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RESEARCH ARTICLE

A new tool for setting biodiversity management priorities adapted from aquatic invasive species management: A pilot using Atlantic salmon (*Salmo salar*) in NS, Canada

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Abstract

1. Aquatic invasive species (AIS) are a leading cause of global loss of biodiversity. However, the relationships between AIS and vulnerable species (e.g. species at risk and endemic species) are not well-documented and few studies have combined risk of AIS invasion with species distribution modelling of vulnerable species.
2. An integrated management approach was developed and applied to assess the effects and risks of AIS on Atlantic salmon (*Salmo salar*) in Nova Scotia (NS), Canada. A semi-quantitative risk assessment tool was used to evaluate the risk of introduction, establishment and ecological impact of eight AIS currently found across NS. A suitable habitat for Atlantic salmon was predicted using a random forest model and identified watersheds of high conservation value. A vector-based screening-level risk assessment was developed to determine the relative risk of potential vectors introducing AIS into each primary watershed in NS, alongside other anthropogenic pressures. Finally, a matrix was developed to provide recommendations to AIS managers based on species invasion stage and invasion risk score.
3. Results from this study showed that ecosystem engineer species (e.g. crayfish and invasive plants) were more likely to affect invaded ecosystems, but were less widely reported in NS While invasive piscivores (e.g. chain pickerel [*Esox niger*], smallmouth bass [*Micropterus dolomieu*]) had less potential ecosystem impacts, they were more widely reported in the assessment area. Hitchhiking on watercraft and fishing gear were the riskiest vectors for continued spread of AIS in NS. The AIS Management Matrix supports recommendations of scenarios in which AIS could be eradicated or where response plans may be developed to control, contain and respond to new introductions. The Herring Cove Medway and the Salmon Mira were the top two watersheds recommended for Atlantic salmon

conservation and AIS control or prevention based on habitat conservation value. Water temperature and physical changes to freshwater habitat (especially adjacent land use) were the model variables that were most important to predict Atlantic salmon habitat suitability.

4. At a time of heightened global biodiversity loss, but limited dedicated conservation resources, the integrated management approach developed in this study can be applied to recommend geographically specific actions to managers for strategic vulnerable species conservation planning and AIS management.

KEYWORDS

aquatic invasive species, Atlantic salmon, conservation, cumulative pressures, habitat suitability model, random forest model

1 | INTRODUCTION

The United Nations Convention on Biological Diversity (CBD) provides guidance to conserve species and protect biodiversity. Yet, the decline of biodiversity worldwide is quickly outpacing conservation efforts (McGeoch et al., 2016). Regional identification processes (such as ecologically or biologically significant Areas; EBSA) have been used to draw attention to unique aquatic habitats and biodiversity hotspots for conservation. However, these areas are rarely accompanied by regulatory protection and may be at risk of high degrees of anthropogenic pressures, such as aquatic invasive species (AIS) and climate change, two related factors that are considered to disproportionately alter global biodiversity (Ricciardi & MacIsaac, 2011; Vitousek et al., 1997). The growing number of vulnerable species across the world is an indication that a new approach is urgently needed to prioritize conservation efforts and reduce biodiversity losses.

Frameworks, such as the Drivers-Pressures-State change-Impact-Response (DPSIR), have been widely adopted in conservation planning since it was first developed in the 1990s (Patricio et al., 2016). However, many studies that claim to have applied the DPSIR framework have been purely conceptual and lacked real-time application (Patricio et al., 2016). Existing guidance on DPSIR lacks clarity on how the framework should be applied and how to assess cause-effect relationships in ecosystems where pressures are not mutually exclusive (Patricio et al., 2016). Furthermore, uncertainties around the direct and indirect impacts of pressures on vulnerable species are difficult to conceptualize given the complexity of interactions between pressures or the ability of one pressure to disproportionately affect the overall ecosystem. Hence, more complex, region-specific, nested models are needed to fill the current guiding framework gaps. One solution would be to develop an Integrated Management Approach (IMA) where species, sites and pathways are considered within a larger assessment area.

An IMA is a promising avenue for prioritizing conservation efforts as it can simultaneously assess the effects of multiple stressors, such as AIS and climate change, on vulnerable species through a semi-quantitative risk assessment. Notably, an IMA examines pressures (e.g. use of land adjacent to stream with vulnerable species) that lead to a state change (e.g. increased nitrogen leaching), determines the proportion of each pressure acting on each aquatic system (e.g. watersheds), determines whether each pressure has an effect on the species of concern and prioritizes the pressures according to importance to the species of concern. An IMA may be considered as a more precise examination of the DPSIR steps, as it effectively combines qualitative and quantitative methods into a single system or species/ecosystem management approach (McGeoch et al., 2016) and streamlines management actions. As such, it has the potential to save resources and time, through increased efficiency by integrating information to inform management decisions (Price, 2019).

In this study, we adapted the IMA developed by McGeoch et al. (2016) to analyse the impacts of multiple stressors, including AIS, on Atlantic salmon (*Salmo salar*) at the primary watershed level in NS, Canada. Wild Atlantic salmon was selected as the case study species because it is an iconic species in Eastern North America and Europe with significant cultural, social, economic and ecological importance. Unfortunately, the species' decline is outpacing conservation efforts, despite its value (Bull et al., 2022; Thorstad et al., 2021). Conservation planning for Atlantic salmon is complicated due to the complexity of the species life history, its large geographical range and the consequential need for inter-governmental management (Thorstad et al., 2021). Additionally, conservation efforts and species management are limited in the allocation and availability of resources, resulting in conservation plans implemented in only a few select areas, which frequently do not include analyses of the pressures affecting the species throughout their historic range (Carwardine et al., 2009; Moilanen & Arponen, 2011; Vimal et al., 2011). Moreover, AIS are listed as a pressure on wild Atlantic salmon, but the context in which AIS affect Atlantic salmon is not well understood. The risks of vectors to introduce or spread AIS into areas of high-value Atlantic salmon habitat are not yet known either (Fisheries and Oceans Canada, 2019). Thus, there is a gap in assessing the relationships between species of high conservation concern, the pressures affecting those species and the implications of the pressures on the species of concern. This study helps to fill these gaps by examining the interactions between AIS and Atlantic salmon by ranking AIS presence amongst other ecosystem pressures, determining which AIS are most likely to affect Atlantic salmon and assessing vectors active within NS that could lead to AIS introduction and/or spread into Atlantic salmon habitat.

2 | MATERIALS AND METHODS

The IMA was adapted from McGeoch et al. (2016) and has three steps: (1) identify the species of concern (can be applied to vulnerable species, invasive species, etc. depending on what the IMA is meant to inform), (2) locate areas of high conservation value, and (3) consider which pathways and vectors could lead to AIS introduction (Figure 1).

2.1 | Nodes of the integrated management approach

The nodes of the IMA, derived from the steps listed above, are species, sites and pathways. First, the nodes are identified and assessed separately. The intersections between nodes are then examined and relevant management recommendations, considerations and actions explored in an integrated fashion.

2.1.1 | SPECIES: AIS Assessments and the Management Matrix

To address the first node of the IMA, we adapted a matrix concept from the ISEIA (Invasive Species Environment Impact Assessment) protocol (Matthews et al., 2017), which categorizes non-indigenous species into different lists based on their degree of risk (low, medium or high: based on ISEIA score) and the 'stage of invasion' (absent, isolated population, restricted distribution or widespread), by developing a Management Matrix. As the assessment area in this study (i.e. NS, Canada) utilizes different management tactics than countries where the ISEIA was piloted (i.e. Canada has a single, federal list for AIS excluding parasites and diseases, listed in the *Aquatic Invasive Species Regulations*, whereas other countries such as Belgium have multiple list types), the categories within the matrix were altered to provide AIS managers with action-based recommendations. The categories included as follows: *Prevention* (i.e. using tools and methods, such as public education and outreach, restricting importations and biosecurity), *Eradication* (i.e. attempting to contain and eradicate all occurrences of the species), *Species-Based Response* (i.e. attempting to contain, control or eradicate the species whenever new, unconnected reports are encountered), *Vector-Based Spread Mitigation* (i.e. identification of a common vector and completing actions based on that vector, e.g. *International Ballast Water Regulations*), *Species-Based Management* (i.e. where eradication or species control is unlikely, other option could be pursued such as the use of smallmouth bass in Southern NS as a recreational fish) and *Taxon-Based Management* (i.e. taking management actions or decisions based on a large grouping of common species, for example all aquatic plants within a certain family). To sort species into these categories, the y-axis, 'Invasions Stage', reflected the number of reports of each species throughout NS and within each primary watershed, and the x-axis, 'CMIST Score', estimated the species' invasion risk using the Canadian Marine Invasive Species Tool (CMIST, Drolet et al., 2016). For this assessment, we defined the thresholds for the invasion stage as *Absent* (i.e. no reported presence of species), *Isolated Populations* (one waterbody or a close grouping of waterbodies invaded), *Restricted Range* (isolated watersheds with less than 30% of watershed, portion of area within a watershed, with reported species presence) and *Widespread* (multiple invaded watersheds with greater than 30% of each watershed invaded). For the *x*-axis, CMIST Score provided estimates of invasion risk by multiplying the average likelihood of environmental impact by average likelihood of invasion. For this assessment, species that have a CMIST score of less

