Fisheries and Oceans Canada
Pêches et Océans Canada

Ecosystems and Oceans Science
Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2024/008

National Capital Region

National Aquatic Invasive Species (AIS) Risk Assessment for Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*Dreissena rostriformis bugensis*), April 2022

Mark A Wilcox[1], Andrea M Weise[2], Andrew J Guerin[2], Jackson WF Chu[3], and Thomas W Therriault[1]

[1]Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, British Columbia V9T 6N7

[2]Fisheries and Oceans Canada
Maurice Lamontagne Institute
850 route de la Mer
Mont-Joli, Quebec G5H 3Z4

[3]Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road
Sidney, British Columbia V8L 5G5

February 2024

Foreword

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

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-69718-5 Cat. No. Fs70-5/2024-008E-PDF

Correct citation for this publication:

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

Aussi disponible en français :

*Wilcox, M.A., Weise, A.M., Guerin, A.J., Chu, J.W.F., et Therriault, T.W. 2024. Évaluation nationale des risques liés aux espèces aquatiques envahissantes pour les moules zébrées (*Dreissena polymorpha*) et quaggas (*Dreissena rostriformis bugensis*), avril 2022. Secr. can. des avis sci. du MPO. Doc. de rech. 2023/008. iv + 92 p.*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*D. rostriformis bugensis*) are aquatic invaders with substantial economic and ecological impacts that continue to spread in Canada. A new ecological risk assessment (that differs from the 2012 assessment) was conducted by Fisheries and Oceans Canada (DFO) Science for freshwater ecosystems across Canada incorporating updated and improved data with greater resolution (9,260 × 9,260 m grid cell). This risk assessment characterized the potential for mussels to be introduced (propagule pressure) and establish (habitat suitability), along with their potential ecological impacts to derive a metric of Ecological Risk for two separate scenarios of establishment using either a calcium-based model or a maximum entropy (MaxEnt) habitat suitability model. Ecological Risk values are not absolute, and areas of Low risk do not necessarily indicate that Zebra and Quagga Mussel cannot be introduced, establish, or impact those Canadian ecosystems, but rather indicates that the risks are lower relative to areas at higher risk. As such, both scenarios identified Low to High risk areas with sub-drainages with the highest risk in proximity to the current distribution of these species, particularly the Laurentian Great Lakes system (both Zebra Mussel and Quagga Mussel) and Manitoba (Zebra Mussel). Outside of the current distribution, calcium-based models for both species identified Moderate risk areas throughout the southern portions of most provinces. In the Maritime provinces for which data was not available in the previous assessment, most habitat suitability models identified the area as Moderate risk for both Quagga and Zebra Mussel, particularly New Brunswick which also exhibited some discrete areas of High risk. For the rest of Canada, including Newfoundland and Labrador and the Territories for which data were also unavailable in the previous assessment, the risk for both species across most habitat suitability models was predominantly Low, with most of the Arctic Archipelago being below the thermal tolerance for both species. To facilitate Aquatic Invasive Species (AIS) management decision-making, Ecological Risk is summarized at the sub-drainage level for all of Canada which was the spatial scale used in the 2012 assessment.

1. INTRODUCTION

1.1. RISK ASSESSMENT

1.1.1. Context and Rationale

Invasive species are important drivers of ecosystem change, including biodiversity and habitat loss (Sala et al. 2000, Clavero and García-Berthou 2005, Gallardo et al. 2016, Mollot et al. 2017). In freshwater ecosystems, Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*D. rostriformis bugensis*) are two species that have caused significant ecological and economic impacts in Europe and North America (Mackie and Claudi 2010, Van der Velde et al. 2010). These invasive filter feeders act as ecosystem engineers, restructuring energy flow from pelagic to benthic pathways, changing the physicochemical conditions in the water column, contributing to increases in aquatic vegetation and shifts in native communities, and forming dense colonies attached to hard substrates, including on native mussels which may result in decreased survival and productivity (Karatayev et al. 2002, Mackie and Claudi 2010, Nakano and Strayer 2014).

Risk assessments can be used to identify the likelihood and consequences of an invasion and guide management actions. In 2012, Fisheries and Oceans Canada (DFO) Science conducted an ecological risk assessment for three dreissenid mussels in Canadian freshwater ecosystems with an emphasis on Western Canada, Ontario, and Quebec (DFO 2013 a, b, Therriault et al. 2013). In addition to several already invaded sub-drainages in Ontario and Quebec, the 2012 risk assessment identified several High risk areas, including many sub-drainages in Western Canada as well as in southern Quebec. However, data were unavailable at that time to fully assess the risk to sub-drainages in the Maritimes, Newfoundland and Labrador, and the Canadian Arctic.

Over the past decade, dreissenid mussels have continued to expand their distribution in Canada. In 2013, Zebra Mussel was discovered in Lake Winnipeg (predicted as High risk in Therriault et al. 2013) and spread throughout the system and into adjacent waterbodies during the following years, including the Manitoban portion of the Red River, Cedar Lake, Nelson River, and Lake Manitoba (Laureen Janusz, Manitoba Department of Economic Development, Investment Trade and Natural Resources, pers. comm.). In Eastern Canada, despite the presence of dreissenid mussels since 1990 in the freshwater portion of the St Lawrence River, expansion into Quebec inland lakes only recently occurred in 2017 when Zebra Mussel was detected for the first time in Lake Memphremagog (Picard and Doyon 2018) and more recently in 2021 in Lake Massawippi (L'actualité 2021) (predicted as High risk in Therriault et al. 2013). Zebra Mussel was also found in moss ball products (a spherical ball of hair-like algae) associated with the aquarium trade across Canada in 2021 increasing their potential for spread (DFO 2021a).

In response to a request from DFO's Aquatic Invasive Species National Core Program, the objective of the present assessment is to identify the ecological risk posed by Zebra and Quagga Mussel in all Canadian freshwater ecosystems by expanding the spatial coverage across Canada, including updated species distribution data and a greater number of environmental variables at an increased spatial resolution, and by using two habitat suitability modelling approaches. Sources of uncertainty and data gaps will also be identified. This new risk assessment and subsequent science advice arising from this process will inform management actions, including early detection, response planning, and/or regulatory and policy measures aimed at mitigating potential risk posed by invasive Zebra and Quagga Mussel to Canadian freshwater ecosystems.

1.1.2. Scope and Scale

This risk assessment focuses on the potential ecological risks posed by Zebra and Quagga Mussel to Canadian freshwater ecosystems in the current climate and does not consider socio-economic aspects which are beyond the scope of this assessment.

The geographic scope of this risk assessment was expanded from the 2012 risk assessment to include all freshwater ecosystems of Canada, including all provinces and territories. Coastal marine or estuarine habitats were not included in the present work and as such, the Dark False Mussel (*Mytilopsis leucophaeata*), which was assessed in the previous risk assessment, is excluded here.

Compared to the 2012 risk assessment (Therriault et al. 2013), this assessment was conducted at a higher spatial resolution (grid cells of 9,260 × 9,260 m) and included additional environmental variables such as calcium concentrations and pH interpolated across Canada. For modelling purposes, the extent of the study area included Canada and the continental United States. It is important to note that results are not directly comparable to the 2012 assessment as they are based on updated data and different modelling approaches. Further, there are differences with respect to how certain components of invasion risk were determined. For example, in the 2012 assessment, connectivity as part of the estimation of potential propagule pressure was modelled as a simple function of whether a sub-drainage was adjacent to an invaded sub-drainage whereas here, connectivity was modelled as a geospatial function (see below) of proximity to invaded areas. Similarly, habitat suitability was modelled using two different approaches with each a refinement over the 2012 assessment. Finally, there are some differences with respect to terminology. Since the true probabilities for each step in the invasion process that leads to successful establishment is unknown, proxies for these probabilities using available variables known to be related to invasion risk were used. However, ecological risk still represents the product of the potential for invasion and ecological impacts expected from an invasion which is fundamentally the same as the previous assessment.

1.2. BIOLOGY, HABITAT PREFERENCES, AND ECOLOGICAL IMPACTS

1.2.1. Biology and Habitat Preferences

Therriault et al. (2013) provided extensive details on taxonomy, species descriptions, habitat preferences, life history, and population genetic structure. As these have not changed since the original assessment, only a brief overview is given here.

Although the species are remarkably similar morphologically, Zebra Mussel are less round and usually have a striped pattern as opposed to the more concentric rings of the Quagga Mussel (Figure 1). Adult individuals of both species typically average 2-3 cm in shell length, but Zebra Mussel may reach 4-4.5 cm compared to 3.5-4 cm for Quagga Mussel (Mackie and Claudi 2010).

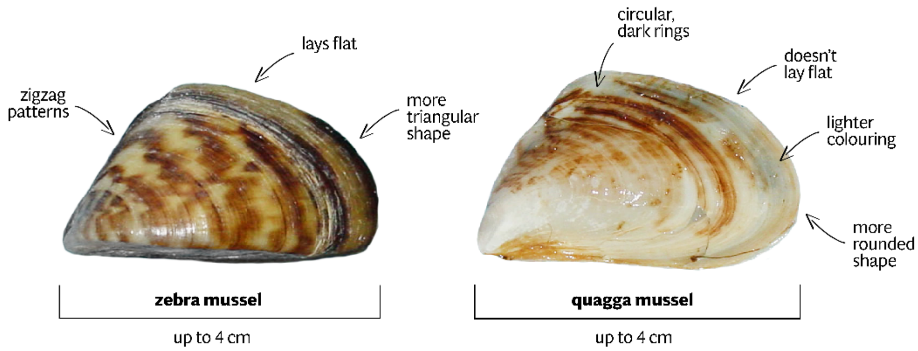

Figure 1. Photographs of a Zebra Mussel and Quagga Mussel. The Zebra Mussel has zigzag patterns, a triangular shape, and lays flat while the Quagga Mussel has a lighter coloring, a more rounded shape, circular rings, and does not lay flat (Photos by Amy Benson, US Geological Survey, bugwood.org and modified by the Invasive Species Centre).

Zebra and Quagga Mussel are typically found in lakes and rivers attached to a wide variety of hard substrates such as rocks, shellfish, and aquatic plants (Garton et al. 2013). Despite their similar appearance, Quagga and Zebra Mussel differ in temperature and salinity tolerances, growth, depth of occurrence, and life history traits (Ram et al. 2011, Karatayev et al. 2015). Both species have short life spans but are prolific breeders producing 1×10^4 to 1×10^6 eggs per female per year depending on size and environmental conditions (Pollux et al. 2010). Although they have broad environmental tolerances, a variety of factors may limit their distribution, including temperature, calcium, pH, substrate, and nutrients (e.g., Strayer 1991, Neary and Leach 1992, Ramcharan et al.,1992, Mellina and Rasmussen 1994, Mackie and Claudi 2010) in addition to biotic resistance (Carlsson et al. 2011, Dominguez Almela et al. 2022).

Calcium concentrations are considered a major factor in the potential for establishment and development of large populations as a significant quantity of calcium is required for shell development (Mackie and Claudi 2010). European and North American Zebra Mussel populations show different calcium thresholds (Mackie and Schloesser 1996, Cohen and Weinstein 2001). For example, Ramcharan et al. (1992) reported that Zebra Mussel was not found in European lakes where calcium concentrations were below 28.3 mg/L and pH below 7.3. However, in North America, Zebra Mussel has been reported from several lakes with calcium concentrations between 13-25 mg/L (Strayer et al. 1996, Mellina and Rasmussen 1994). The scientific literature suggests that minimum calcium concentrations for North American Zebra Mussel populations are around 8-9 mg/L for adult survival, 11-12 mg/L for short-term veliger survival, and 15-22 mg/L for veliger development (Hincks and Mackie 1997, Mackie and Claudi 2010). Benson et al. (2022) similarly reported that North American Zebra Mussel populations require 10 mg/L calcium to initiate shell growth and 25 mg/L to maintain shell growth. In their literature review of threshold limits for growth, reproduction, and survival of Zebra Mussel, Mackie and Claudi (2010) suggested calcium concentrations: < 8 mg/L (no potential for adult survival), 8-15 mg/L (little potential for larval development), 15-30 mg/L (moderate potential for nuisance infestations), and > 30 mg/L (high potential for massive infestations). For Quagga Mussel, Mackie and Claudi (2010) similarly reported calcium thresholds of < 10 mg/L (no potential for adult survival), 10-12 mg/L (little potential for larval development), 12-30 mg/L (moderate potential for nuisance infestations), > 30 mg/L (high potential for massive infestations).

In addition to calcium, temperature and pH were also identified as important factors governing the establishment of dreissenid populations. Zebra Mussel was found to have no potential for adult survival at temperatures below 10°C or greater than 32°C, with the highest potential for massive infestations between 20 and 26°C (Mackie and Claudi 2010). Quagga Mussel, which are typically more abundant than Zebra Mussel at greater depths (Roe and MacIsaac 1997, Ricciardi and Whoriskey 2004), have a lower reported thermal threshold of 5°C for growth and reproduction (Roe and MacIsaac 1997). Mackie and Claudi (2010) similarly reported little potential for larval development at 2-10°C, no potential for adult survival at < 2°C, and concluded that 16-24°C were optimal temperature conditions for massive Quagga Mussel infestations. With respect to pH, Mackie and Claudi (2010) note that both dreissenids have no potential for adult survival below a pH of 7.0, little potential for larval development between pH 7-7.8 and 9-9.5, with moderate and high potential for infestations at pH 7.8-8.2 and 8.2-8.8, respectively.

1.2.2. Ecological Impacts

The effects of dreissenid invasions on water quality, flora, and fauna of invaded habitats are well described in the scientific literature (e.g., Higgins and Vander Zanden 2010, Higgins 2014, Therriault et al. 2013). There is little doubt that dreissenid mussels can induce significant and ecologically relevant negative impacts on water quality and all major trophic levels from sediment bacteria to apex predators (e.g., piscivorous fishes). A temporal analysis of environmental variables in invaded habitats including secchi depth, chlorophyll *a* concentration, and total phosphorus concentration showed that the effects of a dreissend infestation were pervasive, with no evidence of decline 20 years post-establishment (Higgins et al. 2011, Higgins 2014). The effects of dreissenid mussel infestations have been shown to be directional, affecting the pelagic-profundal energy and the benthic-littoral pathways differently with a marked decrease in energy transfer within the pelagic-profundal pathway and a marked increase in energy transfer within the benthic-littoral pathway (Figure 2 and Table 1). However, members of two families of native freshwater mussels, Unionidae and Sphaerriidae, which are part of the benthic-littoral energy pathway and who compete for space and/or food with dreissenid mussels, are an exception as it has been well documented that populations of these species either decline significantly or are completely lost from the system when dreissenids invade (e.g., Gillis and Mackie 1994, Ricciardi et al. 1996). It is important to note that the magnitude of impact on biota within the pelagic-profundal pathway is related to the filtration capacity of the mussel population, which is a function of population density, the ecosystem size, and a variety of factors that affect individual filtration rates (e.g., temperature, water velocity, turbidity) and access to the water-column (e.g., depth, vertical and horizontal mixing) (Higgins 2014). Dreissenid densities can vary by several orders of magnitude over space (within and among lakes or rivers) and time (e.g., years), and whole-ecosystem densities typically are unknown. However, impacts appear to scale with ecosystem size, with smaller ecosystems and the littoral zones of large lakes showing the largest impacts (Higgins and Vander Zanden 2010).

