratiotes* Linnaeus), the climate-related modifiers were sufficient to result in considerable increases in the ranking of their scores. However, the climate-related modifier resulted in a decreased Invasion Potential module score (and thus total risk score) in species such as Northern pike and mysis shrimp (*Mysis relicta* Lovén, 1862).

When comparing total risk scores (Figure 4), quagga mussel (*Dreissena rostriformis bugensis* Andrusov, 1897) and Asian clam (*Corbicula fluminea* O.F. Müller, 1774) were identified as the highest risk species. Plant species such as Eurasian water milfoil, purple loosestrife, European common reed (*Phragmites australis australis* (Cav.) Trin. Ex), reed canary grass, water hyacinth, and Brazilian elodea (*Egeria densa* Planch.) were identified as some of the highest risk species to FEOW 120. Fish species such as common carp and goldfish (*Carassius auratus* Linnaeus, 1758) were ranked high for this area as well. Aquarium species added in the additional 11 lower risk species, such as tiger hillstream loach (*Sewellia lineolata* Valenciennes, 1846), rabbit snail (*Tylomelania* sp. Sarasin & Sarasin, 1897), and neon tetra (*Paracheirodon innesi* G.S. Myersm, 1936) ranked among the lowest of the species assessed owing to a combination of limited propagule pressure, poor habitat suitability and no documented impacts.

Discussion

The new tool developed here (NISST) addresses several of the common gaps previously identified with respect to screening tools and the challenges with implementing them (Drolet et al. 2017; Therriault et al. 2018; Srébalienė et al. 2019) and has been developed to be consistent with standards set within the framework by Roy et al. (2018). More specifically, few existing tools explicitly incorporate criteria addressing socioeconomic impacts despite the recognition that many funding decisions are related to those species having significant economic impacts. Where other tools may have considered specific impacts, such as CMIST which assessed impacts to aquaculture and commercially fished species (Drolet et al. 2016), or impacts more generally such as the level of socioeconomic impacts as a whole (Pergl et al. 2016), the Socioeconomic Impact module developed here provides a reasonably comprehensive characterization of these impacts, addressing a breadth of criteria related to human activities and interactions with the environment. The effects of climate change are also infrequently incorporated into screening level assessments (Srébalienė et al. 2019) but again, this is changing with a growing recognition that climate change is affecting the risk of both current and potential invaders (see Copp et al. 2016 for AS-ISK; also, Vilizzi et al. 2022, 2024). Through assessing how impacts or factors influencing the invasion process are likely to change with a changing climate, we provide a semiquantitative method that integrates climate change considerations directly into the score rather than providing an independent measure of climate change effects and, when visualized using a vector plot (Figure 3), it makes it clear to managers how risk is expected to change.

In general, there was good agreement in scores between assessors by question, however, the degree of agreement varied by module. The assessors scored most similarly across questions in the Invasion Potential and Ecological

Impacts modules whereas the assessors showed greater variability in the Socioeconomic Impact module. Naturally, differences in assessor experiences and biases that may not be captured in the data gathered will contribute to deviations in scores between assessors. For the Socioeconomic Impact module disparity in agreement is likely compounded by the sparsity of documented impacts of this type in the primary literature and the experiences of the assessors with respect to evaluating the magnitude of socioeconomic impacts. For both impact modules, thorough evaluations of ecological and socioeconomic impacts published in the primary literature are key to correctly characterize risk and improving future assessments requires considerable efforts to characterize these for a much broader suite of species and endpoints than are currently available. Also, the Socioeconomic Impact module may be more easily and precisely scored by separate assessors with greater experience in this field (i.e., limitations on readily available information are such that assessor experience becomes more important), although it could induce a different source of inter-assessor variability. Although agreement was significant among assessors, it may be prudent to score all modules using multiple assessors, especially when information may be lacking (i.e., specific impact endpoints). Regardless, this new tool appears to be fairly robust, with the inter-assessor scores for the entire assessment in good agreement among the four assessors with a similar (or slightly higher) range of correlation coefficients to those observed for total scores of CMIST and MI-ISK (Marine Invertebrate Invasiveness Screening Kit: Copp 2013) across multiple ecoregions using two assessors (Drolet et al. 2016).

Using the Monte Carlo procedure-generated scores based on the assessor probability distributions, rather than using discrete bounds, clearly provides assessors additional flexibility when screening species. Given much of the documented data on invasive species in the literature are often context-dependent it is essential that assessors have this flexibility. In order to screen specific species, assessors often have to extrapolate information to the area of interest based on documented impacts elsewhere or traits and tolerances of the species derived from either its native or invaded range which may not be similar or have differing levels of resolution. For example, would the potential impact to rice farms in Madagascar by marbled crayfish (Jones et al. 2009) yield similar magnitudes of impacts to emergent lake vegetation in FEOW 120? In other cases, there may be insufficient or a complete lack of documented impacts leading assessors to infer impacts based solely on the biology of the species within its natural habitat, such as for the white cloud mountain minnow, which has no documented impacts given that it is currently not known to be invasive anywhere. Using the Monte Carlo procedure, assessors can now score questions on a more continuous scale to better reflect the assessors perceived level of risk. In addition, the modification of the scoring rubric itself, especially in the

Invasion Potential module where differences in scores are on orders of magnitude, reduces the ambiguity faced by assessors. An added benefit is that this has increased the speed of assessments using NISST, typically taking less than a couple of hours to complete an assessment once data have been gathered, rather than several days.