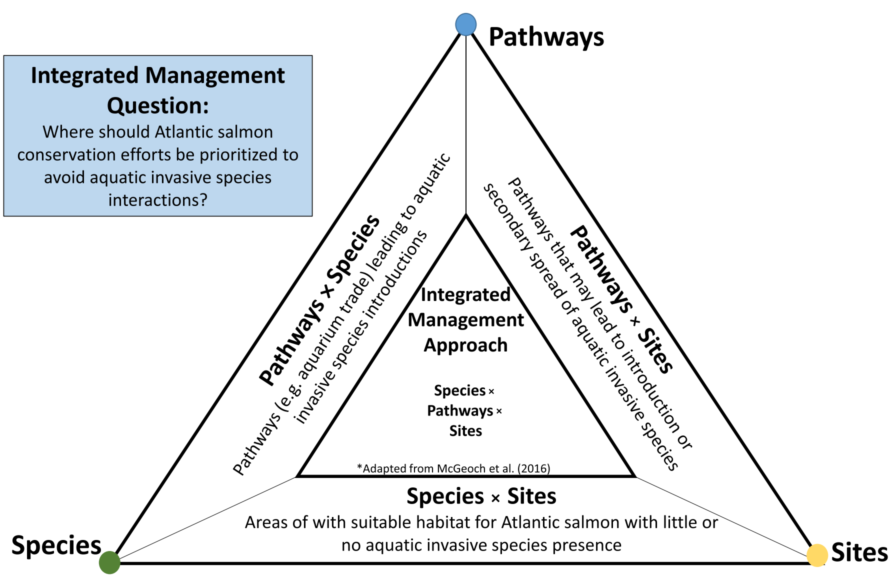

FIGURE 1 Integrated management triangle adapted from McGeoch et al. (2016) explains how considering species, sites and pathways can be combined to ensure that species management decisions integrate all three aspects of invasive species management to maximize positive management impacts and decrease resources used. The triangle can be adapted to various management questions and is not limited to application to aquatic invasive species.

than three were categorized as 'low-risk', species that scored 3–6 were 'medium-risk', and species that scored more than 6 were considered 'high-risk'. Species considered in this assessment were limited to freshwater species with reported 'presence' on open-source repositories, such as iNaturalist or the Province of NS Recreational Fish Records, in the assessment area and included smallmouth bass (*Micropterus dolomieu*), chain pickerel (*Esox niger*), Chinese mystery snail (*Cipangopaludina chinensis*), goldfish (*Carassius auratus*), fanwort (*Cabomba caroliniana*), spinycheek crayfish (*Faxonius limosus*), yellow floatingheart (*Nymphoides peltata*) and purple loosestrife (*Lythrum salicaria*). These AIS represent various taxonomic groups, life histories (which are reflected within CMIST assessments), pathways of introduction and stages of invasion (Table 1). Details on CMIST risk scoring and data used to assess species' invasion stage are found within Supplementary Materials (SS1 and SS5). Additionally, species CMIST assessments were submitted to the CMIST database (https://www.bio.gc.ca/science/monitoring-monitorage/cmist/index-en.php). A list of data sources used in the study are provided in the Data Sources section.

2.1.2 | SITES: Habitat suitability models and correlation plot

Step 2 of the IMA identified sites of high conservation value by identifying locations of predicted suitable habitat for Atlantic salmon in New Brunswick, NS, and Prince Edward Island. All three Maritime provinces were included in the habitat suitability modelling (HSM) because data layers were available and already formatted appropriately for their inclusion, but only NS sites were carried further through the IMA. Random forest modelling was used to predict habitat suitability for Atlantic salmon in each cell of a HUC12 grid (i.e. a grid representing hydrographic units). These HUC12 predicted probabilities were later averaged when scaled up to the primary watershed level when used in the flower plots. Notably, the grid cell size for each section of the assessment changed due to the quality of data available. Models were constructed using data from the Nature Conservancy Canada (NCC) for the Northern Appalachian/Acadian Ecoregion, specifically the NCC Stream Classification v2.0 and NCC Watershed Health Assessment layers (Millar, Noseworthy, et al., 2019; Millar, Olivero-Sheldon, et al., 2019). Models were trained and validated using Fisheries and Oceans Canada electrofishing data collected between 2016 and 2020. Details on the data are found in the Supplementary Materials (SS1) and a list of data sources used are found in the Data Sources section. For more information on HSM construction, training, validation and further testing, refer to Supplementary Materials (SS2).

Additionally, a correlation plot was generated to examine parameter clumping and collinearity that may mask parameter importance. All model parameters that were not statistically significant (p-value >0.05) were denoted with an 'x'. The correlation analysis was completed in R Studio (R version 4.2.2) using the *corrplot* package (R Core Team, 2022; Wei & Simko, 2021). *Corrplot* includes statistical analyses of pairs of matrix parameters with Kendall's test to produce p-values.

The correlation plot found some parameters were strongly correlated, but these parameters are logically correlated (e.g., human population density [Pop. Density], paved road density and percentages of adjacent land that is urbanized [% Urban]) and the HSM was able to distinguish between correlated parameters. Random forest models use bootstrap sampling and feature sampling that allows these models to better handle collinearity, even if multiple parameters have this issue. Bootstrap and feature sampling means that both the rows and columns of a data frame are randomly sectioned k times, and that the model parameters used to build each tree

TABLE 1 Aquatic invasive species (AIS) CMIST score and species establishments based on occurrence records. This information was categorized and visualized in the Management Matrix (M.M.; Figure 2).

Species	CMIST score	CMIST impact score	CMIST likelihood of invasion score	CMIST risk level (*x*-axis M.M.)	Number of invaded watersheds in NS (46 primary watersheds total)	Extent of establishment (*y*-axis M.M.)
Fanwort—*Cabomba caroliniana*	7.33	2.76	2.65	High	1	Isolated population
Goldfish—*Carassius auratus*	6.56	2.47	2.65	High	5	Restricted range
Chinese mystery snail—*Cipangopaludina chinensis*	4.97	2.03	2.44	Moderate	4	Isolated population
Chain pickerel—*Esox niger*	6.68	2.43	2.75	High	14	Restricted range
Spinycheek crayfish—*Faxonius limosus*	7.19	2.62	2.75	High	1	Isolated population
Purple loosestrife—*Lythrum salicaria*	4.50	1.83	2.46	Moderate	34	Widespread
Smallmouth bass—*Micropterus dolomieu*	6.55	2.47	2.65	High	26	Widespread in Southern NS Restricted range in Northern NS
Yellow floatingheart—*Nymphoides peltate*	6.58	2.57	2.56	High	4	Restricted range