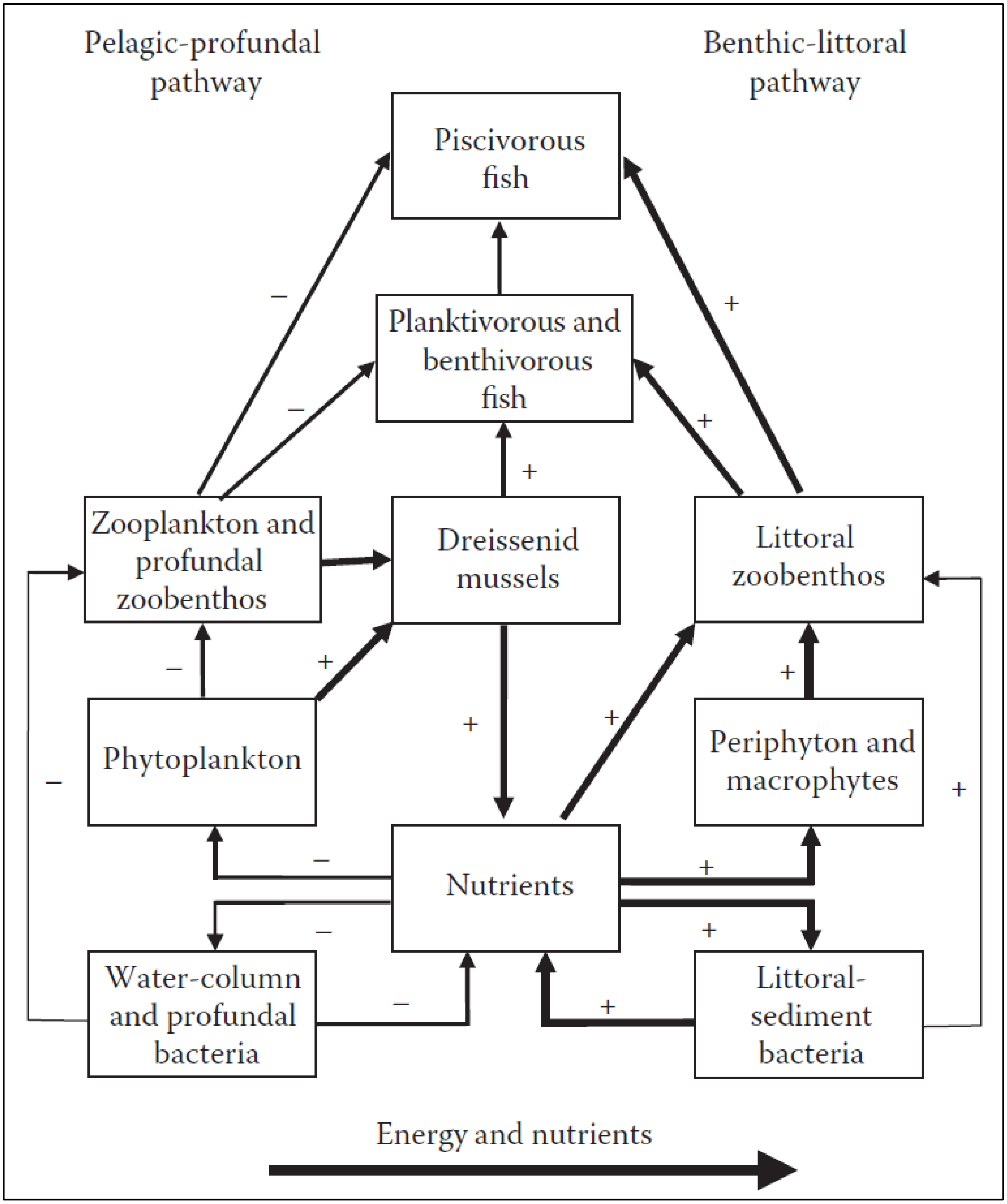

Figure 2. Framework for the restructuring of food webs in freshwater ecosystems after dreissenid invasion. Arrows represent the direction of flow. Bold lines and plus symbols (+) represent increased fluxes, while minus symbols (−) represent reduced fluxes (source: Higgins 2014).

Table 1. Ecological impacts associated with Zebra and Quagga Mussel invasions as reported in the scientific literature (from Therriault et al. 2013, modified from Higgins and Vander Zanden, 2010).

Element	Survey/Literature Results		
	Direction	Magnitude	Uncertainty
Physical habitat			
Water clarity	Increase	High	Very Low
Thermocline depth	Increase	Low	High
Littoral zone depth	Increase	Moderate	Low
Hard substrate fouling	Increase	High	Very Low
Soft substrate fouling	Increase	Moderate	Very Low
Deepwater anoxia	Increase	Low	Very High
Sediment anoxia	Increase	Moderate	High
Chemical habitat			
Particulate nutrients	Decrease	Moderate	Very Low
Soluble nutrients (Lakes)	Increase	Low	Very Low
Soluble nutrients (Rivers)	Increase	High	Very Low
Suspended sediments	Decrease	High	Very Low
Biota			
Sediment bacteria	Increase	High	Very Low
Phytoplankton (total)	Decrease	High	Very Low
Phytoplankton (toxin producing cyanobacteria)	Increase	Moderate	Very Low
Periphyton	Increase	High	Very Low
Macrophyte cover	Increase	Moderate	Very Low
Zooplankton	Decrease	Moderate	Very Low
Zoobenthos (littoral)	Increase	High	Very Low
Zoobenthos (profundal)	Decrease	Moderate	Very Low
Unionid mussel (abundance)	Decrease	Very high	Very Low
Fish (planktivore)	Decrease	Moderate	Moderate
Fish (benthivore-littoral)	Increase	Moderate	Very Low
Fish (deepwater benthivore)	Decrease	High	Moderate
Fish (piscivore)	Decrease	Moderate	Moderate
Avian botulism	Increase	Moderate	High
Biodiversity			
Unionid mussel	Decrease	Very High	Very Low
Sphaeriid mussel	Decrease	Very High	Low
Species at Risk	Decrease	Low to High	Very High

As dreissenid mussels remove phytoplankton and other suspended particulate matter from the water column, water clarity often increases substantially (Table 1). Water clarity is a contributing factor to the penetration of solar energy into lakes, affecting the thermocline depth and heat budgets of lakes, and the growth of algae and plants on the lake bottom. Increasing thermocline depths reduces the volume of the hypolimnion, which could increase deep-water anoxia in some lakes and reduce cold-water habitat for some fish species (Mills et al. 2003). In some systems, such as the lower Laurentian Great Lakes (Lakes Ontario, Erie, and Michigan), dreissenid invasions led to dramatic increases in nuisance blooms of the benthic alga *Cladophora glomerata* (Higgins et al. 2008). These blooms significantly modified benthic habitats, fouled recreational beaches, municipal and industrial water intakes, were associated with increased abundance of indicator bacteria (e.g., *E. coli*) and pathogenic bacteria (e.g., *Salmonella,* *Shigella, Campylobacter*), were thought to contribute to avian botulism, and to cause localized anoxia to sediments and sediment biota within depositional areas (Higgins et al. 2008). In some locations (e.g., Saginaw Bay [Lake Huron] and Lake Erie) and inland lakes in Michigan, dreissenid invasions led to an increase in toxin producing phytoplankton species, and their toxin (microcystin), even as total phytoplankton biomass declined (Raikow et al. 2004, Knoll et al. 2008). This hepatotoxin is known to affect liver function and is a concern both for native biota and humans (Wilson et al. 2008).

When there is spatial overlap between dreissenid mussels and at-risk native species, the negative effects of an infestation are expected to be very high. For example, dreissenid mussels have had significant negative impacts on at-risk native unionid mussels in the Great Lakes following their introduction, including significant declines in abundance and species diversity (Schloesser et al. 1998, Ricciardi et al. 1998). Further, in British Columbia, the Rocky Mountain Ridged Mussel (*Gonidea angulata*) was classified as Endangered due to the potential of a dreissenid invasion. As of February 2022, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has identified 21 at-risk freshwater molluscs including 13 Endangered, three Threatened and five of Special Concern. Similarly, should dreissenid mussels establish high-density populations in freshwater systems beyond their current range in eastern North America, they could potentially affect the fitness of several COSEWIC-listed fish species (COSEWIC 2021), notably molluscivores and planktivores.

1.3. VECTORS

Both dreissenid species were likely introduced to the Great Lakes via ballast water rather than hull fouling due to the longer transit times and oceanic environments that would exceed reported salinity tolerances (e.g., Hebert et al. 1989, Therriault et al. 2004).

In contrast, secondary invasions of both species have been linked to overland transport of recreational boats (e.g., Johnson and Padilla 1996, Orlova et al. 2004, Pollux et al. 2010, Karatayev et al. 2015, Drake et al. 2017). Both dreissenid species can also spread via natural dispersal (e.g., pelagic larval dispersal and secondary settlement) or other human-mediated activities (e.g., intra-basin ballast water discharge, canal creation, waterway operations, etc.) (e.g., Johnson and Carlton 1996, Orlova et al. 2005, Ricciardi 2006). Natural dispersal is especially important for downstream dispersal in larger systems with upstream lakes or reservoirs that can act as a source of propagules (e.g., Therriault et al. 2004, 2013). Finally, the recent detection of Zebra Mussel in moss ball shipments highlighted an unexpected vector and new pathway through the pet/aquarium plant trade (DFO 2021a). Although assessing the risk of this specific vector is beyond the scope of this assessment, the pathway risk assessment of organisms in trade in Canada by Chan et al. (2021) demonstrated that risk was greater in urban areas which is at least partially captured by the Human Footprint Index used in this risk assessment (see below).

1.4. DISTRIBUTION

1.4.1. Native Range

Both Zebra and Quagga Mussel are native to the Ponto-Caspian Region of eastern Europe. Zebra Mussel is considered native to the Black Sea basin, including the Sea of Azov (Van der Velde et al. 2010) while Quagga Mussel is native to the Dnieper and Bug Limans of the Black Sea basin (Son 2007).

1.4.2. Introduced Range

Zebra Mussel has an extensive freshwater introduced range due to an invasion history that dates to the late 18th century in Europe (see Therriault et al. 2013). It arrived in the Laurentian Great Lakes of North America in the mid-1980s, due to ballast water discharge from commercial shipping, and has spread extensively around the Great Lakes basin and along the Mississippi River and its tributaries. By 1998, the Zebra Mussel had colonized most of the major river systems in the eastern United States (Mackie and Claudi 2010, Benson et al. 2022). More recently this species has been found in Manitoba and additional parts of southern Quebec but is not reported in Saskatchewan, Alberta, British Columbia, Atlantic Canada or any of the Territories (Figure 3A).

Quagga Mussel also has invaded parts of Europe and North America. In contrast to the rapid expansion noted for Zebra Mussel in the eastern United States, the Quagga Mussel has remained more contained to the Great Lakes basin. Although long range overland transport of this species has occurred in several western states of the United States, Quagga Mussel is not yet known to have invaded Western or Atlantic Canada (Figure 3B).

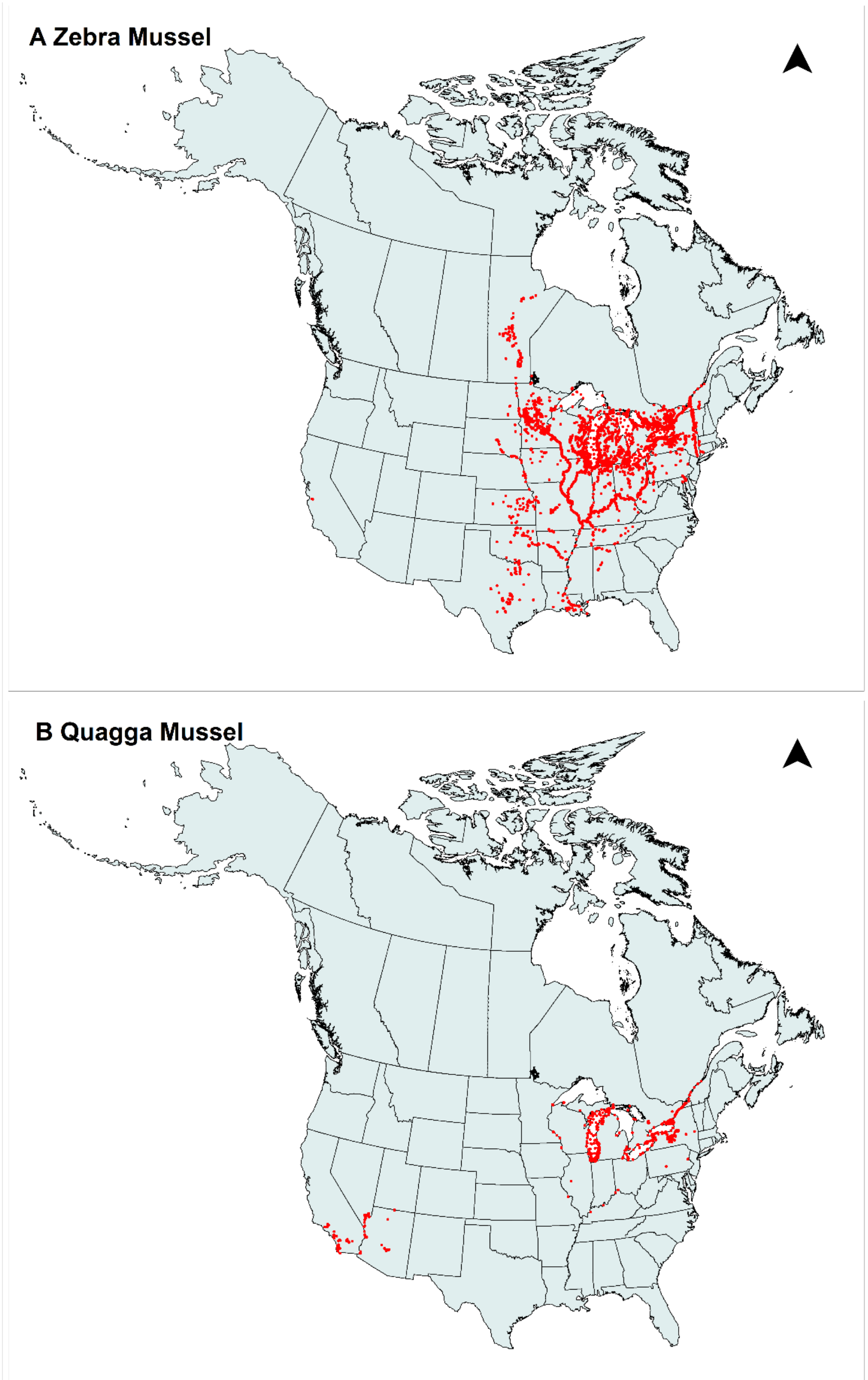

Figure 3. Established Zebra (A) and Quagga (B) Mussel populations (red circles) reported between 1986 and 2021 and between 1989 and 2021 in North America, respectively (sources are listed in Table A1).

2. RISK ASSESSMENT METHODOLOGY FOR ZEBRA AND QUAGGA MUSSEL

In general, risk represents the product of the probability of an event occurring and the consequences of that event. Thus, in this assessment, Ecological Risk for Zebra and Quagga

Mussel represents the likelihood of an invasion occurring and the consequences or expected impacts of that invasion for each of the spatial units (grid cells) over an approximate period of about 5-10 years (representing current climatic conditions). The likelihood of invasion represents the sequential steps in the invasion process where an organism must be entrained in an invasion vector, moved by that vector to a new location, survive transit, be released from the vector into a new ecosystem, encounter conditions amenable for survival and reproduction, and then spread from the initial introduction point (e.g., Blackburn et al. 2011). As such, invasions are complex with many unknowns and uncertainties such that true probabilities around this sequence of events leading to a successful invasion are not known thus requiring the use of proxies. This assessment integrates several metrics relating to the potential for the species to be introduced and establish along with the ecological impacts to determine Ecological Risk (Figure 4). For Zebra and Quagga Mussel to invade a new location (and pose a risk), propagules must reach suitable habitat. Thus, introduction is a function of both proximity to invaded locations (that are supplying propagules; using occurrence points up to 2021) and the human-mediated activities or natural dispersal that can move propagules from source locations to new recipient destinations on the landscape (the latter of which is modelled here using the Human Footprint Index) (see Section 2.1). There is insufficient data to model species- and location-specific entrainment and movement. Once propagules reach a new location, they must encounter conditions that allow them to survive and reproduce to establish new populations that will have ecological consequences. Thus, establishment represents the overlap between the physiological requirements/tolerances of the invader and environmental conditions in the assessment area. The potential for a species to establish was derived here by considering both a calcium-based model and a maximum entropy (MaxEnt) habitat suitability model (see Sections 2.2.3 and 2.2.4) with both incorporating a temperature threshold below which larval survival is no longer conducive (see Section 2.2.5). Both methods have strengths and weaknesses in their ability to predict suitable habitat and thus are presented as separate calculations for determining Ecological Risk as it is not possible to identify a preferred model. Given the scope of this assessment and limited location-specific data, the potential for secondary spread was not determined explicitly. However, given the rapid expansion of these species across North America and Europe there is little doubt that human-mediated activities combined with natural downstream dispersal of veligers will re-distribute Zebra and Quagga Mussel at smaller spatial scales across the Canadian landscape. For both Zebra and Quagga Mussel the ecological consequences of their invasions have been very high with impacts across multiple trophic levels regardless of the system they have invaded. Finally, the likelihood of an invasion was combined with the consequences of an invasion using a heat matrix to determine overall Ecological Risk (see Section 2.5). The environmental variables and dispersal factors that were used for the modelling are shown in Table 2 and are described in more detail in the following sections. All data layers (rasters) were projected into North American Albers Equal Area Conic (AEAC) with a high resolution (9,260 × 9,260 m cell size; hereafter referred to as the grid cell resolution) at an extent that covers both Canada and the continental United States.