When generating prioritized lists of invasive species using screening tools, conveying the uncertainty around the assessor's scores assists end users in interpreting the level of risk. Most tools do not explicitly consider uncertainty within the scoring, instead providing an independent score (e.g., EPPO 2011; Gallardo et al. 2016) or level of confidence in sections of or the entire assessment (e.g., Pheloung et al. 1999; Booy et al. 2017; Copp et al. 2016; Vilizzi et al. 2022, 2024). Integrating the uncertainty explicitly within the score can provide a quick visualization of where the assessor would likely score the species relative to others. Much like CMIST, NISST directly provides an estimate of error based on Monte Carlo simulations. However, that error is calculated for each question based on the assessor generated distribution of question-specific scores and then propagated to produce an error estimate for the module and total risk scores (rather than a 95% confidence interval for the simulated total scores). By having assessors explicitly create their probability distributions, rather than using *a priori* distributions, allows the Monte Carlo simulations to be more reflective of the assessors' actual uncertainty and thus will provide scores that more accurately convey the risk. While determining actual thresholds for risk levels lies with the risk tolerance of managers, providing a structured measure of uncertainty around each species screened should facilitate a better understanding of risk and allow managers to more clearly categorize or rank species.

The arrangement of questions within NISST into modules also improves the flexibility that users have to adapt the tool to ensure it is fit-for-purpose. When using all three modules, ecological and socioeconomic impacts are equally weighted when generating the total impact score. However, these weightings could easily be modified if there was a desire (and justification) for increasing the contribution of one module over another (e.g., an impact assessment where only specific types of impacts are considered). Further, the modules themselves can be used separately if, for example, one was only interested in characterizing the invasion potential of a species and wasn't interested in its impacts. Within the impact modules, assessors may consider modifying questions, potentially focusing on specific impacts of interest (certain species or habitats). The equal weighting of each question in the impact modules also makes it easier to remove any questions pertaining to impacts that are deemed out of scope for the assessment. However, it should be noted that if either the questions or their weighting change it is the responsibility of the assessor to document these and convey them to the manager as was done by Brown and Therriault (2022) when they modified CMIST to assess crayfish invaders in Canada.

When we applied the climate change modifier within NISST, the module and total scores generally increased over the unmodified or current condition scores. This was not overly surprising given that the species assessed here for FEOW 120 are typically from ecoregions with similar or warmer climates to the south such that the warming climate projected for this area is likely to improve environmental suitability and facilitate larger populations that could lead to increased impacts. The magnitude of change in the scores varied by species and module, particularly the Invasion Potential module which exhibited greater average increases in score due to climate change than the Ecological or Socioeconomic Impact modules. Again, this is not surprising given that climate change is most likely having an effect on the physical and biological limitations of the invasion potential of these species while it is less likely that impacts will be on entirely new ecological or socioeconomic endpoints.

For species screened here, on average, plants tended to score higher than other taxa (6 of the top 10; Figure 4). This may be due to inherent biological features of plants that naturally lend themselves to scoring higher based on the screening criteria, such as a high degree of adaptational plasticity (Riis et al. 2010) that could lead to greater ecological impacts across all questions. In contrast, most fish, plants, and invertebrates associated with the aquarium trade such as white cloud mountain minnow and rabbit snails tended to score quite low. This was not surprising in that most were included to more rigorously evaluate the tool rather than a preconceived notion that they were potentially higher risk invaders for FEOW 120. Although we did not screen species with absolutely no possible invasion vector or climate match, NISST was able to successfully separate the lower risk aquarium species from others with varying degrees of invasion potential and impacts.