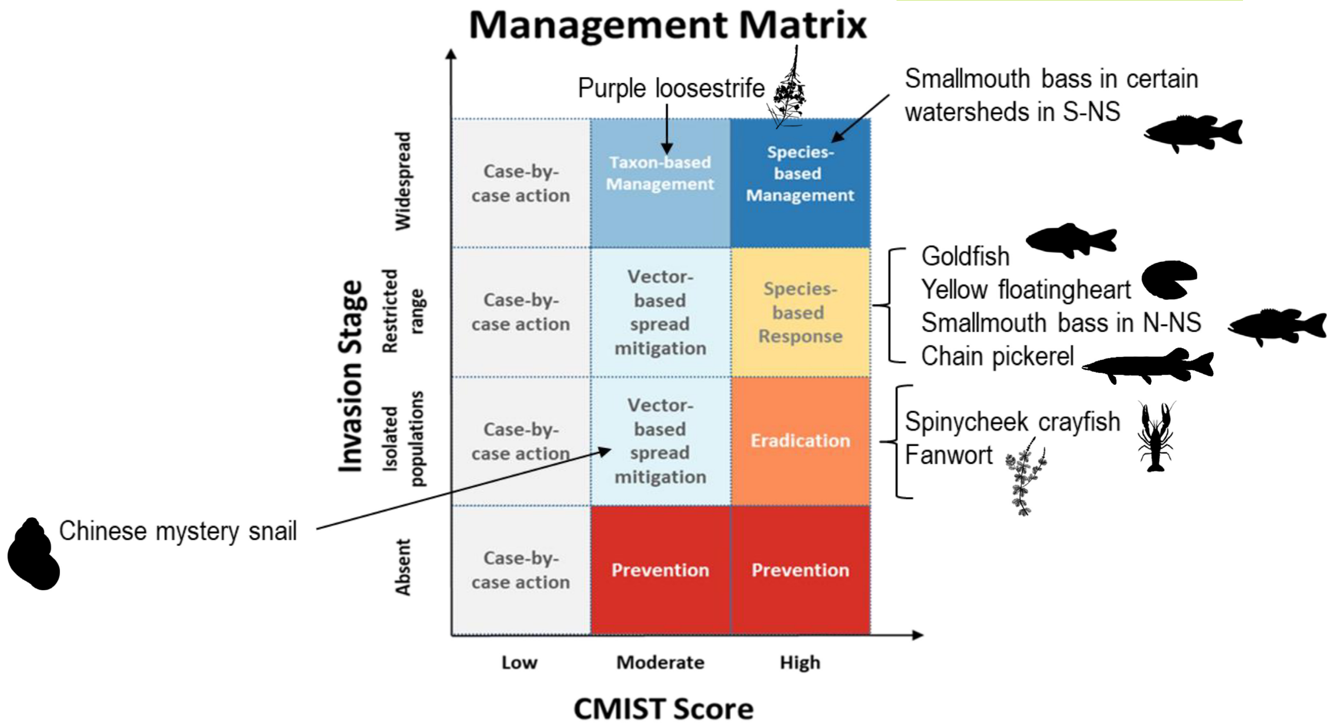

FIGURE 2 Based on the CMIST scores and the establishment assessments, each of the eight species were placed into one of the categories of the Management Matrix. These categories represent generalized concepts and not specific actions.

within the forest are randomly sampled for each of those *k* sections (Raj, 2019).

2.1.3 | PATHWAYS: Risk assessment of AIS vectors

Finally, the 'pathways' step in the IMA applied an adapted screening-level risk assessment (SLRA) from Brancatelli and Zalba (2018) to potential vectors present in NS freshwater environments (identified via a region-specific literature search) to rank vectors contributing to the spread of AIS by their level of risk. Details on the semi-quantitative vector-based SLRA are found in Supplementary Materials (SS4). As far as the authors are aware, this is the first application of an analytical method to quantify vector risk of introducing freshwater AIS in Canada that incorporated information on whether the species is/would be difficult to control if introduced. Our vector-based SLRA built upon components of species' CMIST scores and included a measure of the relative magnitude of each vector (i.e. transport capacity and transport frequency). An overall risk score was calculated for each vector in each of the primary watersheds in NS by using the following equations:

$$\mathrm{RV} = \frac{[(2 \times \mathrm{SI}) + \mathrm{TV}]}{3}$$

$$\mathrm{TV} = \frac{(\mathrm{TP} + \mathrm{TC})}{\mathrm{TV}_{\max}}$$

$$\mathrm{SI} = \frac{(\mathrm{PIV} + \mathrm{CDV})}{\mathrm{SI}_{\max}}$$

$$\mathrm{CDV} = 100(\mathrm{species}_{\text{high CD}}) + 10(\mathrm{species}_{\text{medium CD}}) + 1(\mathrm{species}_{\text{low CD}})$$

$$\mathrm{PIV} = 100(\mathrm{species}_{\text{high PI}}) + 10(\mathrm{species}_{\text{medium PI}}) + 1(\mathrm{species}_{\text{low PI}})$$

where RV is the risk associated with each vector, SI is the impact severity, and TV is the transportable volume. Notably, the vector-based SLRA is additive and not multiplicative because this is a screening-level tool and, thus, does not handle predicting outcomes (typically included in a detailed-level risk assessment). TV is determined using transport capacity (TC) and the number of available propagules of transport (TP), which is estimated by using the likelihood of invasions (from CMIST assessment) multiplied by propagule duration (i.e. number of months per year that each vector is active in the assessment area, can be estimated). SI is determined using the potential impact of each vector (PIV) and the control difficulty of each vector (CDV). PIV is determined using the potential impact of each species (PI), which is determined using the impact of invasion score from CMIST. CDV is estimated using the control difficulty of each species (CD). For the PI calculations, species were considered high-impact if CMIST impact score was 2–3, medium-impact equated to 1–2, and anything less than 1 was low-impact. For CD calculation, a yes/no test was created and applied, species answering 'yes' to at least four out of six questions were considered high control difficult, species with at least two and three 'yes' were medium difficult, and species with only one or no 'yes' were low difficulty. Below are the yes/no control difficult test questions:

Species features that result in species being more difficult to control:

1. species that occur in difficult to assess habitat (e.g. deep sea species);
2. species with high fecundity/rapid reproduction rates;
3. species that have a wide range of ecological tolerances;
4. species with a highly successful early life stage (e.g., prolong planktonic larval stage, release of fully formed offspring);
5. species with no known eradication options; and
6. species that lack clear legislative authorities for control, rapid response or management.

NS AIS vectors assessed in this study included pet stores (e.g. aquarium dumping and mercy releases), water garden centres and nurseries (e.g. planting ornamental flowers along waterfront properties), recreational fishing (e.g. intentional release to establish a new fishery, bait bucket transfers), and unclean boats and gear (e.g. canoes, kayaks, paddleboards and recreational water gear). All identified and ranked vectors were grouped into categories of 'pathways'. In terms of standardized pathway categories: pet stores, water garden centres and nurseries fall within the *Escape Pathway*; recreational fishing falls within the *Release Pathway*; unclean boats and gear fall within the *Stowaway Pathway* (IUCN, 2018). The *Nova Scotia Live Fish Possession Regulations* restrict the movement and sale of live bait. Therefore, all AIS introductions from recreational fishing are likely intentional releases.

2.2 | Intersection of integrated management approach nodes

The intersection of nodes was assessed by including aspects of each node into the assessment of the node intersections. For example, flower plots were constructed to integrate AIS presence with HSM and other considerations (e.g. positive habitat aspects), to identify sites where AIS-Atlantic salmon overlap was expected and where it was not expected (i.e. of all the sites suitable for Atlantic salmon, where overlaps with current AIS distribution?). Notably, there exists a range of AIS presence and Atlantic salmon habitat suitability combinations (e.g. high AIS presence and low HSM, low AIS and low HSM). The goal of the *species x site intersection* was to compare watersheds to identify areas where there is high HSM and low AIS presence, that is, sites where habitat conservation value is high and AIS pressure is low to prioritize management efforts to areas were species/ecosystem conservation is most likely possible. However, the flower plots offer a quick visual summary of the relative proportion of each pressure and each positive attribute per primary watershed and are a tool for comparing watersheds based on available data.

2.2.1 | Species × sites

The HSM results were overlaid with additional data layers representing social, cultural, economic, and ecological features and pressures, and visually represented with flower plots. These additional data layers were used to prioritize sites (i.e. watersheds) for conservation, using an ecosystem-based approach. Each petal in the flower plots (representing individual features/pressures as listed in Table 1, Supplementary Material SS1) were weighted as either positively (+1) or negatively (−1) affecting Atlantic salmon based on ecological theory, Committee on the Status of Endangered Wildlife in Canada (COSEWIC) threat calculator assessment, *Species at Risk Act* recovery documents and literature. Sites (watersheds) were then ranked from 1 to 100 (100 being the highest priority) based on the cumulative positive or negative influence of these features and pressures (the sum of their weights); watersheds were given higher priority if there were greater positive habitat attributes (e.g. parks and protected areas, higher predicted habitat suitability) and lower presence of negative pressures (e.g. AIS presence) and lower priority if the opposite was true.

These flower plots were generated to look beyond the predicted suitable habitat, to review the pressures acting on each primary watershed within NS and other ecosystem factors that could positively or negatively affect Atlantic salmon conservation (e.g. native fish assemblages are expected to be a benefit). The flower plot concept was adapted from the Ocean Health Index (OHI) as it provides a method for visualizing the relative influence of factors that are important to species managers, which are used to estimate ocean ecosystem health (Ocean Health Index Team, 2021). The flower plots were developed in R Studio using code modified from the OHI GitHub (O'Hara et al., n.d.), with petals arranged around a central score representing the weighted rank (conservation prioritization) described above. Some parameters were included as petals (for better visualization), but did not contribute to watershed prioritization scores because they were previously included in the HSM (e.g. proportion of pressure presence) or were included for information purposes only (e.g. the proportion of Atlantic salmon stocking sites that are within each watershed [Sal. Stocking]). The summation of flower petals that contributed to the prioritization score (the central number) included those metrics identified in Table 1 (Supplementary Materials SS1). The flower plot petal acronyms are explained within figure text (refer to Supplementary Materials for more details on how each petal was weighted and/or used to contribute to the central priority score). The prioritization scores reflect the sum of the portion of the watershed that has positive versus negative attributes. Each attribute was its own map layer overlaid with primary watershed polygons. The portion of each attribute is the geographic amount of each watershed affected by each attribute. Watersheds with more positive attributes score higher than those with greater negative attributes. For this assessment, each petal was equally weighted, but the tool is flexible, and weighting of petals can be assigned by the assessor(s). The pressures that were included within the HSMs were visualized in the flower plot to easily assess post-analysis which pressures may influence a greater portion of each watershed, but were not included in the prioritization score as this would 'double count' pressures.