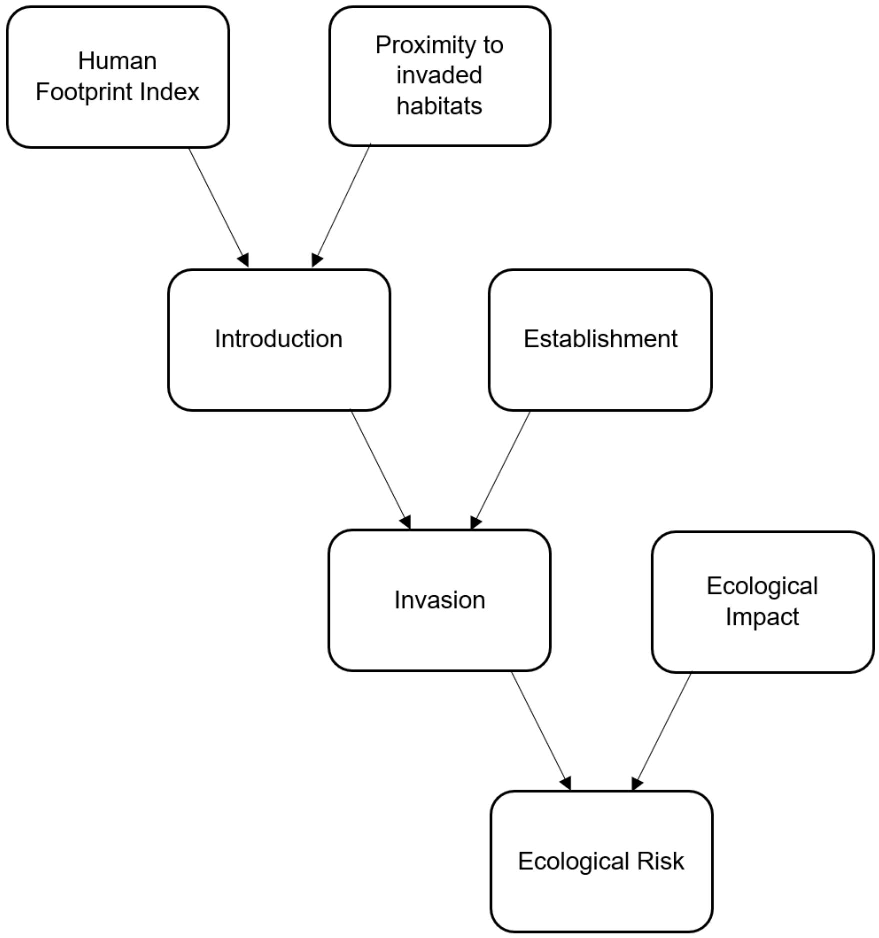

Figure 4. Conceptual flow diagram of the risk assessment process for Zebra and Quagga Mussel invasion into Canadian freshwaters. Two modelling scenarios were used to determine suitable habitats for establishment: a calcium-based model and a MaxEnt model.

Table 2. Data layers (variables) used to assess the probability of Zebra and Quagga Mussel introduction and establishment.

Data Layer	**Modelling Step**	**Justification**	**Source**
Human Footprint Index	Potential for Introduction (Both models)	This index is used as a proxy for propagule pressure since human activities are known to influence the spatial distribution of invasive species and the magnitude of potential vectors. It is a composite factor of human influence that integrates data of land use, urbanization, population density, transportation networks, and other human activities that are known to facilitate species invasions.	Modified from Venter et al. (2018)
Connectivity Metric	Potential for Introduction (Both models)	Because recreational boating is known to be an important vector of secondary spread of aquatic invasive species (Drake 2017, Drake et al. 2017), a metric was developed based on proximity to invaded habitats and distances typically travelled by recreational watercraft. It also	Developed in the present study

Data Layer	Modelling Step	Justification	Source
		accounts for potential natural dispersal in that waterbodies near an invaded location have a higher probability of introduction.	
Calcium	Potential for Establishment (Both models)	Calcium represents a critical constraining factor for dreissenid mussel invasion success as it is required for basic metabolic function as well as shell building (Hincks and Mackie 1997, Cohen and Weinstein 2001, Jones and Ricciardi 2005). Previous models have excluded calcium because data was unavailable in the format of a continuous global or North American layer.	Developed in the present study
pH	Potential for Establishment (MaxEnt)	pH levels influence dreissenid mussel survival and growth (Mackie and Claudi 2010). Previous models have excluded pH because data was unavailable in the format of a continuous global or North American layer.	Developed in the present study
Air Temperature	Potential for Establishment (MaxEnt)	Water temperature is important for the reproduction, spawning, and growth of dreissenid mussels (McMahon, 1996, Mackie and Claudi 2010). WorldClim air temperatures are used as a proxy for water temperatures, as these are assumed to be correlated (Stefan and Preud'homme, 1993).	Fick and Hijmans 2017
Precipitation	Potential for Establishment (MaxEnt)	Precipitation can influence lakes nutrients and productivity (Collins et al. 2019). It may also affect the discharge and depth of rivers and lakes and therefore habitat availability.	Fick and Hijmans 2017

2.1. POTENTIAL FOR INTRODUCTION

For Zebra and Quagga Mussel to pose a risk to a Canadian ecosystem they first must be introduced to that system. The Potential for Introduction is related to both the ability of propagules to be moved from a source population and the proximity of that population (as both likelihood and survival is greatest over shorter distances). While natural dispersal certainly contributes to the spread of invasive dreissenid mussels within waterbodies, human mediated transport such as recreational boater movements is widely considered to be the primary vector for introduction among waterbodies both in North America and Europe (e.g., Johnson and Padilla 1996, Orlova et al. 2004, Pollux et al. 2010, Karatayev et al. 2015, Drake et al. 2017). Further, the geographic distance of novel waterbodies to the current distribution of invaded habitats has been shown to be an appropriate indicator of invasion risk in lake systems (e.g., Karatayev et al. 2015). As such, a connectivity metric was developed based on geographic distance from the currently known distribution for each dreissenid species (up to 2021) to approximate the likelihood of dispersal (both natural and anthropogenic) between source and sink locations. These values were then scaled to reflect boater activity with respect to the distances traveled by recreational boaters, the most likely vector for overland dispersal of these species. This metric was combined with the Human Footprint Index (Venter et al. 2016, 2018) which is a relative index based on human population density and activity as a means of accounting for geographic variability in the magnitude of boating activity (or other human-mediated movements). Novel vectors such as contaminated aquarium moss balls are also likely represented by the magnitude of human activity. For example, Chan et al. (2021) showed that aquarium shops are aggregated in urban areas where population density is greater, which is captured by the Human Footprint Index.

2.1.1. Human Footprint Index

The Human Footprint Index (Venter et al. 2016, 2018) was employed as a proxy for the magnitude of boating activity and has been used in previous modelling studies (e.g., Liu et al. 2011, Gallardo et al. 2015, Srivastava et al. 2019). This index provides a global map of the cumulative human pressure on the environment in 2009 using eight variables including built-up environments, population density, electric power infrastructure, crop lands, pasture lands, roads, railways, and navigable waterways (Venter et al. 2016, 2018). Since many input variables are terrestrial this index does not extend over bodies of freshwater and thus was modified for this application. Specifically, values from surrounding grid cells were interpolated to those with "no data" for lakes and large rivers using the geospatial data abstraction library (GDAL) Fill No Data algorithm in Quantum Geographic Information System (QGIS) (Figure 5).

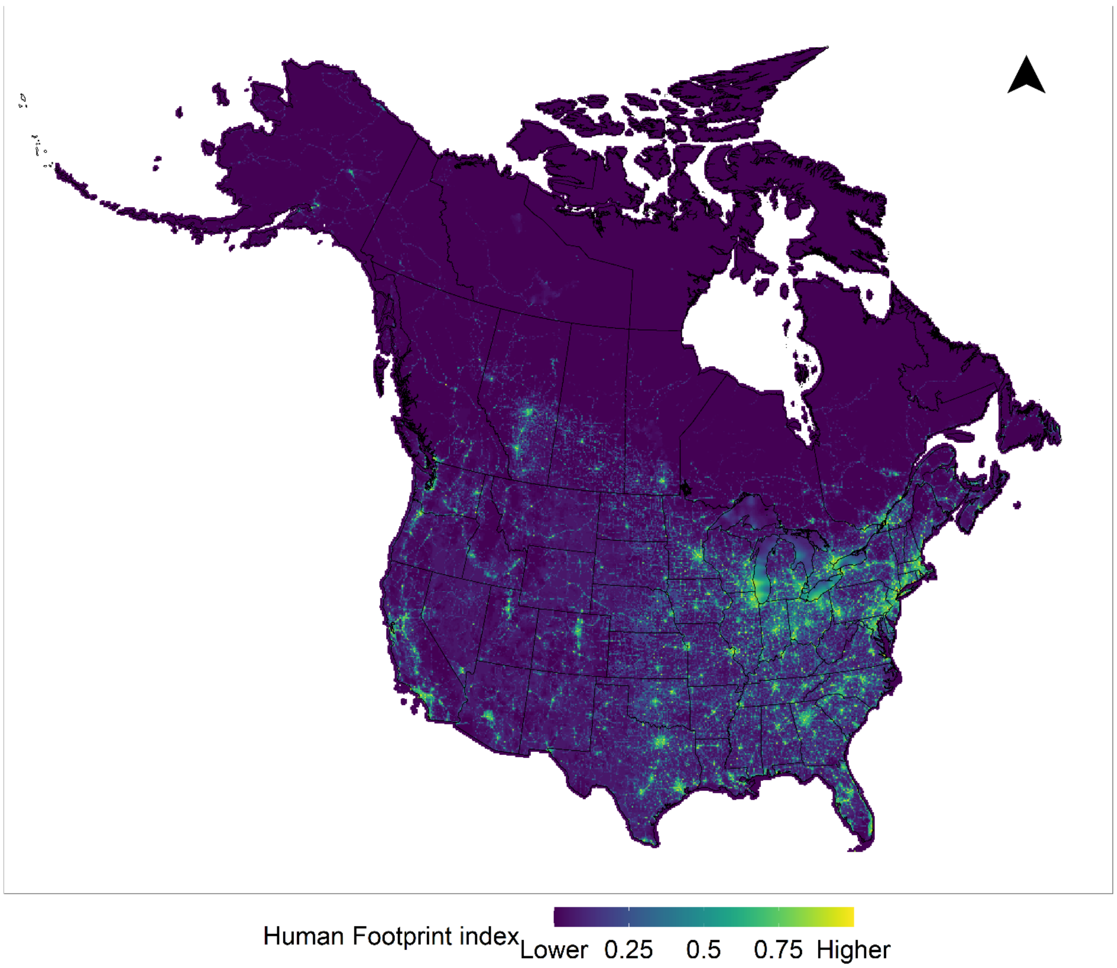

Figure 5. Propagule pressure derived from the Human Footprint Index (modified from Venter et al. 2018). The Human Footprint Index is a composite factor of human influence that integrates data on land use, urbanization, population density, transportation networks, and other human activities that are known to facilitate species invasions.

2.1.2. Connectivity Metric

Several studies have noted that many recreational boats travel relatively small distances among waterbodies and that these shorter distance movements may facilitate the spread of dreissenid mussels (Dove and Wallis 1981, Johnstone et al. 1985, Buchan and Padilla 1999). Further, natural dispersal is more likely in connected systems and over smaller spatial scales. A connectivity function was created using occurrence records to account for the contribution of these components to the Potential for Introduction. Sample points were created using the spsample function from R package sp (Pebesma and Bivand 2005) at a cell size of 4,630 × 4,630 m for the working extent which ensured that at least one sample point would be contained within each cell when creating the raster at the grid cell resolution. Sample points were then masked to remove any points generated in marine environments. The minimum great circle distance (distance along the surface of a sphere) between each sampling point and each occurrence point was then calculated using distHaversine function from R package geosphere (Hijmans et al. 2021). The resulting values for distance were then scaled between 0.00001 and 1 (very low to high connectivity, respectively) to standardize this metric and facilitate integration with other data layers (rasters). The scaling function was based on data from several studies examining the cumulative distribution of recreational boater travel distances. Several studies conducted in the United States, Canada, and New Zealand reported high proportions of recreational boaters travelling less than 150 km (e.g., 97.8% of boats remained within 150 km in Wisconsin, Buchan and Padilla 1999; 97.5% of boats remained within 125 km on the North Island of New Zealand, Johnstone et al. 1985; 90.1% of boaters in British Columbia travelled less 125 km, Dove and Wallis 1981) and as far as 450 km (Buchan and Padilla 1999). However, these studies had a smaller geographic scope than the present assessment and it is likely boaters could travel far greater distances in certain situations. Thus, to extend the results of these studies, an analysis of the distribution of boater travelling distances was conducted using data from boat inspections for British Columbia from 2017-2021 (M. Beck, British Columbia Ministry of Environment and Climate Change Strategy, pers. comm) which given the coastal positioning of the province likely represents an extreme for boater travelling distances. For this analysis, only records where the origin or destination was British Columbia were retained. For each state, province, or territory that was either the origin or destination, a reference point was approximated for the centroid of that geographic area. For provinces other than the Maritimes, where the geographic distribution of the population is skewed to the south, the reference point was placed within the centroid of populated areas (generally towards the south). Great circle distance was then calculated between each centroid to the centroid for British Columbia and the cumulative distribution of travel distances was calculated. While the precision may not be high due to the assumption of similar distance for all individuals travelling to or from the state, province, or territory, the general trends corresponded with the aforementioned studies on recreational boater traveling distances. The greatest proportion of travelers remained within British Columbia (70%) likely representing travel distances less than 200 km. Of the remaining travellers whose destinations or origins were beyond the provincial borders, approximately 25% of boaters travelled 600 km or less and only approximately 1% travelled further than 2000 km. To scale each value of connectivity, a polynomial equation was applied to the distance values derived for each sampling point (see Table 3). This polynomial was developed using the following data: designated values of 1 for distances of 0 km, 0.5 for a distance of 600 km, and 0.25 for a distance of 1000 km, with all values greater than 1500 km set to a value of 0.00001. Scaled values for each sample point were then set to a raster using the rasterize function from R package raster (Hijmans 2021) at the grid cell resolution with value of each cell representing the mean value of sampling points contained within that cell. The maps of connectivity for Zebra and Quagga Mussel invaded habitats are shown in Figures 6A and 6B, respectively.