Among the highest risk species were several filter-feeding bivalves, plant species, and several generalist fish species. Filter feeding invertebrates such as Asian clam and quagga mussel, which scored highest (Figure 4), are well known to impact energy flow throughout invaded systems, causing numerous impacts to multiple trophic levels, including competition with native filter feeders, many of which are species of conservation concern (Schloesser et al. 1998) such as the Rocky Mountain ridged mussel (*Gonidea angulate* Lea, 1838) or shortface lanx (*Fisherola nuttallii* Haldeman, 1841) (COSEWIC 2023). Asian clam, for instance, are known to cause large ecosystem-wide impacts including to populations of other freshwater bivalves through competition for food and displacement of habitat via burrowing and bioturbation activities and ingestion of bivalve gametes and larvae when in dense populations (Araujo et al. 1993; Sousa et al. 2008). Eurasian water milfoil, which was the highest-ranking plant, is a prolific and impactful species well-known for rapidly invading disturbed areas and forming dense canopies through fragmentation. Within invaded areas, plants can shade and impact other submerged species (Madsen et al. 1991), alter the hydrology of waterbodies (Bates et al. 1985), form dense decomposing mats which decrease dissolved oxygen (Cronin et al. 2006; Unmuth et al. 2000), impede fish (including salmonid) movement (COSEWIC 2003), and have socioeconomic impacts for industrial activities (e.g., water intakes, commercial fishing, real estate devaluation, etc.), recreational boating, and swimming (Eiswerth et al. 2000). Purple loosestrife, the second highest ranking plant species, similarly has high ecological impacts, such as the formation of dense mats leading to subsequent decomposition, which potentially shifts the seasonality of nutrient availability, impacting fish who rely on winter/spring food web peaks (Blossey et al. 2001). Among the highest-ranking fish species, common carp and goldfish are known to be environmental generalists, able to survive in a wide range of habitats. Goldfish in particular are also widely available in the aquarium trade and thus their potential (illegal) release is an ongoing concern (Chan et al. 2019). Their ability to consume plant and animals, including eggs, makes them a potential threat to most aquatic organisms at some life stage, and their feeding activities can cause increased turbidity and disruption of aquatic plants, modifying the habitat resulting in both ecological and socioeconomic impacts (Deacon et al. 1964; Moyle 1976; Richardson et al. 1995).

On the opposite end of the spectrum, lower risk species typically either had low impacts or lower potential for invasion (or both). For example, Mysis shrimp scored relatively low for invasion potential which can be, at least partially, attributed to their low dispersal potential, restricted habitat requirements of deeper, cool lakes, and low introduction potential given the limited, historical targeted introduction of the species was initially to improve food sources for salmon. This species did score moderately for ecological impacts, which was not surprising given that they have been found to negatively impact salmonid populations within localized areas of FEOW 120 where they were intentionally introduced (Walters 1995). Aquarium species such as white cloud mountain minnow, tiger hillstream loach, and rabbit snail were scored low by assessors for both impacts and invasion potential. In the case of white cloud mountain minnow, the invasion potential is limited in FEOW 120 due in part to low propagule pressure as this species is restricted in British Columbia, despite being a common aquarium fish in neighboring jurisdictions. Information on environmental tolerances, reproduction, and even potential movement must all be interpreted from data derived from the aquarium industry given that natural populations are relatively unknown in this species. As with many aquarium species, there is little documented evidence that the species we screened here are known to be invasive elsewhere and as such there is a lack of publications on their impacts (although some aquarium species like goldfish have had significant impacts that are well documented). Thus, based on their biology and in the absence of information to the contrary, assessors typically scored these species lower for most impacts, but uncertainty was slightly higher relative to other species assessed here.

Conclusion

The Non-Indigenous Species Screening Tool is a highly flexible and robust tool for prioritizing invasive species. The results presented here for FEOW 120 suggest that it is not taxa dependent, and while these tests were restricted to freshwater systems, the questions contained within are not specific to these ecosystems. The tool reflects the many stages of invasion and the suite of potential impacts across both ecological and socioeconomic endpoints. The new functionality that allows the assessor to score their own probability distributions per question, will provide more accurate depictions of risk and uncertainty and the Monte Carlo simulation will allow managers to more easily understand risk among species. Scoring with any tool is more precise and accurate with greater strength of data, highlighting the need for more studies into the impacts of these introduced species, especially socioeconomic ones where there is a dearth of information readily available. We encourage the use of this tool for prioritizing NIS not only within aquatic systems, but across all habitats and taxa.

Authors' contribution

MW, DL, CD, TT contributed to the conception; MW, DJ, KD, DG, DL, CD, TT design and methodology; MW, DJ, KD, DG, DL, CD, TT data analysis; MW, DJ, KD, TT drafted and revised the manuscript.

Acknowledgements

This study is dedicated to our late colleague and friend Dr. Gordon H Copp. Gordon was a strong proponent for risk assessments, especially to inform decision making, and was always willing to listen to alternative ways they could be done. It was through multiple conversations over the years at various conferences, symposia and ICES Working Group meetings that spurred our interest in developing the screening tool we present here. He was always generous with his time and a strong champion for early career scientists, especially those in under-represented areas. Gordon will be missed. We would also like to thank the University of Victoria coop students and Vancouver Island University practicum students who compiled much of the background information used in this assessment including: Kyle Danielewicz, Chantal Gudbranson, Yuliya Malasayeva, William Rock, and Allie Unger. Finally, we would like to thank the two anonymous reviewers for their constructive comments during the review process which greatly improved this manuscript.

Funding declaration

AIS Science Program at Fisheries and Oceans Canada. Pacific Salmon Commission: Southern Endowment Fund. Pacific Salmon Science Initiative at Fisheries and Oceans Canada. The funders had no specific role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Data availability statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study. We are exploring options to make the screening tool generated here (NISST) and the supporting guidance document available through GitHubs.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Example species scoring using NISST.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2025/Supplements/MBI_2025_Wilcox_etal_SupplementaryMaterial.xlsx