As part of the HSM, models ranked pressures from most to least important for Atlantic salmon presence/absence in variable importance plots (details provided in Supplementary Materials SS2). The Mean Decreased Gini (MDG) provided insights into which parameters were most important for trees within the random forest model to correctly predict Atlantic salmon presence/absence, which then indicates which environmental pressures affect Atlantic salmon. By combining the variable importance plots with the flower plots, managers can assess which pressures are most influential to Atlantic salmon. Also, based on petal length per flower plot per watershed, managers can target resource and action to these high-priority pressures first.

2.2.2 | Pathways × sites

Pathways × sites intersection was assessed to identify which pathways are most likely to introduce AIS to areas of high conservation value for Atlantic salmon at the primary watershed scale. A shapefile containing locations of pet and aquarium stores, water garden centres and nurseries, and public boat launches was compiled and overlaid with the primary watershed polygon shapefile to determine the presence and frequency of each vector in each watershed. Additionally, the popularity of recreational fishing per county was estimated based on a survey of sportfishing within the assessment area from 2010 (Nova Scotia Department of Fisheries and Aquaculture, n.d.). Therefore, the magnitude of each vector is a rough estimate, which would benefit from further studies of water access and use within the assessment area.

2.2.3 | Species × pathways

The vector-based screening-level risk assessment (SLRA) was built to include multiple aspects of AIS management and builds upon species CMIST score components (see section 1.3). The integration of species risk scores into the vector-based SLRA allowed for evaluation of the *species × pathways intersection*, as vectors are prioritized based on the severity of AIS that could be introduced by that vector. Furthermore, the inclusion of the control difficulty metric (from the SLRA, described in Section 2.1.3) enhanced the practicality of the tool. Vector risk score was higher for species that are more difficult to control, either due to life history or regulatory limitations. Thus, the tool prioritizes vectors that are known to introduce AIS that are affecting multiple native species, arrive in greater quantities or frequencies and are difficult to manage. Therefore, the tool prioritizes scenarios where prevention is pivotal.

3 | RESULTS

3.1 | Species screening-level risk assessments (SLRA)

Six of the eight AIS assessed using CMIST (chain pickerel, smallmouth bass, goldfish, yellow floatingheart, spinycheek crayfish and fanwort) fell within the categories for the highest impact score and the highest likelihood of invasion score (Table 1). The species with the largest ecological impact scores were ecosystem engineers (e.g. crayfish and plants). Chain pickerel and spinycheek crayfish were assessed as the species most likely to successfully establish a new population if introduced in a new habitat. Purple loosestrife and Chinese mystery snail were assessed to have the least ecological impact and the least amount of suitable habitat, respectively.

3.2 | Invasion stage

The invasion stage assessments found that both purple loosestrife and smallmouth bass are widely reported throughout southern NS (occupying more than 30% of primary watersheds in NS). Goldfish, yellow floatingheart and smallmouth bass were considered to have restricted ranges in northern NS (>1 watershed invaded but <30% of all NS watersheds). Spinycheek crayfish and fanwort were identified as isolated populations because each species is found within only one watershed in NS. Chain pickerel is present within >30% of NS watersheds, which would typically place the species within the 'widespread' category, but the species is placed within the 'restricted range' category on the Management Matrix, which reflects the regional interest of the species. Similarly, the Chinese mystery snail is present in >1 watershed, but is reported to have a restricted range, mostly around the major cities within NS (i.e. Halifax and Truro), with an unconfirmed population in the Annapolis River (Kingsbury et al., 2020). Therefore, Chinese mystery snail is, thus far, a species isolated to one municipality with very few occurrences outside the Halifax Regional Municipality. See Supplementary Materials for maps of location and quantity of public reports per species per watershed (SS5).

3.3 | Management Matrix

The categorization for each species based on the Management Matrix (Figure 2) was as follows: spinycheek crayfish and fanwort were recommended for *Eradication* (high-risk score with isolated population); goldfish, yellow floatingheart, smallmouth bass in northern NS and chain pickerel were identified for *Species-Based Response* (high-risk scores with restricted range); Chinese mystery snail fell within *Vector-Based Spread Mitigations* (moderate risk score, with moderate isolated population); smallmouth bass in southern NS for *Species-Based Management* (high-risk score, but already widely dispersed); and purple loosestrife within *Taxon-Based Management* (moderate risk score but widely spread). Initially, chain pickerel was placed within the *Species-Based Management* category based on the species' invasion stage. However, the existing management actions associated with chain pickerel are most reflective of those within the *Species-Based Response* category to reflect the regional prioritization of preventing further introductions and responding to new detections of chain pickerel (Arany, 2019; Mitchell et al., n.d.). This demonstrates the flexibility of the framework to balance both science and management required when managing AIS. As a result, chain pickerel could be categorized in either *Species-Based Response* or *Management* depending on the goals of species managers.

3.4 | Atlantic Salmon habitat suitability model

The HSM was included as a flower plot petal and predicted that the most suitable locations for Atlantic salmon are in the Annapolis, Herring Cove/Medway and LaHave watersheds in southern NS (Table 2). In eastern NS, the Tangier, East/West Sheet Harbour, Liscomb, St. Mary's, and some parts of the Country Harbour watersheds contained suitable habitat. On the western side of mainland NS, only a few watersheds, namely East/Middle/West Pictou and River John, along the Northumberland Strait, were predicted to be suitable. Most of Cape Breton Island was classified to have above 50% (and frequently much higher than 50%) likelihood of containing habitat that would sustain Atlantic salmon populations. Further details regarding the HSM model are found in Supplementary Materials (SS2) including HSM maps, model data, layer compilation and various model validation test results.

3.5 | Pressure correlation and importance

Both the correlation plot (Figure 3) and the variable importance plot (Figure 4) found that non-native fish presence did not significantly overlap with current Atlantic salmon presence (i.e. Salmon Presence in Figures 3 and 4) and did not influence the HSM. Moreover, the HSM variable importance plot (Figure 4) revealed that parameters that affected water temperature, such as the velocity of temperature change and average water temperature increases (Water Temperature Change in Figures 3 and 4), were the most important model parameters that contributed to Atlantic salmon presence/absence. Total road density, cumulative of unpaved road density and paved road density, and road crossings (Stream Xing in Figures 3 and 4) were also, but to a lesser extent, highly correlated with Atlantic salmon presence/absence. Physical habitat attributes and stressors, such as aquatic barriers (A. Barriers), habitat area (km squared) and amount of land composed of impervious surfaces (Imperv.), were moderately important parameters for predicting Atlantic salmon presence. Land-use types, including percentage of clear-cut land (% Clear Cut), percentage of urban developed land (% Urban), percentage of crop land (% Crop Land), percentage of pastureland (% Pasture Land) and total percentage of agricultural land (% Agri. Land), were relatively important to Atlantic salmon presence/absence. Percentage of clear-cut land within a grid cell seems to have the most strongly negative

TABLE 2 Watershed prioritization for Atlantic salmon conservation based on flower plots.

Watershed name	Score
Annapolis	55
Barrington Clyde	38
Cheticamp River	48
Clam Harbour St. Francis	48
Country Harbour	37
East Indian River	32
East Middle West Pictou	61
East West Sheet Harbour	57
Economy	37
French	46
Gaspereau	40
Gold	53
Grand[a]	54
Grand 1[a]	47
Herring Cove Medway	69
Indian	46
Isle Madame	36
Kelly MacCann Hebert	41
Kennetcook	41
LaHave	56
Liscomb	53
Margaree	50
Mersey	37
Meteghan	46
Missaguash	37
Musquodoboit	44
New Harbour Salmon	46
North Baddeck Middle	52
Parrsboro	40
Philip Wallace	55
River Denys Big	56
River Inhabitants	49
River John	36
Roseway Sable Jordan	27
Sackville	47
Salmon Debert	46
Salmon Mira 1[a]	63
Salmon Mira[a]	44
Shubenacadie Stewiacke	42
Sissiboo Bear 1[a]	40
Sisiboo Bear[a]	38
South West	49
St. Croix	29
St. Marys	50
Tangier	48
Tidnish Shinimicas	42

TABLE 2 (Continued)

Watershed name	Score
Tracadie	41
Tusket River	47
Wreck Cove	48

[a]Watersheds split by relatively large bays often generated a separate smaller portion of the watershed on either side of the bay. Therefore, some watershed names are the same but a '1' was added to denote this split. Therefore, these watersheds are one watershed with a dominant east/west or north/south split.

correlation with Atlantic salmon presence. Other parameters such as tidal influence, stream length (km), relative habitat size, water temperature, relative alkalinity and various types of pollution (i.e. point source, metals and metalloids, nutrient and organic) were relatively less important for model predictions of Atlantic salmon presence. However, pesticides use ranked in the top half of the variable importance plots and chemical limit exceedance, nitrogen leeching (N Leeching) and phosphorus leeching (P Leeching) ranked about mid-way on variable importance plots representing some influence on model predictions.