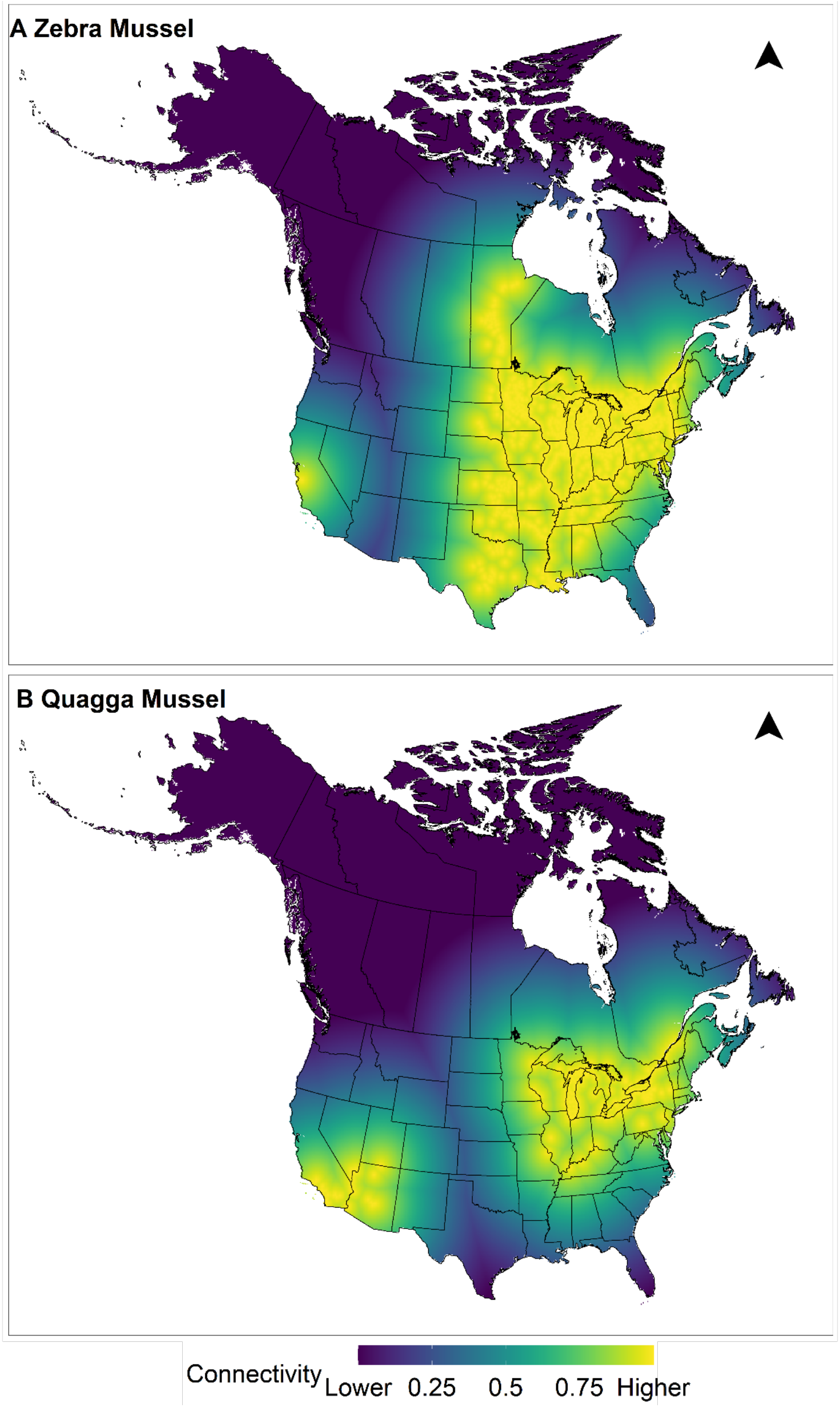

Figure 6. Map of connectivity for Zebra (A) and Quagga (B) Mussel invaded habitats.

Table 3. Scaling equations used to standardize metric values within rasters.

Standardization	Equation
Scaling of distance values for connectivity based on boater activity (units = m)	$0.0000000000002x^2 - 0.0000009612x + 1$ With distances > 1500000 m set to a scaled value of 0.00001
Scaling of calcium values based on biologically meaningful values (units = mg/L)	Zebra Mussel: $-0.00005x^3 + 0.0016x^2 + 0.0321x + 0.00001$ With all concentrations > 30 mg/L set to a scaled value of 1
	Quagga Mussel: $-0.00068x^2 + 0.0543x - 0.01448$ With all concentrations > 30 mg/L set to a scaled value of 1

2.1.3. Combing the Human Footprint Index and Connectivity Metric

While both the magnitude of human activity and connectivity clearly contribute to the potential for dreissenid mussels to be introduced, the relative contribution of each metric to propagule pressure is unknown. Thus, the Potential for Introduction was calculated as an equally weighted integration of both factors (see Figure 4). The resulting raster therefore represents the mean value of the Human Footprint Index and connectivity metric for each cell, with values between 0 and 1 (very low and high Potential for Introduction, respectively). Given that there is no data to suggest any areas are impermeable to introduction, all values for this metric are greater than 0 (i.e., propagules can theoretically reach any location in Canada).

2.2. POTENTIAL FOR ESTABLISHMENT

The likelihood that an invasive species will establish is dependent on the degree to which the environmental parameters in the destination or receiving system are conducive to survival and completion of the invading organisms’ lifecycle. In the case of dreissenid mussels, calcium concentrations have been commonly used as an indicator of environmental suitability given the requirement of dissolved calcium for deposition of calcium carbonate in shell formation and growth (Whittier et al. 2008). Alternatively, habitat suitability modelling uses a suite of environmental factors and the current distribution of the invaded species to predict the suitability of habitat across a landscape by determining the relative importance of those environmental variables to the current distribution. Both methods have their advantages and disadvantages. Habitat suitability modelling can incorporate a wider range of environmental factors influencing the distribution of these invasive organisms; however, it is based on the current distribution, and thus it is likely that this does not represent the fully realized suite of suitable habitats that the mussels could invade. Determining the potential for dreissenid mussels to establishment based on calcium alone, however, considers only one of the many environmental factors that contribute to constraining their actual distribution, but it is not constrained by whether the current distribution represents the fully realized suite of habitat niches. Both methods have been applied separately in this assessment as it is not possible to identify a preferred model given these invasions are ongoing. Table 2 presents the environmental variables that were used and each is discussed in more detail below. Although both Zebra and Quagga Mussel have broad environmental tolerances it is possible they may encounter conditions that do not allow survival or reproduction. Thus, a temperature tolerance threshold for larval development in each species was applied to both suitability measures such that areas failing to reach this threshold would be deemed unsuitable. Even if dreissenid mussels were introduced and were able to survive for a short time period, not being able to successfully reproduce suggests the invasion would ultimately fail and the resulting ecological risk would be negligible. It is important to note that while either adaption or climate change could alter this relationship, neither are considered when modelling suitability in this assessment.

2.2.1. Calcium and pH Layers

All calcium and pH data handling and interpolation were conducted using R (R Core Team 2021). Data obtained for the 2012 Risk Assessment were combined with additional data from relevant federal, provincial and territorial agencies, publicly accessible databases, and primary research publications (Table A2). Raw data were compiled into a suitable format, with dates and positions converted into consistent scales, and data were split into separate files for each water quality variable. Calcium and pH data were then processed and prepared for interpolation. Data for the United States of America were primarily obtained from the Water Quality Portal, which combines data from multiple agencies and other sources. The R package dataRetrieval (De Cicco et al. 2018) was used to generate a list of sites with calcium or pH data collected between 2000 and 2021 for each of the 49 continental United States, and then to download this data directly into R (Water Quality Portal accessed 15th February 2021).

Data were aggregated at the province/territory level to facilitate data cleaning and identification of problematic records, apart from some data sources (e.g., Atlantic Datastream data) which covered multiple provinces. Where calcium fraction was specified, ‘Dissolved Calcium’ was preferred, but others were accepted if ‘Dissolved Calcium’ data were not available. Certain fractions, such as ‘Filterable Calcium’, which were obviously not equivalent, were excluded. All calcium concentrations were converted to consistent units (mg/L). Records were also excluded if they lacked critical information (i.e., position, date, and units), had obviously incorrect positions, had impossible, extreme or unfeasible values (e.g., negative or zero calcium), or were from inappropriate site or media types (e.g., marine waters, industrial effluents). Freshwater calcium levels rarely exceed 450 mg/L (Weyhenmeyer et al. 2019), but records with much higher values were present, likely resulting from measurement errors, data entry errors, or inclusion of industrial/contaminated water samples. Thus, all records with calcium concentrations higher than 500 mg/L were excluded, which represented a low proportion of all records (< 0.5% of all records obtained from the Water Quality Portal were excluded on this basis). To further reduce the impact of potentially extreme or non-representative records, sites characterized by single records (more than 30% of sites) were also excluded from the United States of America Water Quality Portal data, since this had a negligible impact on spatial coverage. While there were also single-record sites in Canada, these were retained since their removal drastically reduced the spatial extent of data coverage, especially in already under-sampled areas such as the north. Only records from 2000 onwards were used, except for certain data sources covering Nunavut and the Northwest Territories, or other areas where coverage was less comprehensive, some older records were included for these areas (see Table A2).

Duplicate (or duplicate-like) data were present for a variety of reasons such as accidental data duplication, presence of records in multiple data sources, lab and field replicates, or multiple simultaneous samples from different depths. As it was not always feasible to remove duplicate data, all duplicate types were handled by averaging calcium concentrations for each site on each date sampled. All calcium data were then combined, and an average (median) calcium value was calculated for each site across all dates sampled.

pH data were handled identically, except that records with a pH lower than 3 or higher than 12.5 were excluded, to remove extreme, unfeasible, and impossible values. For most data sources this was not required, almost all records fell within this range.

Calcium and pH rasters for Canada and the United States of America were generated *via* spatial interpolation using Inverse Distance Weighting (IDW). Median calcium concentration and pH data for each site were converted into spatial point data using the R package sf (Pebesma 2018) and reprojected into the North America Albers Equal Area Conic projection. Spatial models were fitted using the R package gstat (Pebesma 2004). Interpolation was carried out using the interpolate function in the R package raster (Hijmans 2021), on a rasterized grid with cell size (9,260 × 9,260 m) and spatial extent matching the other data layers. An inverse distance weighting parameter (IDP) of 1 and nmax (maximum number of data points used to interpolate the value for each grid cell) of 15 were selected by using the optim function to search for values which minimized root-mean-square error (RMSE) during a cross validation routine. An alternative interpolation approach, kriging, was tested and generated very similar rasters, with similar RMSE and other error metrics. Interpolated rasters were masked using outlines of Canada and the United States of America from the R package rnaturalearth (South 2017).

2.2.2. Bioclimatic Variables

Nineteen bioclimatic variables (BioClim) believed to affect an aquatic species' distribution were downloaded from the WorldClim global climate database (Fick and Hijmans 2017). These are globally continuous layers generated from annual trends in temperature and precipitation between 1970 and 2000 (version 2.1). BioClim variables such as temperature (e.g., annual and extreme temperatures such as highest temperature in the warmest month and lowest temperature in the coldest month) and amount of precipitation (e.g., annual and in the warmest quarter or coldest quarter) focus on aspects that could control species distributions (McDowell et al. 2014). BioClim's air temperatures were used as a proxy for water temperature due to the lack of available data for water temperature nationally. Bioclimatic variables have been used in previous studies to predict the potential distribution of dreissenid mussels (e.g., Drake and Bossenbroek 2004, Gallardo and Aldridge 2013, Barnes and Patino 2020) as air temperature is related to water temperature (Stefan and Preud'homme 1993), although water temperature may be locally influenced by several factors including source of water, the degree of shade/isolation, elevation, drainage area, water current and stratification. Precipitation can affect many components related to the functioning of aquatic ecosystems thereby influencing species distributions. For example, precipitation can influence nutrient availability and cycling thus affecting productivity (Collins et al. 2019). It may also affect the discharge and depth of rivers and lakes and therefore habitat availability for benthic species such as dreissenid mussels.

2.2.3. Calcium-based Modelling

Since calcium has been identified as a critically important variable for dreissenid mussels, a model (raster) was developed to predict suitable habitat for Zebra and Quagga Mussel based on calcium concentrations. Calcium concentrations were not used as thresholds given that the suitability at a given concentration is likely to vary based on other factors such as pH which contribute to the solubility of calcium carbonate needed for shell building. To account for this uncertainty in the specific relationship between concentration and suitability at lower calcium concentrations, a continuous function was applied to scale habitat suitability such that the resulting metric of Potential for Establishment would be very low when calcium concentrations are close to 0 mg/L and increasing as they approach levels at 30 mg/L where survival and establishment are not impaired. Thus, values were scaled between 0.00001 and 1 (very low to high suitability, respectively) to standardize metrics and facilitate integration of rasters. The scaling of calcium-based habitat suitability values was based on biologically relevant calcium concentrations for each mussel species (Therriault et al. 2013, Mackie and Claudi 2010). The threshold values identified in Mackie and Claudi (2010) were used not as thresholds but rather to train a polynomial regression for the scaling of habitat suitability values. In the present study, calcium concentration values of 8, 15, and 30 mg/L were set to represent low, moderate, and high calcium suitability (respectively) for the establishment of Zebra Mussel. The polynomial regression equation (Table 3) for scaling calcium concentrations for Zebra Mussel was derived using a regression on the following data: values of 0 for a concentration of 0 mg/L, 0.33 for 8 mg/L, 0.66 for 15 mg/L, and 1 for 30 mg/L with all values beyond 30 mg/L set also to a value of 1 (Table 3). Similarly, for Quagga Mussel, calcium concentrations of 10,12, and 30 mg/L were set as low, moderate, and high calcium suitability (respectively) for establishment of Quagga Mussel. The polynomial regression equation (Table 3) for scaling calcium concentrations for Quagga Mussel was derived using a regression on the following data: values of 0 for a concentration of 0 mg/L, 0.33 for 10 mg/L, 0.66 for 12mg/L and 1 for 30 mg/L with all values beyond 30 mg/L also set to a value of 1 (Table 3).

2.2.4. Habitat Suitability Modelling using MaxEnt

MaxEnt models were developed to project areas of habitat suitability for Zebra and Quagga Mussel. MaxEnt is a machine learning method that is commonly used as a predictive habitat suitability model when only species presence records are available (Phillips et al. 2006). Background samples are generated by sampling within the area of interest to characterize the general habitat conditions across the area of interest and contain no information on species presence or absence. Although many predictive habitat models exist, MaxEnt has generally ranked high among presence-background models (Elith et al. 2006). MaxEnt (v.3.4, Phillips et al. 2006) models were run using the R package dismo (Hijmans et al. 2017).

2.2.4.1. Predictor variable selection

General best practice methods for developing predictive habitat models include reducing multicollinearity among environmental variables used as predictors to prevent model overfitting (Merow et al. 2013). While MaxEnt is reasonably robust with multicollinearity among predictors, a backward selection process with variance inflation factors (VIFs) was used to reduce the set of environmental data layers used as model predictors. Starting with the complete set of available environmental data layers (n = 27), variable values were extracted using the occurrence records of each species (1986-2021 for Zebra Mussel and 1989-2021 for Quagga Mussel). The presence data was spatially thinned to one record per grid cell resulting in 2,490 Zebra Mussel and 391 Quagga Mussel records for the MaxEnt modelling. The variable with the highest VIF predictors was iteratively removed until the remaining subset of variables all had VIF < 10 (Nephin et al. 2020). pH, calcium, and BioClim variables BIO5 (Maximum temperature of the warmest month), BIO6 (Minimum temperature of the coldest month), BIO10 (Mean temperature of the warmest quarter), BIO11 (Mean temperature of the coldest quarter) were preferentially retained based on their physiological relevance for dreissenid mussels. This procedure was used for both Zebra and Quagga Mussel with MaxEnt models developed using their respective occurrence data. Table 4 summarizes the data layers used in MaxEnt model development for each species. VIFs were calculated using the R package usdm (Naimi et al. 2014).

Table 4. Presence records, background records, and predictors used to train final MaxEnt models for each species.

Species	N Presence Records	N Background Records	Predictors
Zebra Mussel	2,490	100,000	Calcium, pH, Isothermality (BIO3), Maximum temperature of the warmest month (BIO5), Minimum temperature of the coldest month (BIO6), Mean temperature of the wettest quarter (BIO8), Mean temperature of the driest quarter (BIO9), Precipitation of the wettest month (BIO13), Precipitation seasonality (BIO15), Precipitation of the warmest quarter (BIO18)
Quagga Mussel	391	20,000	Calcium, pH, Maximum temperature of the warmest month (BIO5), Minimum temperature of the coldest month (BIO6), Mean temperature of the wettest quarter (BIO8), Precipitation of the wettest month (BIO13), Precipitation seasonality (BIO15), Precipitation of the coldest quarter (BIO19)

2.2.4.2. Background data sampling

A general assumption of predictive habitat models, including MaxEnt, is that a species distribution has been systematically or randomly sampled throughout the area of interest. Most available datasets are often spatially biased due to site accessibility or pooling of records over multiple studies to cover large study areas. When unaccounted for, sampling bias can introduce model errors in assigning significance of environmental predictors thereby detrimentally affecting ecological interpretability and model accuracy (Merow et al. 2013). To account for spatial sampling bias, presence records were spatially thinned for each species by reducing the occurrence data to include only one record per grid cell in the predictor layers. This best practice procedure reduces the number of records in heavily sampled areas. An additional step to control for sampling bias is the use of bias files which modify the background sampling procedure to select points that have the same sampling bias as the occurrence data (Phillips et al. 2009). Bias grids were created using the presence records for each species to generate a two-dimensional kernel density estimate using the R package MASS (Venables and Ripley 2002). Based on inspection of preliminary models, a range of sample sizes for background points were tested (n = 10,000-100,000). Based on final model performance, final sample sizes of 100,000 and 20,000 were generated using the bias grids for Zebra and Quagga Mussel, respectively. Table 4 summarizes the final ratio of presence and background records used in the MaxEnt models for each species.