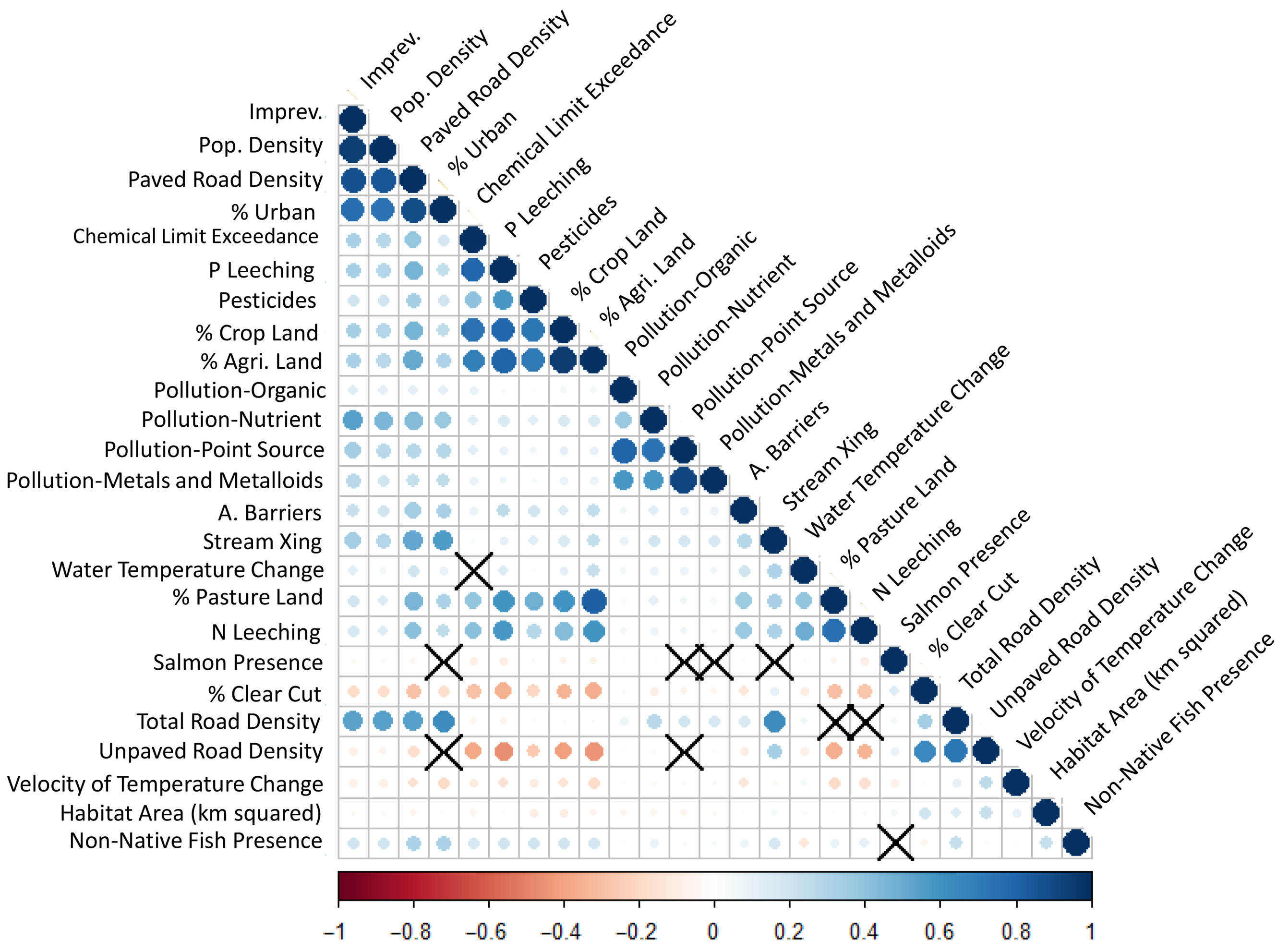

FIGURE 3 Pressure parameters from the Nature Conservatory of Canada (NCC) Habitat Health Assessment dataset, used in habitat suitability modelling for Atlantic salmon (*Salmo salar*) based on salmon presence/absence surveys, were compared to determine potential correlation. The blue circles represent positively correlated parameters, circle size and darkness of shading increased with higher correlations. Orange to red circles indicated a negative correlation, with circle size and darkness of shading increasing with greater negative correlations. The black 'x' marks are for parameters that are not statistically correlated (i.e. $p > 0.05$). Variables that are highly correlated were often expected correlations (e.g. human population density, Pop. Density, was highly correlated with paved road density, and percentage of urbanization, % Urban, per hydrographic unit). Other parameters were negatively correlated (e.g. velocity of temperature change and salmon presence). In terms of aquatic invasive species, the presence of non-native fish species did not statistically correlate with Atlantic salmon presence. Notably, Atlantic salmon presence was not strongly correlated with other model parameters. 'Stream Xing' = stream crossings, 'A. Barrier' = aquatic barriers, 'Imprev.' = impervious surfaces, 'Pop. Density' = human population density, 'N Leeching' = nitrogen leeching, 'P Leeching' = phosphorous leeching, 'Water Temp.' = water temperature, '% Agri. Land' = percentage of agricultural land.

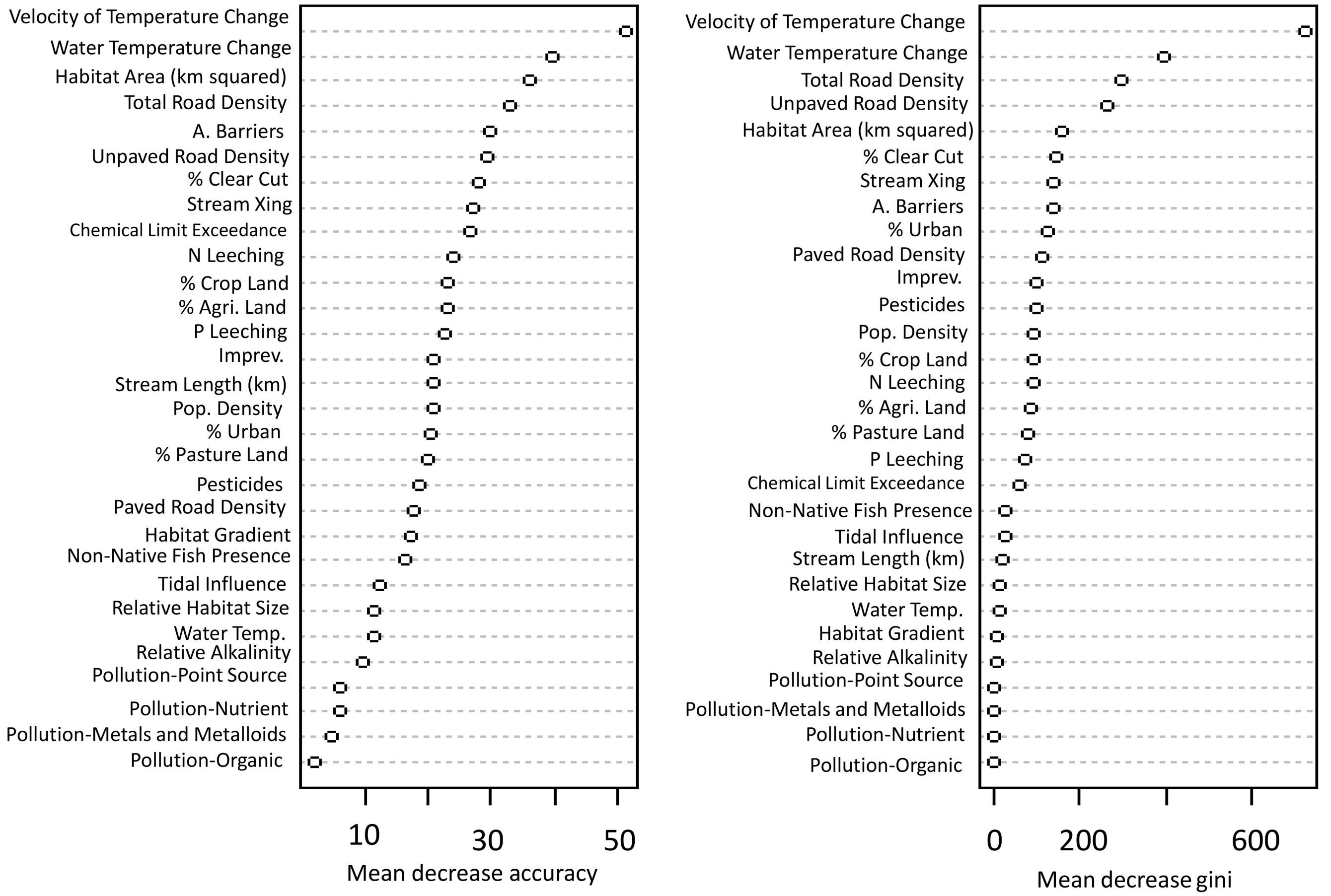

FIGURE 4 Mean Decrease Accuracy plot indicates the parameters required by the model to accurately predict Atlantic salmon presence/absence in order of most necessary (higher on the *y*-axis) to least, and the Mean Decrease Gini, which indicates parameter importance (higher on *y*-axis equates to more important), are similar in the parameter ranking. It seems that climate change velocity and water temperature change are the most important variables impacting Atlantic salmon presence/absence. The point-source pollution parameters all ranked lowest for model importance and accuracy. Environmental parameters ranked relatively low too. These plots indicate that Atlantic salmon presence/absence is most driven by physical alterations to the habitat (e.g. change in temperature, construction or removal of aquatic barriers and land use). Due to the data layers available, only non-native fish presence was included as a pressure (i.e. did not include non-native invertebrates or plants). 'Stream Xing' = stream crossings, 'A. Barrier' = aquatic barriers, 'Imprev.' = impervious surfaces, 'Pop. Density' = human population density, 'N Leeching' = nitrogen leeching, 'P Leeching' = phosphorous leeching, 'Water Temp.' = water temperature, '% Agri. Land'= percentage of agricultural land.

3.6 | Watershed prioritization

Based on the flower plots (Figure 5) and the HSM (SS2), the Herring Cove/Medway (Figure 5a) watershed was scored as the highest priority for Atlantic salmon conservation with a mean priority score of 69, followed by the Salmon Mira (Figure 5b) watershed, which had a score of 63. When compared to the lowest scoring watershed, the Roseway Sable/Jordan (Figure 5c, score of 27) watershed, both the Herring Cove/Medway and Salmon Mira had greater proportions of positive attributes, that is, Indigenous reserve land, native fish biodiversity, less threatened salmon population (Salmon Status), higher predicted suitable habitat (HSM), ecological and biologically significant areas (EBSA) and species at risk critical habitat; and fewer pressures such as AIS detections, large and rapid predicted changes in water temperature (Vel. Of Temp.), and less disturbance from recreational fishing in terms of boat launches and popularity of an area for recreational fishing (Rec. Fishing).

3.7 | Vector risk assessment

The vector-based risk assessment tool (Figure 6) determined that unclean boats or gear used in and around the water was the highest risk source of primary and secondary introductions for the AIS evaluated in this study. The unclean boats and gear represent the hitchhiking vector, within the stowaway pathway. Species introduced through this pathway have a high probability of continuous spreading through fouling items that enter contaminated waterways. The second most problematic vector was recreational fishing, which falls

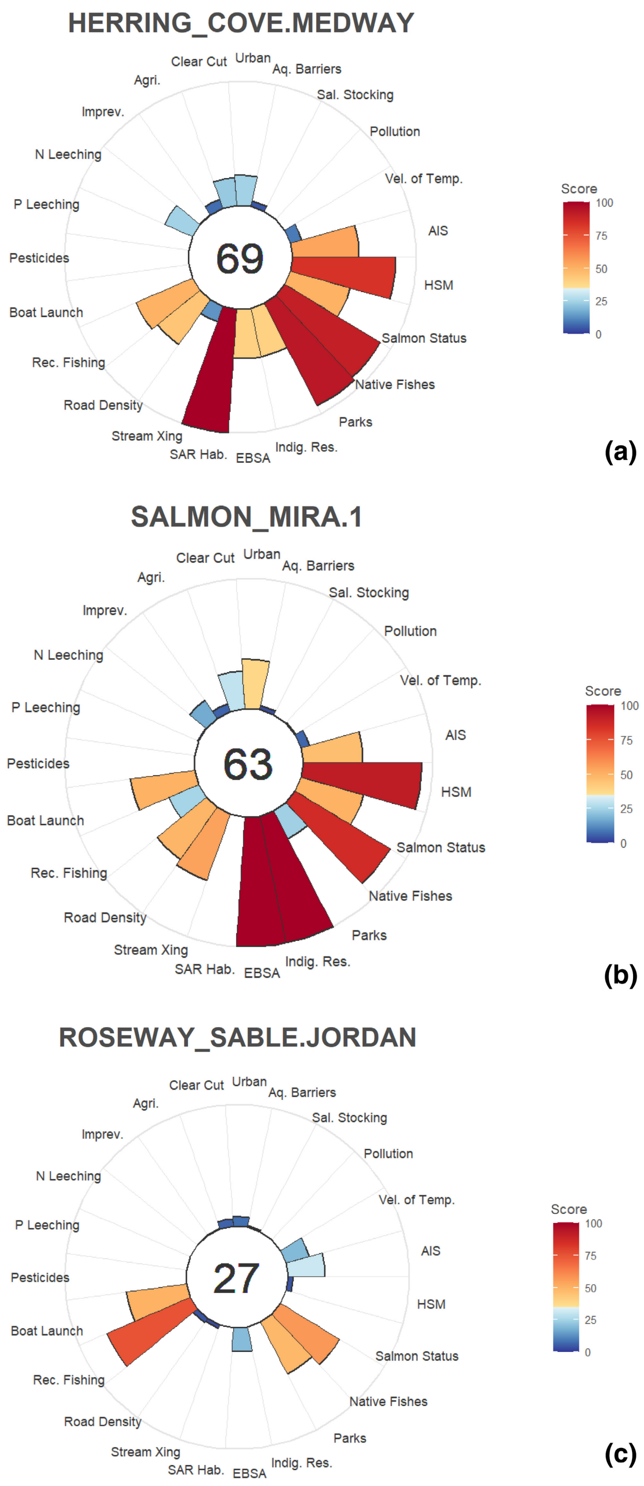

FIGURE 5 Flower plots of each watershed allow for visualization of each parameter used in the habitat suitability models (HSM) without 'double-counting' these parameters towards the mean priority (i.e. the number in the centre circle). Likewise, the flower plots enable visualization of positive attributes to each watershed of aspects such as those that offer some form of habitat protection (e.g. parks and protected areas). The above plots are examples of the flower plots that are found in the Supplementary Materials (Watershed Flower Plots section). Plots (a and b) were the highest ranked watersheds for prioritization, plot (c) was the lowest. 'Sal. Stocking' = Atlantic salmon stocking, 'AIS' = aquatic invasive species, 'Aq. Barriers' = aquatic barriers, 'Agri.' = agriculture land, 'Imprev.' = impervious surface, 'N Leeching' = nitrogen leeching, 'P Leeching' = phosphorous leeching, 'Rec. Fishing' = recreational fishing, 'Stream Xing' = stream crossing, 'SAR Hab.' = species at risk habitat, 'EBSA' = ecologically and biologically significant areas, 'Indig. Res.' = Indigenous reserve land, 'Parks' = parks and protected areas, 'HSM' = habitat suitable model.

within the release pathway. Based on the results of non-native fish species invasion stage assessments (SS5), this vector is active in NS. Numerous watersheds resulted in nearly identical scores for pet stores, recreational fishing and unclean boats and gear (SS4). These ranking clusters for each watershed were often a result of low/no access to public boat launches, low/no presence of pet stores and low intensity of recreational fishing. Furthermore, water garden centres and nurseries were scored as the least risky source of AIS introductions, likely due to the limited number of water garden centres.

4 | DISCUSSION

The IMA applied here to AIS management includes understanding which AIS are expected to affect species of conservation concern through SLRAs, determining potential management strategies to decrease those impacts and then finding geographic areas of high conservation value habitat where AIS introduction can be prevented, or existing populations can be contained. One overarching concern of AIS is their ability to reproduce rapidly through the use of different life-history strategies compared with native species. This case study included AIS spanning a continuum of invasion stages (from widely reported to rare) and a wide range of physiological tolerances and taxonomic groups.

It is well known that there is greater economic benefit in preventing AIS introduction or quickly containing and controlling the species before it becomes widely established, the expected economic returns on investments in prevention (1:100) versus asset-based protection (<1:1–5) (Harris et al., 2018). Yet, determining the direct and potential indirect impacts of AIS on species of conservation concern (e.g. Atlantic salmon) is challenging because each AIS will affect native species in different ways. Therefore, the true socio-economic cost of a new species may not be known until well after it becomes widely established. Hence the need to prioritize species management at the early stages of invasion.