2.2.4.3. MaxEnt model validation

General model performance was assessed using a five-fold cross-validation procedure. The set of occurrence data (presence and background samples) were randomly split into five equal data partitions. Models were trained on four of the partitions and tested with the fifth. This procedure was repeated five times with a unique partition being used as the test set each time. Predictions generated from the final models used the entire set of occurrence data for training.

The area under the receiver operator curve (AUC) was used as a general metric to evaluate predictive accuracy of models (Phillips et al. 2006). AUC ranks the probability of a randomly chosen presence record is ranked higher than a randomly chosen background point. AUC = 1.0 indicates a model perfectly predicts all presence and absences in the study area and AUC = 0.5 indicates the model performs no better than random. AUC > 0.8 suggests good model performance, AUC between 0.8 and 0.7 suggests moderate performance, and AUC < 0.7 suggests poor performance (Mandrekar 2010). AUC was used as the primary metric during tuning of model parameters and evaluation of preliminary models. During model tuning, all combinations among a range of regularization parameters (beta = 1, 2, 3, 4, 5) and feature class inclusions used to fit the environment-species curves (L, LQ, LQH, LQHP, LQHPT; linear [L], quadratic [Q], hinge [H], product [P], and threshold [T]) were tested to balance model complexity with model performance. Final MaxEnt models for both Zebra and Quagga Mussel were fitted using a beta value of 1 (beta = 1.0) and included all feature classes (LQHPT). Model tuning was done using the R package ENMeval (Kass et al. 2021).

Additional threshold-dependent metrics were calculated to evaluate the general performance of the final models. Threshold-dependent metrics are based on confusion matrices (Liu et al. 2005) where a threshold-value is used to transform the relative occurrence rate (ROR), or the probability response, into a binary response where ROR values greater than the threshold are classified as presence and ROR values below the threshold are absences. From the binary response, three metrics were calculated: percent correctly classified (PCC) is the proportion of the occurrence data that is correctly classified into presence and background categories, sensitivity is the proportion of correctly classified presence records, and specificity is the proportion of correctly classified background (i.e., absence) records. PCC, sensitivity, and specificity are calculated by converting the logistic predictions of a model into a binary presence-absence value using a threshold value. For each model we used a threshold value that maximized the sum of the sensitivity and specificity (Liu et al. 2005).

2.2.4.4. Identifying relative importance among variables

The relative importance of the variables used to develop models for each species was assessed with the two default methods used by MaxEnt: (1) percentage contribution and permutation importance, and (2) a jackknife test (Phillips 2005, Elith et al. 2011). Percentage contributions are dependent on how MaxEnt arrives at the optimal solution for the model. Different paths can be used to arrive at the optimal solution; therefore, percentage contributions depend on the path and can change. Permutation importance is calculated from the final MaxEnt model (not the path used to arrive at it) where values of each variable are randomly permutated with the presence and background points and the decrease in AUC is calculated. Large decreases in AUC (normalized to give percentage) indicate that the final model is highly dependent on that variable. Percent contributions should be interpreted cautiously if variables are highly correlated.

The jackknife test used by MaxEnt is an alternative to estimating variable importance. For each variable in turn, a model is created that excludes that variable (using all other variables) and a model is created with only that variable. Results of the jackknife test models are presented in gain which is a measure of goodness of fit related to deviance. Leave-one-out models with the biggest decrease in gain when compared to the full model indicate a variable that contains the most information that is absent in the other variables. Highest gain in variable-only models indicates a variable that has the most useful information by itself.

2.2.5. Temperature Threshold

The temperature thresholds applied to both suitability models were set at 10°C for Zebra Mussel (Pollux et al. 2010) and 5°C for Quagga Mussel (Peyer et al. 2010), recognizing that this species is better adapted to deeper, cooler waters. Because water temperatures were unavailable at the national scale, BioClim air temperatures were used as a proxy for water temperature as these are assumed to be correlated (Stefan and Preud'homme 1993). Thus, a mask was applied using the data from BioClim 10 (Mean temperature of warmest quarter) to denote areas where the temperature was lower than the threshold value for the mean temperature of the warmest quarter (Figure 7). Values for these areas were set to 0 for the Potential for Establishment in both habitat suitability scenarios (i.e., calcium-based model and MaxEnt).

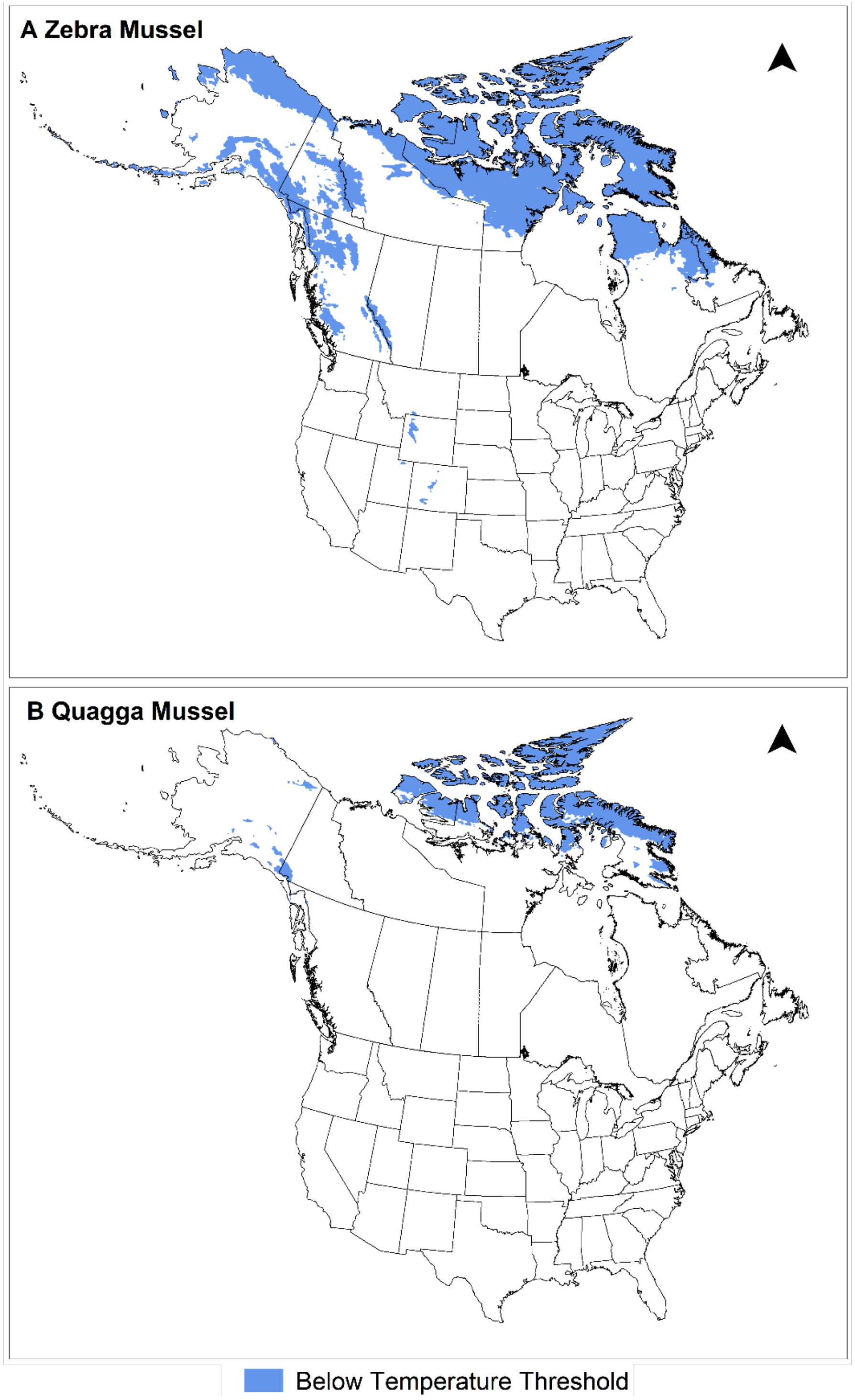

Figure 7. Temperature threshold for Zebra (A) and Quagga (B) Mussel where mean air temperature for the warmest quarter of the year (Bioclim 10; as a proxy for water temperature) is less than 10°C and 5°C, respectively.

2.3. POTENTIAL FOR INVASION

Like the previous assessment, the Potential for Invasion was determined by combining the Potential for Introduction and Potential for Establishment (Figure 4). Since the relative importance of each of these components is unknown, they were given equal weighting and represent the product of the two metrics.

2.4. POTENTIAL FOR ECOLOGICAL IMPACTS

To ensure consistency across models and species with respect to the criteria for determining expected Ecological Impacts (Figure 4), the approach used in Therriault et al. (2013) and modified from Therriault and Herborg (2008) was adopted. This approach identifies five categories for each impact, ranging from Very Low to Very High (Table 5). In the present study, there are no established metrics for either species that are available at the extent or resolution required to differentiate the geographic variability in ecological impacts. Given that Zebra and Quagga Mussel invasions have well-documented negative ecological impacts on the systems they are introduced to, the Ecological Impact metric in the present study is expected to be Very High across the entire study area. The uncertainty is expected to be very low given that these impacts have been well documented in both North America and Europe.

Table 5. Five categories of ecological impacts from Therriault and Herborg (2008) and Therriault et al. (2013).

Impacts	
Category	**Definition**
Very Low	No measurable negative impact, consequences can be absorbed without additional management action.
Low	A measurable negative limited impact, disruption to the factor in question but reversible or limited in time, space or severity.
Moderate	A measurable widespread negative impact, widespread disruption to the factor in question but reversible or of limited severity or duration.
High	A significant negative impact, widespread disruption to the factor in question that persists over time or is likely not reversible.
Very High	A critical negative impact, extensive disruption to the factor in question that is irreversible.

2.5. ECOLOGICAL RISK

The Ecological Risk (Figure 4) posed by invasive species is the product of the Potential for Invasion and the consequences of that invasion (i.e., potential for ecological impacts). The Potential for Invasion of both Zebra and Quagga Mussel was then combined with the Ecological Impacts using a heat matrix (Table 6, Therriault et al. 2013), recognizing that inherently there are elements of risk tolerance associated with the specific final risk levels or scores (the characterization of which is beyond the scope of this assessment). Given that Ecological Impacts are Very High across all of Canada the final determination of Ecological Risk represents differences in the Potential for Invasion. Thus, Low risk areas have a lower Potential for Invasion than High risk ones but this does not mean Zebra or Quagga Mussels would have less impacts should they invade.

Table 6. Heat matrix to determine final Ecological Risk where: green = Low risk, yellow = Moderate risk, and red = High risk.

		Potential for Invasion				
		Very Low	Low	Moderate	High	Very High
Ecological Impact	Very Low	Low risk	Low risk	Low risk	Low risk	Low risk
	Low	Low risk	Low risk	Low risk	Low risk	Low risk
	Moderate	Low risk	Low risk	Moderate risk	Moderate risk	Moderate risk
	High	Low risk	Moderate risk	Moderate risk	High Risk	High Risk
	Very High	Low risk	Moderate risk	High Risk	High Risk	High Risk

To use the heat matrix, the Potential for Invasion must first be converted from quantitative data to categorical data. Thus, the threshold values for each of the five categories were determined by examining the distribution of values for the Potential for Invasion in areas of dreissenid mussel occurrence (for each species and each of the two habitat suitability models). For each occurrence point, the Potential for Invasion was extracted at that geographic location and the quartiles calculated. The threshold value between each category from Very Low to Very High was defined using the lower extreme, lower quartile, median, and upper quartile. Thus areas which have already been invaded at the time of this assessment would result in a low to very high Potential for Invasion. Raster values for the Potential for Invasion were then combined with the Potential for Ecological Impacts and transformed to the corresponding categorical values of Ecological Risk based on the raster specific threshold values and ranging from low to high for cells above the temperature threshold. The resulting raster depicts the Ecological Risk for each grid cell. Ecological Risk was also determined at the sub-drainage level for management utility as done in the previous assessment. For each of the two habitat suitability models and species, risk values were calculated for each sub-drainage using either the mode (most common Ecological Risk value) or maximum (highest Ecological Risk value) for grid cells within that sub-drainage, with grid cells considered below the thermal tolerance to be of low risk (summarized in Tables B1 and C1 with Figure A1 depicting the sub-drainages with their respective coding - the data has been incorporated into the shapefile developed by the Water Survey of Canada [Environment Canada] by the introduction of the aforementioned attributes to the data for each sub-drainage polygon [Source: ESRI Canada Education and Research; Accessed 31/03/2022; License CC By 2.5 CA]). It is important to note that when interpreting these results that a low Ecological Risk does not represent no risk and that areas that are currently invaded do not automatically translate to high risk. Invasions are complex and can succeed even when the potential for introduction, establishment, or spread is lower, which could result in a lower overall risk score.

3. RESULTS

3.1. SPATIAL INTERPOLATIONS AND MAXENT MODELLING

3.1.1. Spatial interpolations (calcium and pH)

Data from 68,642 sites were used to generate the interpolated calcium layer. These sites had an overall median calcium concentration of 26.3 mg/L with an interquartile range of 49 mg/L. Calcium concentrations were interpolated to 226,084 cells in the final raster, with a median interpolated value of 24.9 mg/L and an interquartile range of 40.8 mg/L.

Data from 148,263 sites were used to generate the interpolated pH layer. These sites had an overall median pH of 7.7 with an interquartile range of 0.9. pH values were interpolated to 226,084 cells in the final raster, with a median interpolated pH of 7.8 and an interquartile range of 0.9.

3.1.2. MaxEnt Model Performance and Variable Importance

In general, models performed well with relatively high scores among metrics used to evaluate model performance (Table 7). Cross-validated test AUC was 0.90 for Zebra Mussel and 0.85 for Quagga Mussel. Similarly, 'thresholded-metrics' (PCC, sensitivity, specificity) indicate both models were relatively accurate at classifying observations into presence and absence (background) observations.

Table 7. Model evaluation metrics. Test AUC (area under the ROC curve), PCC (percent correct classification), Sensitivity, and Specificity summarize the average of the five-fold cross validation models. Training AUC summarizes the final model which uses all records to train the model and generate predictions.

Model	Test AUC	Training AUC	PCC	Sensitivity	Specificity
Zebra Mussel	0.90	0.90	0.76	0.89	0.76
Quagga Mussel	0.85	0.86	0.74	0.87	0.74

Tables 8 and 9 summarize the metrics used to evaluate relative variable importance in the MaxEnt models for Zebra and Quagga Mussel respectively. For Zebra Mussel, Isothermality (BIO3), or the temperature oscillation between day-to-night temperature relative to summer-to-winter oscillations (BIO2/BIO7) and calcium had the highest percent contribution to the final MaxEnt model. Isothermality and the maximum temperature of the warmest month (BIO5) also ranked high based on results of the permutation importance and both jackknife tests (Table 8).

For Quagga Mussel, calcium was the highest rank of percent contribution to the final MaxEnt model. Minimum temperature of the coldest month (BIO6) and calcium also ranked high based on results of the permutation test and both jackknife tests (Table 9).

Table 8. Zebra Mussel variable importance. The highest ranked variable based on relative importance for each test is highlighted in bold. Regularization gain for the full model = 1.2746.

Variable	Percent Contribution (%)	Permutation Importance (%)	Jackknife Test – without variable (gain)	Jackknife Test – variable only (gain)
Calcium (mg/L)	22.0295	5.0201	1.2378	0.3636
pH	0.9841	3.4554	1.2619	0.2168
BIO3 – Isothermality (BIO2/BIO7) (°C)	**23.8653**	**27.182**	**1.1974**	0.4272
BIO5 – Max temp warmest month (°C)	4.9219	16.6392	1.1989	**0.4731**
BIO6 – Min temp coldest month (°C)	11.6479	18.8298	1.242	0.3276
BIO8 – Mean temp wettest quarter (°C)	0.4378	0.9613	1.2683	0.1644
BIO9 – Mean temp driest quarter (°C)	0.7458	2.2179	1.266	0.2887
BIO13 – Precip wettest month (mm)	1.0455	10.0124	1.2691	0.4186
BIO15 – Precip seasonality (CV)	15.3372	12.9095	1.2386	0.2795
BIO18 – Precip warmest quarter (mm)	18.9849	2.7726	1.2716	0.3763

Note. BIO3 = Isothermality (Mean diurnal temp range / *Temp annual range)

*Temp annual range = BIO5-BIO6.