The Management Matrix presented here was a concept adapted from existing watchlist generation tools (Matthews et al., 2017), but considered the regulatory process of the country where the assessment area was located, thus offering appropriate recommendations given the political and legislative realities of the area. As previously noted, Canada has one list for AIS management, therefore, action-based categories are considered a better approach for this assessment area. If the assessment area is within a country having multiple watchlist types then using the ISEIA protocol as is may be the best option. It is important to note that action-based categories do not necessarily equate to immediate action planned for the species, and it should not be assumed that regulators or implicated organizations

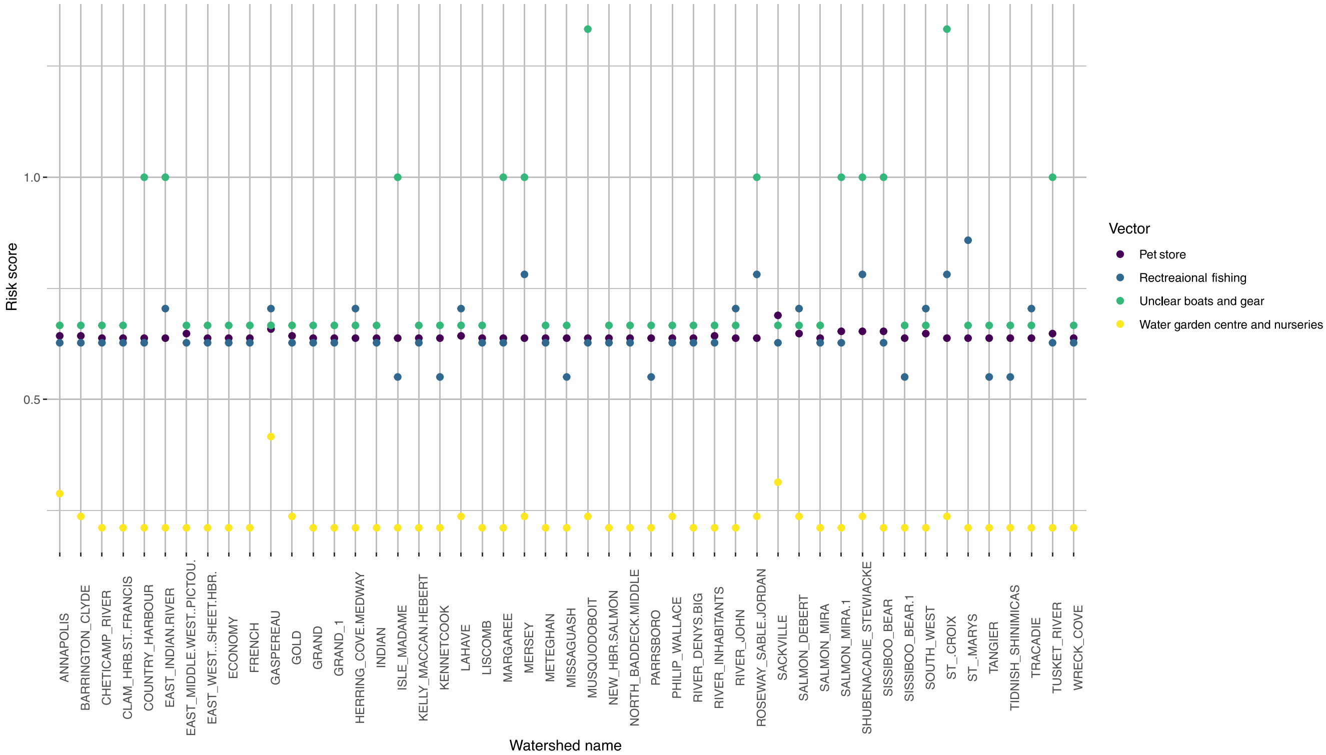

FIGURE 6 Vector-based screening-level risk assessment revealed that unclean boats and gear are the riskiest vector, of the four analysed, to further introduce aquatic invasive species (AIS) in Nova Scotia, Canada. The second most likely vector was pet stores. A few watersheds saw recreational fishing to be more problematic than unclean gear/boats or pet stores, which depended on the popularity of the watershed with anglers (e.g. Margaree and St. Croix). In all watersheds, water garden centres and nurseries were the least likely vector to lead to AIS introduction.

are committed to act. Rather, the Management Matrix provides recommendations based on threat assessments and geographic scope of each species assessment and can be adapted depending on the assessor's resource availability, regulatory processes or sphere of authorities and political realities (as seen with chain pickerel in NS). The important part is for assessors to determine the goal and scope of the matrix when drafting the categories within the matrix and determine which tools will be used to set and assess thresholds along the x- and y-axis. One example of the flexibility of the Management Matrix is yellow floatingheart in Little Albro Lake, Dartmouth. Yellow floatingheart scored in the top right section of the CMIST plots representing high likelihood of invasion and ecological impact. The species invasion stage assessment indicated that this species was reported in >1 watershed, which placed the species in the 'species-based response' section of the Management Matrix. However, given the regional interest in eradicating yellow floatingheart and its occurrence within the Shubenacadie watershed leading to greater socio-economic issues, managers may elect to include eradication within their species-based response where it makes economic and political sense to do so (Berman, 2021). In conclusion, managers may elect to include or exclude different aspects of the Management Matrix's recommendations from a variety of categories based on their needs and priorities, the point of the matrix is to offer recommendations on what managers should consider for each species based on its known range and anticipated impacts.

The second node of the IMA identified sites of high conservation value based on the question the IMA was set to address. This step of comparing sites does not appear within the DPSIR framework, but conceptually could be included as pressures affect habitat quality and, thus, affect the conservation value of sites. A key criticism of the DPSIR framework was the inability of the framework to address how multiple pressures interact to cause a state change (e.g. decrease conservation value of a particular watershed; Patricio et al., 2016). Our novel approach of combining HSMs with correlation plots assesses pressures acting within a system (tied to location) instead of treating the pressure-species interactions as if happening within a vacuum. Likewise, if a pressure is ranked low but we know from experience that the pressure does play an important role in the assessment area, then the model identifies data gaps and/or points to complex pressure–species interactions that need to be assessed on a case-by-case basis.

Generally, the study results indicated the need for freshwater habitat conservation or restoration (Thorstad et al., 2008), as our HSM variable importance plot suggested that higher habitat quality was most frequently associated with Atlantic salmon presence. For this reason, AIS that may alter the ecosystem structure, change water flow regimes or change water quality should be prioritized for prevention or eradication, which would include invasive plants and crayfish (e.g. Albertson & Daniels, 2018). This further exemplifies the importance of understanding how certain pressures interact with or influence one another, as AIS are more likely to indirectly affect Atlantic salmon through habitat alterations.

Species such as chain pickerel and smallmouth bass were not identified as important for predicting Atlantic salmon presence/absence as their presence was not a strong driver of model dynamics and did not significantly overlap with Atlantic salmon presence. This could indicate that there is a poor understanding of where the species occur (i.e. lack of reporting) or that these species do not frequently occupy the same ecological niche (i.e. lake-dwelling invasives versus river/stream Atlantic salmon). However, the invasion stage assessment of both piscivore invasive fish covered much of the assessment area. Again, this highlights the need to determine the establishment of AIS because even species less influential to Atlantic salmon (i.e. chain pickerel and smallmouth bass) have a greater range that overlaps with Atlantic salmon. Therefore, the cumulative impact of invasive piscivores is more influential in the current state of the environment, but ecosystem engineers are predicted to be the most problematic if introduced and established widely. An advantage of the IMA is that it looks at the intersection of the species, sites and pathway nodes to inform management and so these subtle (but extremely important) and complex interactions between AIS and sites with high probability Atlantic salmon suitable habitat become more obvious, thus leading to more efficient (location-specific) allocation of management resources.

Likewise, the specific location(s) targeted for conservation is dependent on the question posed to the IMA (e.g. whether to place resources in an area to conserve a vulnerable species or target areas where there is a higher habitat quality regardless of vulnerable species presence). Previous conservation plans have focused solely on the pressures affecting Atlantic salmon populations that were most at risk of extirpation (Fisheries and Oceans Canada, 2010a, 2010b), which resulted in a concentration of resources into one, relatively small geographic area. This study focused on the relative impact of each pressure (Figure 4), including the presence of AIS and species- (via CMIST) and vector-based risk (Figure 6), in relation to Atlantic salmon presence/absence (via HSM) to find locations where Atlantic salmon populations have the greatest chance of survival (Figure 5). Flower plots visualized in this study (summarized in Table 2) suggest that conservation efforts for Atlantic salmon be focused on watersheds in Cape Breton, some areas along NS's eastern shore, and the Herring Cove/Medway watershed. These areas have relatively limited reported AIS presence, high Atlantic salmon habitat suitability predictions, existing Atlantic salmon populations and greater amounts of potential protections (e.g., Indigenous reserves, parks and protected areas, and other species at risk). Conversely, watersheds with a relatively large number of AIS present and where the HSM predicted low habitat suitability for Atlantic salmon should be placed at a lower priority (e.g., Roseway_Sable, Jordan). It was assumed that a healthy coexistence between AIS and Atlantic salmon was unlikely. Consequently, AIS management should focus on preventing further AIS introduction into areas of high Atlantic salmon conservation value, as a result of recommendations from the Management Matrix. AIS management should be action focused for isolated, high-impact AIS and scaled to be more broadly applied based on the AIS invasion stage and ecological impact.

The vector-based SLRA step should be viewed as a more in-depth analysis of 'activities' than Patricio et al.'s (2016) DPSIR framework, as it quantified the impact of each vector tested in this study. There are other examples of vector-based SLRA for AIS management (Chan et al., 2013; Davidson et al., 2017), but most only considered whether an AIS was likely present in a vector, the impact of species active within each vector and the proximity of the pathway to uninvaded habitat. Here, we took these vector-based SLRAs one step further by also including the transport volume and control difficulty of each vector (Brancatelli & Zalba, 2018). The transport volume considered both the transport capacity (i.e. how much of each species would arrive via that vector) and the number of available propagules of transport (i.e. the likelihood that each AIS active within that vector would be introduced multiplied by the estimated propagule annual duration). Furthermore, the control difficulty of each vector (CDV) added a management lens to the vector-based SLRA because it assumes that managers want to prioritize vector management where AIS introductions are more difficult to control post-introduction and this is baked into the series of yes/no questions used to determine control difficult for each species. For example, AIS that lack clear legislative authorities for control, response or management are more highly scored for CDV because if they are introduced then it will take longer for government organizations to respond, which lends more time to the newly introduced species to establish.

In terms of conservation goals, vectors that lead to introductions of high-impact AIS should be prioritized for management action. Hence, our vector-based SLRA incorporated both the likelihood of invasion and impact of invasion CMIST scores for each species used in the assessments. Within NS, unclean boats and gear were at higher risk of AIS introductions than other vectors, likely because this is a common pathway for biofouling species. Aquatic plants, decapods and molluscs (many of which are ecosystem engineers) are well-known biofouling species in freshwater environments (Davidson et al., 2017). Consequently, AIS managers can assist with biodiversity conservation management by prioritizing social programmes and enforcement of regulations that help mitigate the risk of vectors that are identified as high-risk. For Atlantic salmon conservation, AIS managers could promote 'Clean-Drain-Dry-Decontaminate' programmes (including a mix of regulation enforcement, public education and outreach, and installation of watercraft decontamination stations) and focus on watersheds of high Atlantic salmon habitat suitability with low AIS presence (Fisheries and Oceans Canada, 2021a, 2021b).

4.1 | Management prioritization, recommendations, gaps and future studies

The results of this study suggest that AIS management should focus on species that are ecosystem engineers, especially small, isolated populations where eradication or containment is possible. The vectors that are the highest risk of introducing AIS vary slightly between watersheds, but unclean boats and gear were the highest risk vector for most watersheds. Therefore, it is recommended that AIS managers start with tackling the highest risk vector, focusing on areas with low AIS presence. Regrettably, this study represents a limited test set of AIS and associated vectors. Thus, the results of the study may have been different if we included species that are not yet established in NS or included species that are currently managed as a recreational species within the assessment area (e.g. rainbow trout, *Oncorhynchus mykiss*, and brown trout, *Salmo trutta*) or if we expanded the vector-based SLRA to include a greater number of vectors. It is recommended that future studies include both species that are present and those that have yet to be established. Moreover, inclusion of zooids, bryozoan, parasites and diseases would help form a more inclusive picture of the threat of introductions to the assessment area. Parasites and diseases could be assessed both directly as the AIS and indirectly to determine their impacts on AIS.

Of significance, the model variable importance plot identified that parameters related to water temperature (e.g. climate change velocity, temperature change over distance, percentage of land clear-cut) were the most important parameters affecting Atlantic salmon presence/absence. Further research is needed to determine how these parameters, in combination with AIS presence, are affecting Atlantic salmon in situ. Also, the interactions between model parameters should be more closely examined. For example, timber harvesting in the riparian zone decreases freshwater climate resilience through greater fluctuations in water temperature (Collison & Gromack, 2022; Cunningham et al., 2023). Likewise, terrestrial invasive species such as hemlock woolly adelgid (*Adelges tsugae*), Dutch elm disease (*Ophiostoma ulmi* and *Ophiostoma novo-ulmi*), beech leaf-mining weevil (*Orchestes fagi*) and emerald ash borer (*Agrilus planipennis*) represent risks to forested riparian Atlantic salmon habitat, but are difficult to include in a HSM due to the high spatial and temporal variability in potential impacts to freshwater ecosystems (Emilson & Stastny, 2019; Haughn, 2020; Taylor et al., 2020). Thus, we recommend that some ground-truthing be conducted in priority areas that Atlantic salmon managers may consider for conservation. Investigations into the influence of riparian forest management or groundwater upwelling on stream temperature and Atlantic salmon thermal refugia are also recommended. The study represents an overview of prioritizations within a large-scale assessment area, but finer scale analysis is needed for watersheds identified as a priority because pressures may be very different throughout the watershed itself.

5 | CONCLUSIONS

Although interactions between AIS and Atlantic salmon are incredibly complex, our IMA went a step beyond standard linear (i.e. each pressure occurring sequentially) broader frameworks to provide region-specific advice for conservation goals and proactive AIS management. Our novel approach combined modelling, a management decision matrix, SLRAs, and data visualization to create multiple lines of evidence to identify pressures affecting conservation goals while ranking pressures based on importance and geographic overlap with sites and species of interest. The results of this study are broader than one specific pressure or species, as the study identified areas that benefited multiple native species, classified the risk of AIS, ranked pressure importance to Atlantic salmon presence/absence, and generated new tools that can be used for AIS decision-making for both species and vectors. For AIS managers, this study found that each watershed had a unique assortment of vectors and species but, overall, prioritization should be given to managing ecosystem engineers and halting introductions through unclean boats, equipment and gear. For Atlantic salmon in NS, we found that much of northern NS and a few watersheds within central NS hosted suitable habitat for salmon. Atlantic salmon conservation managers should focus efforts on mitigating pressures that affect habitat quality, especially pressures that increase water temperatures. Given the flexibility that has been enshrined in this framework, managers have the ability to focus on other regional areas or priorities. This study's recommendations are tailored for maximizing conserved habitat value and integrity, while decreasing the amount of resources required.

AUTHOR CONTRIBUTIONS

Andrew G. Lowles provided AIS expert review and collaboration on the thresholds in which the Management Matrix was sectioned. Ben R. Collison provided review and resources on Atlantic salmon habitat requirements, additional support on data gaps, and expert review on links between freshwater and riparian habitat. Ben Lowen advised on manuscript structure, model outputs and correlation plots. Christine Stortini provided additional data analyses for climate change resilience of Atlantic salmon and advised on relevant datasets available in Atlantic Canada. Marc Trudel and J. Derek Hogan provided expertise review and resources on Atlantic salmon. Sarah M. Tuziak advised on Atlantic salmon management. Sarah Kingsbury and Remi Daigle created the Management Matrix and the R code used for species invasion stage assessments and the CMIST Shiny App. Sarah Kingsbury completed all analyses, data collection, and wrote, edited and revised all manuscript drafts. All authors provided the critical review of manuscript drafts and have approved the final draft for publication.

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CONFLICT OF INTEREST STATEMENT

All authors declare no conflicts of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All data used in the assessment are publicly available and references for each data source are listed in the Data Sources section. Please refer to Table 1 of Supplementary Materials-Data Collection (SS1) for more details on which data were used in each analysis. R scripts and hard copies of data layers (e.g. locations of boat launches) can be accessed from https://doi.org/10.5281/zenodo.11067613 (SarahKingsbury-dfo, 2024).

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DATA SOURCES

Please refer to Supplementary Materials (SS1-Data Collection) for further details on which data sets were used for each analysis.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supplementary Materials SS1. Data collection.

Supplementary Materials SS2. Habitat suitability model details.

Supplementary Materials SS3. Watershed flower plots.

Supplementary Materials SS4. Vector screening-level risk assessment.

Supplementary Materials SS5. Species invasion stage and CMIST scores.

Supplementary Materials SS6. Acronyms.

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