Table 9. Quagga Mussel variable importance. The highest ranked variable based on relative importance for each test is highlighted in bold. Regularization gain for the full model = 0.8151.

Variable	Percent Contribution (%)	Permutation Importance (%)	Jackknife Test – without variable (gain)	Jackknife Test – variable only (gain)
Calcium (mg/L)	**33.8857**	18.0218	0.7623	**0.2896**
pH	0.541	1.8597	0.8079	0.2085
BIO5 – Max temp warmest month (°C)	20.88	19.1427	0.7414	0.1826
BIO6 – Min temp coldest month (°C)	11.7328	**31.1011**	**0.713**	0.1892
BIO8 – Mean temp wettest quarter (°C)	2.7873	5.3606	0.7774	0.0582
BIO13 – Precip wettest month (mm)	13.6128	13.239	0.7716	0.2058
BIO15 – Precip seasonality (CV)	2.6327	8.4798	0.7891	0.1392
BIO19 – Precip coldest quarter (mm)	13.9278	2.7954	0.8079	0.1127

3.2. RISK OF ZEBRA MUSSEL INVASION IN CANADA

3.2.1. Potential for Introduction

The Potential for Introduction is greatest in areas that are both proximate to the current known location of Zebra Mussel and to more heavily populated areas of the country (Figure 8). The southern portions of Ontario and Quebec as well as Manitoba where Zebra Mussel is known to have invaded, exhibit some of the highest Potential for Introduction in Canada. Provinces such as Saskatchewan and New Brunswick also exhibit higher Potential for Introduction due to proximity to invaded locations. Areas such as Newfoundland and Labrador, most of the Territories and northern British Columbia are most distal from invaded systems and thus exhibit lower Potential for Introduction.

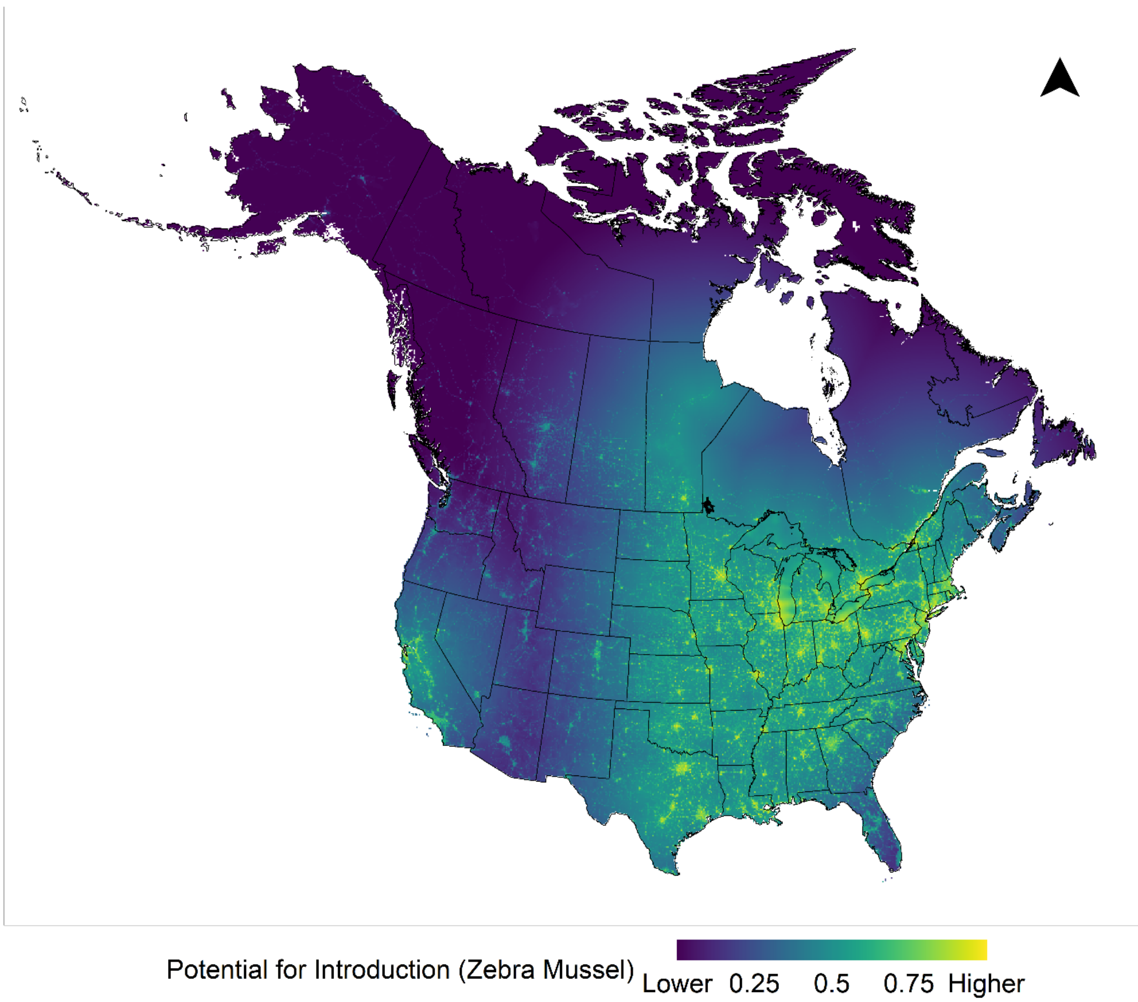

Figure 8. Potential for Introduction of Zebra Mussel based on propagule pressure (Human Footprint Index) and proximity to invaded habitats (Connectivity Metric).

3.2.2. Calcium-based Modelling

3.2.2.1. Potential for Establishment

The concentration of calcium across most of North America is highly suitable (> 30 mg/L) for Zebra Mussel establishment (Figure 9). After accounting for areas with temperatures below the thermal threshold, large areas of highly suitable habitat were exhibited for Yukon and western Northwest Territories, northern and central British Columbia, Alberta, and the southern and central portions of Saskatchewan and Manitoba. Much of southern Ontario, the Laurentian-Great Lakes system and Quebec south of the St Lawrence River also have high suitability. The remainder of Canada, especially on the Canadian Shield, has lower suitability with some small patches of higher suitability through northern Ontario and the Maritime Provinces.

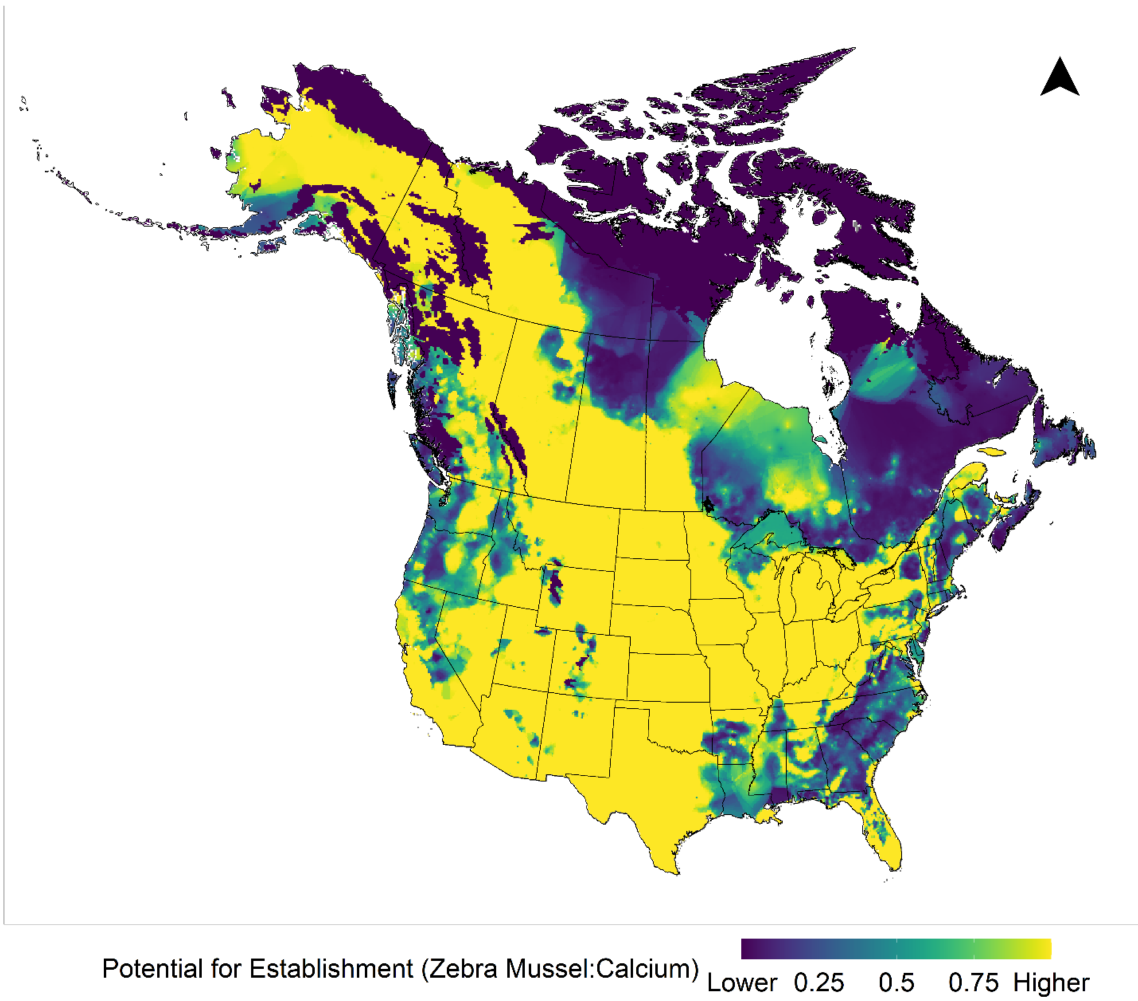

Figure 9. Potential for Establishment of Zebra Mussel based on calcium concentrations and adjusted for unsuitable temperatures.

3.2.2.2. Potential for Invasion

Due to the conditional nature of the invasion calculations, predictions generated with the calcium-based modelling approach were highest in areas where both the habitat suitability and Potential for Introduction were highest. The southern and central portions of the Prairie provinces and up through the Nelson River in Manitoba had higher values compared to the rest of Western Canada and the Yukon and Northwest Territories (Figure 10). Southeastern Ontario and parts of Quebec south of the St. Lawrence River along with some patchy areas in northern Ontario and the Maritime provinces had the highest Potential for Invasion in Eastern Canada.

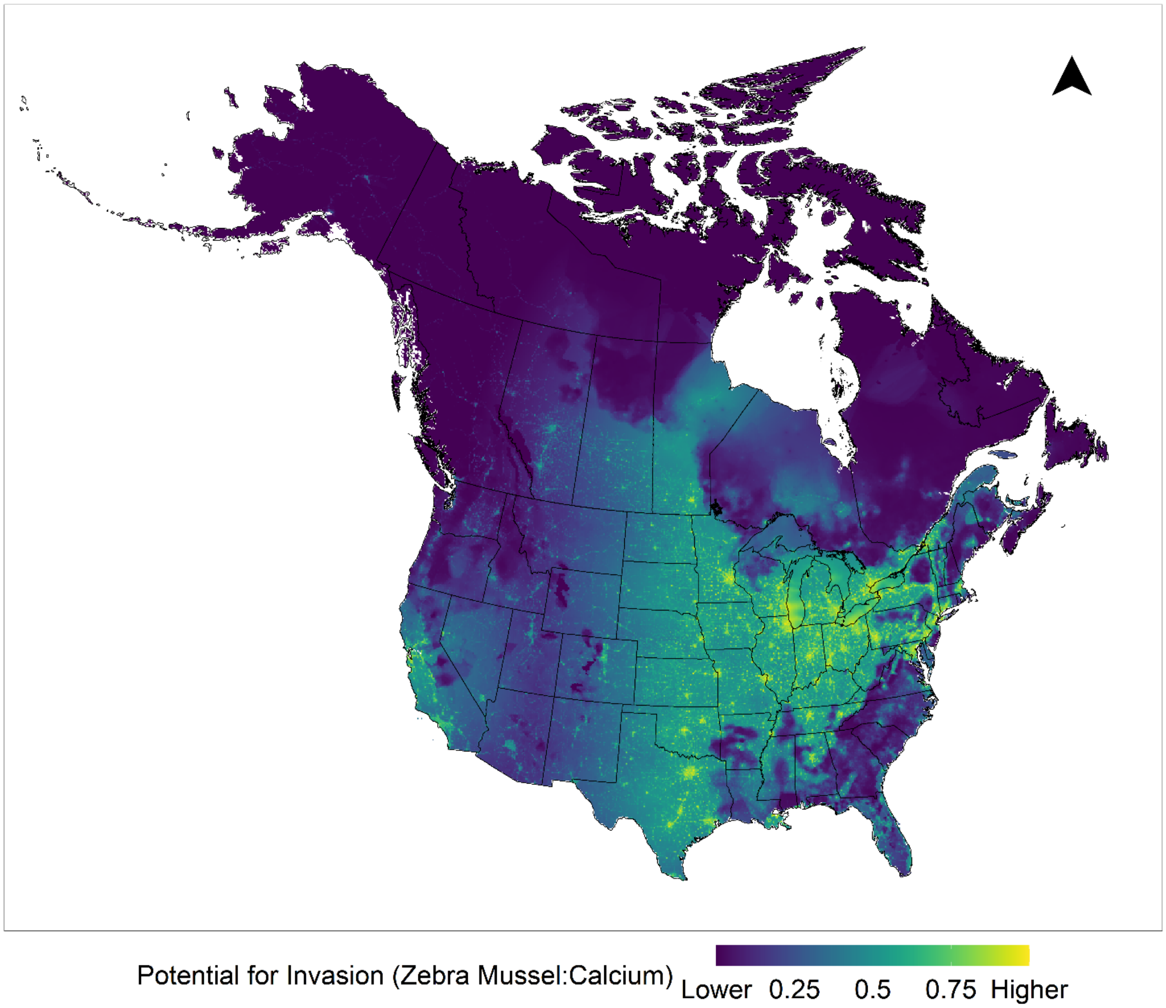

Figure 10. Potential for Invasion of Zebra Mussel in North America based on the Potential for Introduction and Establishment (Calcium-based Model).

3.2.2.3. Ecological Risk

The provinces of Ontario, Alberta, Saskatchewan, Manitoba, Prince Edward Island and New Brunswick were predominately Moderate risk with large areas of Moderate risk through portions of Quebec, British Columbia, and the Northwest Territories (Figure 11). High risk areas were concentrated along the Laurentian-Great Lakes system and areas around Lake Winnipeg, Red River and Nelson River in Manitoba, which is in general agreement with much of the current known distribution of this species. Beyond the current distribution, small, discrete areas of High risk are found in New Brunswick (Fredericton Region), Saskatchewan and Alberta. Mountainous areas in the western provinces, northern regions of Quebec, Labrador, the Northwest Territories, and most of Nunavut are below the temperature threshold and likely of very low Ecological Risk. Ecological Risk is presented at the grid cell resolution for regional extents in Appendix B (Figures B1-B5) and the maximum and mode for Ecological Risk per sub-drainage are presented below (Figure 12).

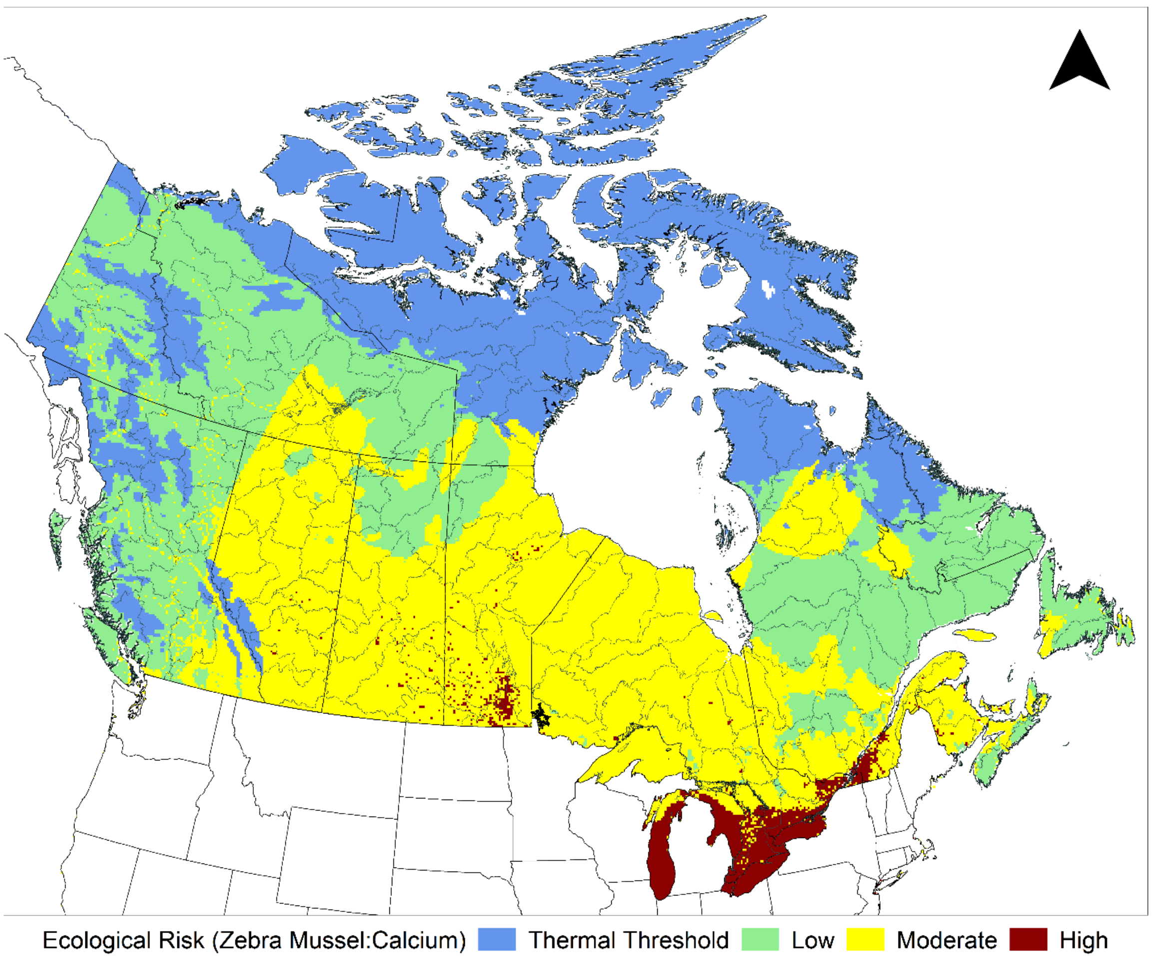

Figure 11. Zebra Mussel Ecological Risk in Canada using the calcium-based model. Ecological Risk is based on the Potential for Invasion and Ecological Impacts. Sub-drainages (grey lines) are overlaid on the map.

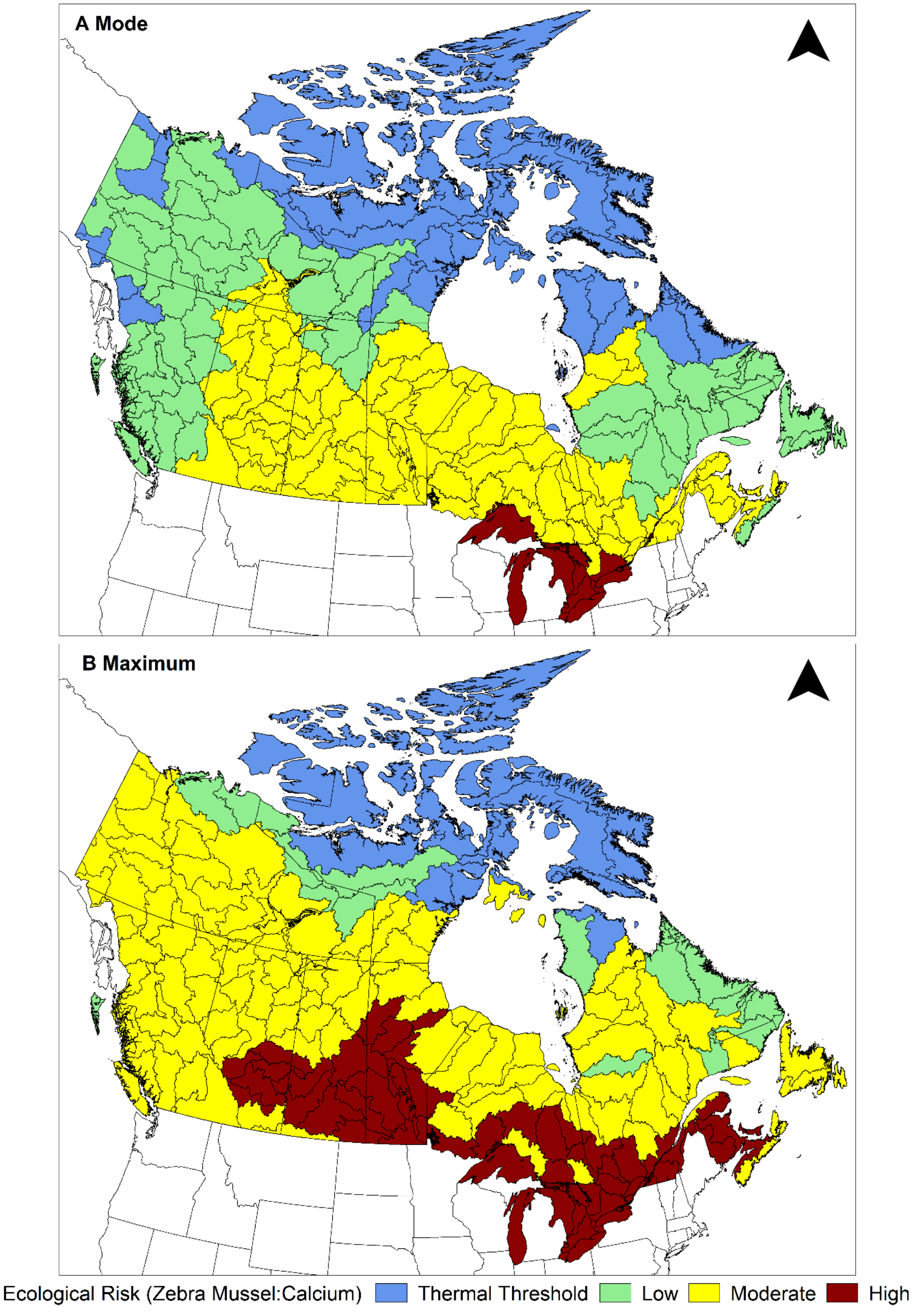

Figure 12. Mode (A) and maximum (B) Zebra Mussel Ecological Risk per Sub-drainage in Canada using the calcium-based model. Note that sub-drainage 020 (Great Lakes and St. Lawrence) does include both freshwater and marine habitat, however marine habitat is unsuitable for both species and thus the risk should be applied to only freshwater portions of the sub-drainage.

3.2.3. MaxEnt-based Modelling

3.2.3.1. Potential for Establishment

Predictions of suitable habitat generated with the MaxEnt model are more restricted geographically compared to that of the calcium-based model (Figure 13). It also strongly corresponds with the current known range within North America, having the highest values for Canada located throughout the Laurentian-Great Lakes system, southern Ontario, and Lake Winnipeg. Southeastern British Columbia, Quebec south of the St Lawrence River, and the Maritime provinces, particularly New Brunswick, also have patches of higher suitability. The remainder of Canada exhibits lower suitability.

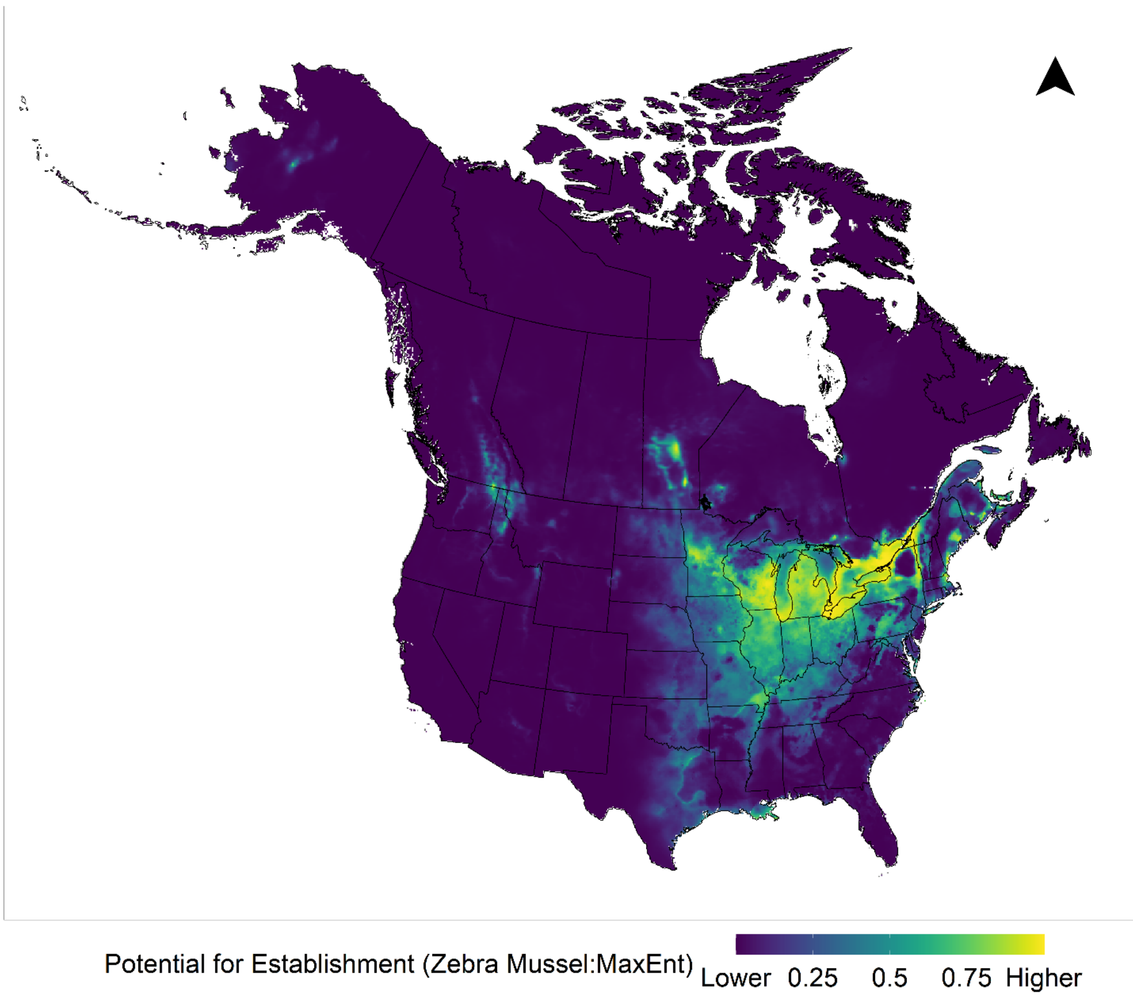

Figure 13. Potential for Establishment of Zebra Mussel using the MaxEnt habitat suitability model and adjusted for unsuitable temperatures.

3.2.3.2. Potential for Invasion

The Potential for Invasion of Zebra Mussel using the MaxEnt model generally mirrors the current known distribution of the species, as it incorporates both proximity (Potential for Introduction) and predicted habitat suitability (Potential for Establishment) (Figure 14). The highest values for the Potential for Invasion are therefore in the Laurentian-Great Lakes system, southern Ontario, and Lake Winnipeg area. Outside of this distribution, there are areas of higher potential in Quebec south of the St Lawrence River and New Brunswick.

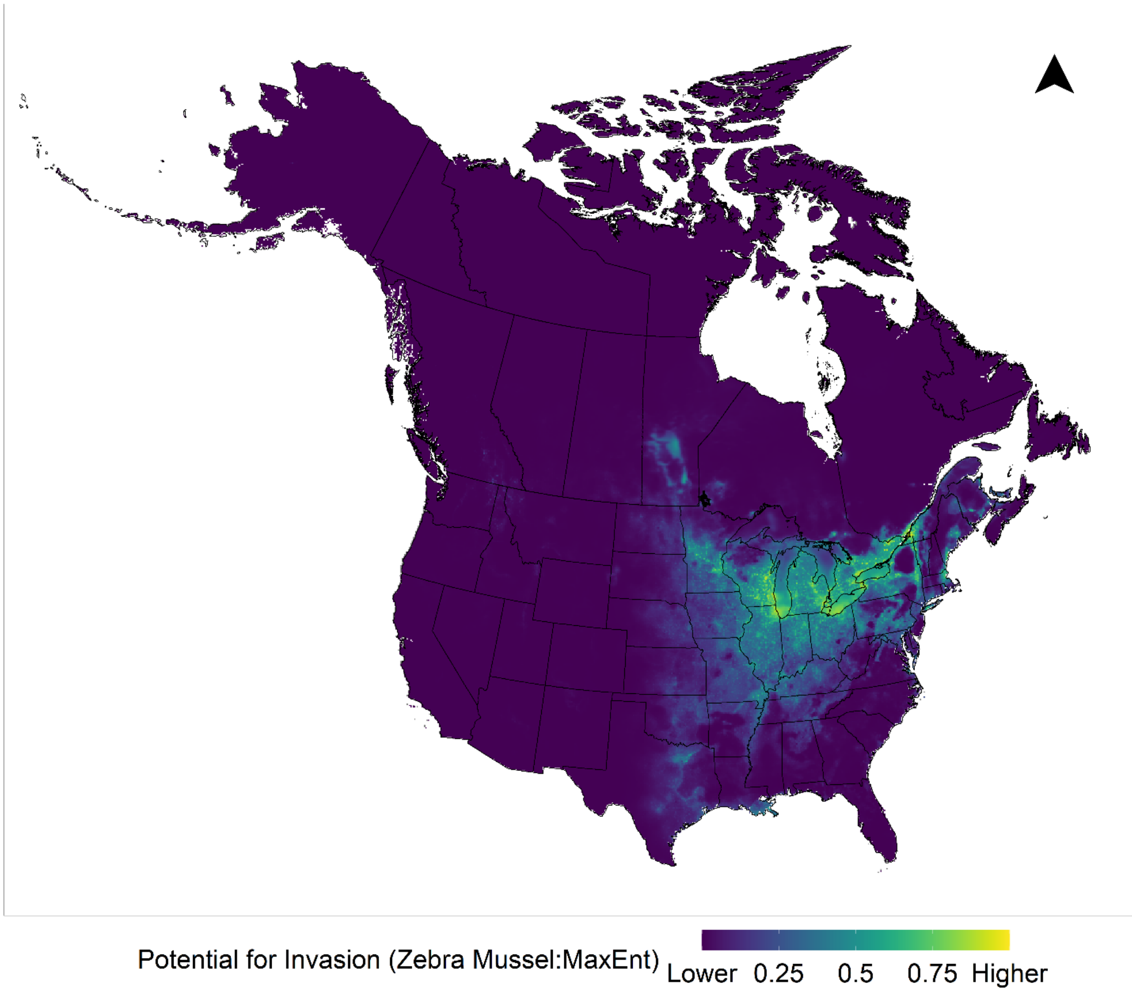

Figure 14. Potential for Invasion of Zebra Mussel in North America based on the Potential for Introduction and Establishment (MaxEnt habitat suitability model).

3.2.3.3. Ecological Risk

The Ecological Risk for Zebra Mussel for most of Canada using the MaxEnt model was Moderate, including throughout most of the Prairies and Eastern Canada (Figure 15). Low risk areas included coastal and northern British Columbia, the Yukon and Northwest Territories, and northeastern Quebec and much of Labrador. High risk areas were concentrated in the Laurentian-Great Lakes area and around Lake Winnipeg, which corresponds to the current known distribution of this species. One area of High risk identified by the MaxEnt habitat suitability model outside the current distribution of the species is New Brunswick. Mountainous areas in the western provinces, northern regions of Quebec, Labrador, the Northwest Territories, and most of Nunavut are below the temperature threshold and likely of very low Ecological Risk. Ecological Risk is presented at regional extents with the grid cell resolution in Appendix B (Figures B1-B5) and the maximum and mode for Ecological Risk per sub-drainage are presented below (Figure 16).

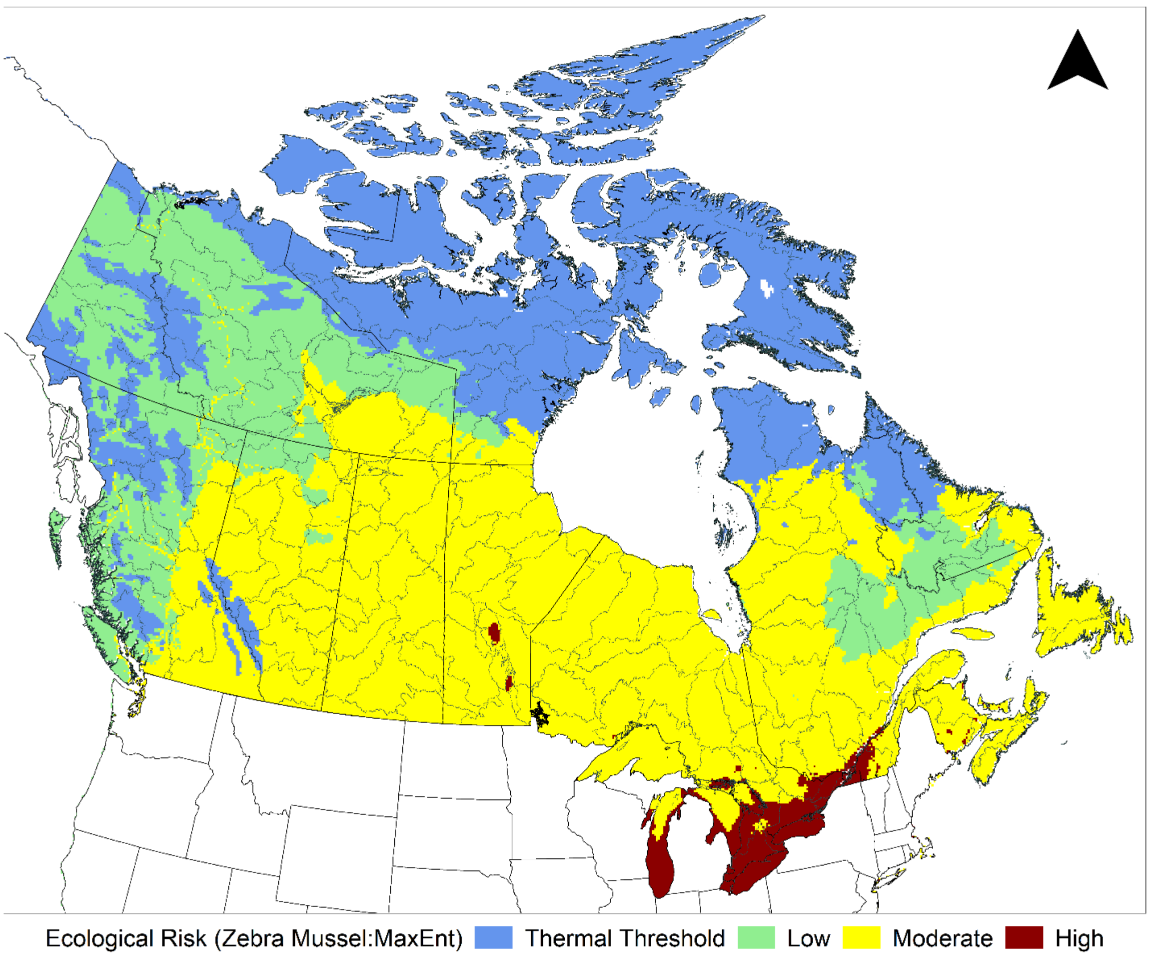

Figure 15. Zebra Mussel Ecological Risk in Canada using the MaxEnt habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts. Sub-drainages (grey lines) are overlaid on the map.

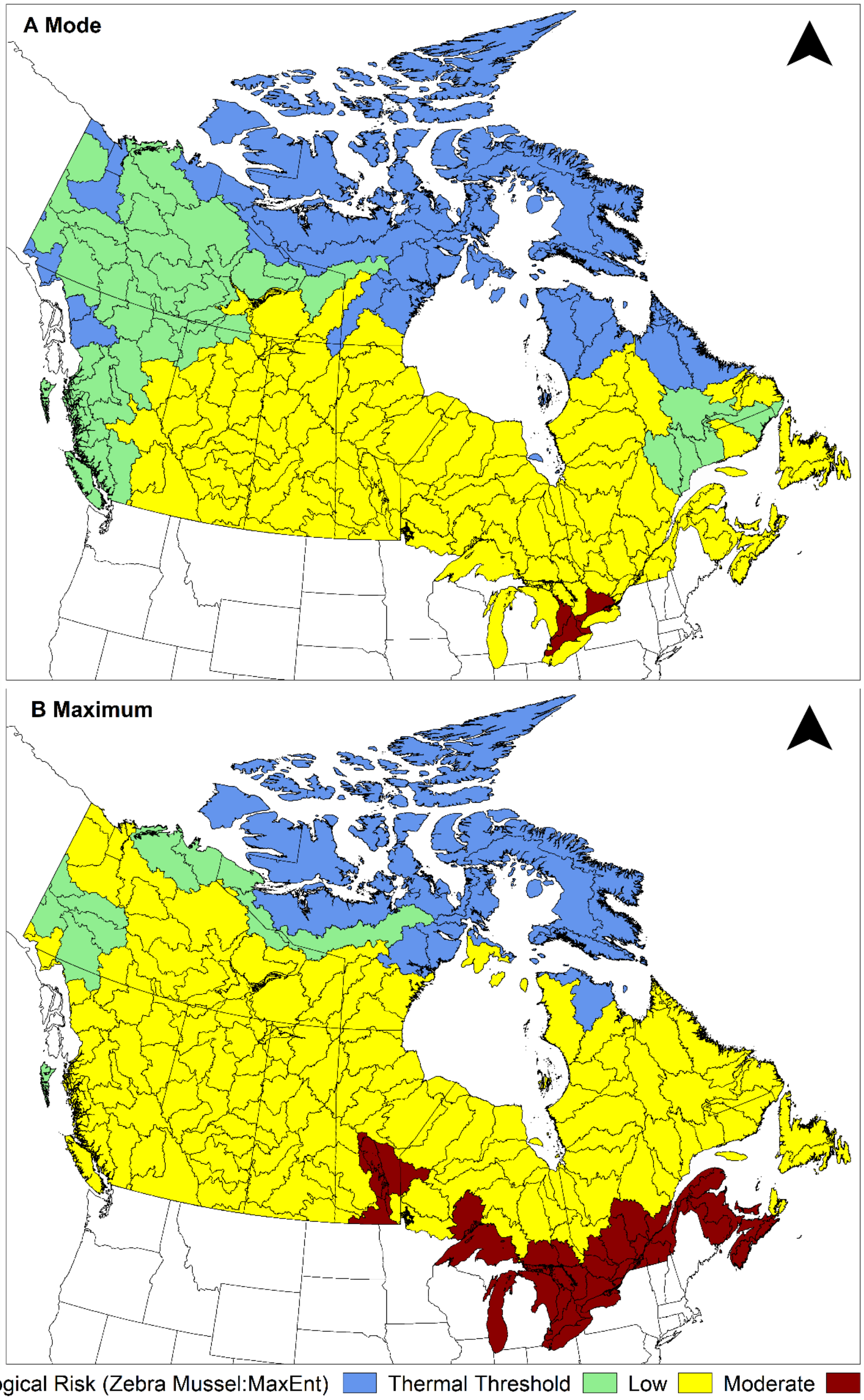

Figure 16. Mode (A) and maximum (B) Zebra Mussel Ecological Risk per Sub-drainage in Canada based on the MaxEnt habitat suitability model. Note that sub-drainage 020 (Great Lakes and St. Lawrence) does include both freshwater and marine habitat, however marine habitat is unsuitable for both species and thus the risk should be applied to only freshwater portions of the sub-drainage.

3.3. RISK OF QUAGGA MUSSEL INVASION IN CANADA

3.3.1. Potential for Introduction

The Potential for Introduction of Quagga Mussel was greatest in southern Ontario and Quebec where they are known to have invaded the Laurentian-Great Lakes system (Figure 17). Parts of New Brunswick and Manitoba, as well as some of the more populated (southern) areas of Saskatchewan and Alberta also had higher Potential for Introduction. The Yukon and Northwest Territories, British Columbia, and northern portions of the Prairie provinces that are most distal from currently invaded systems had lower Potential for Introduction.

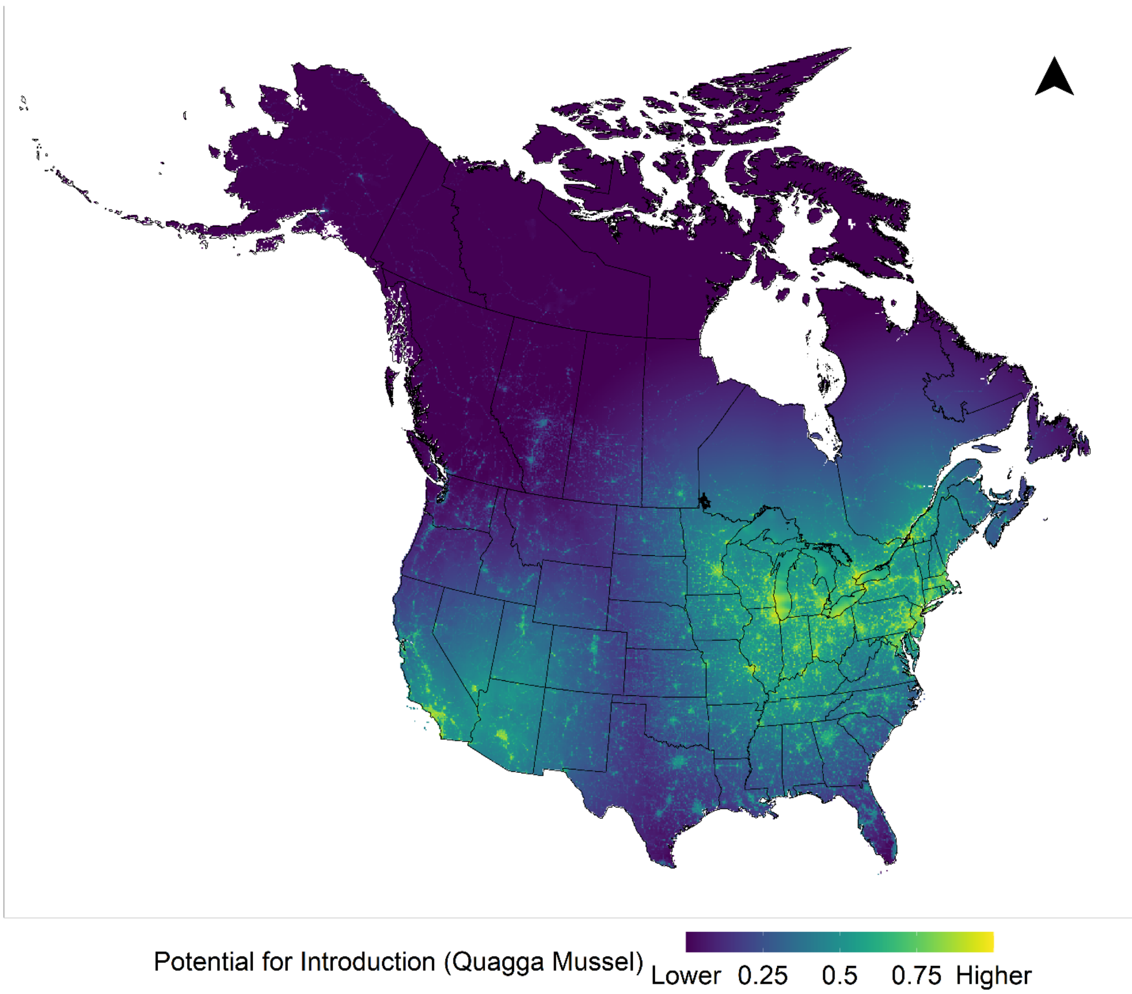

Figure 17. Potential for Introduction of Quagga Mussel based on propagule pressure (Human Footprint Index) and proximity to invaded habitats (Connectivity Metric).

3.3.2. Calcium-based Modelling

3.3.2.1. Potential for Establishment

The concentration of calcium across much of North America is highly suitable for Quagga Mussel (> 30 mg/L) spanning the Yukon and western Northwest Territories, northern and central British Columbia, Alberta, and the southern and central portions of Saskatchewan and Manitoba

(Figure 18). Much of southern Ontario, the Laurentian-Great Lakes system, and Quebec south of the St Lawrence River are also of similarly high habitat suitability. The remainder of Canada has lower habitat suitability with some small patches of higher suitability through northern Ontario and the Maritime Provinces.

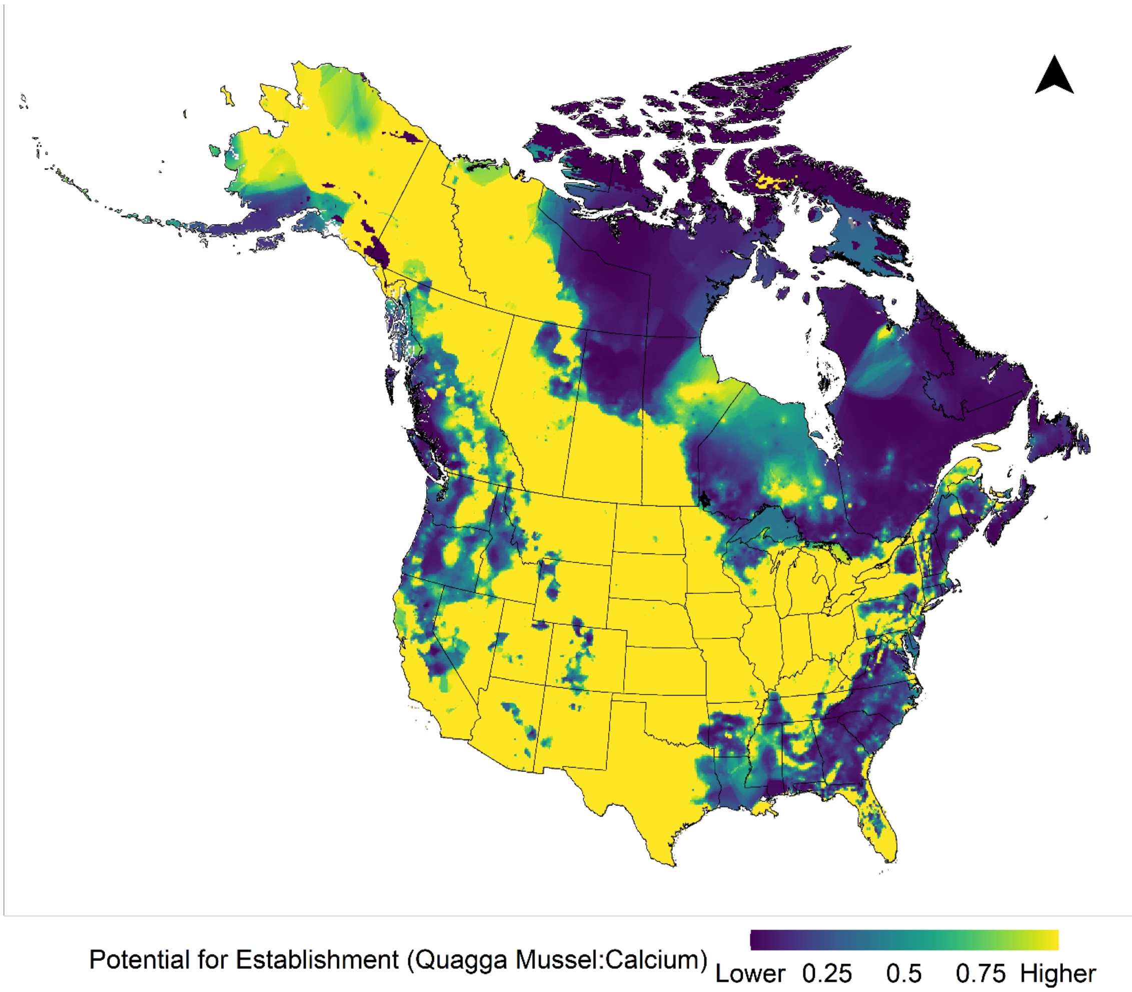

Figure 18. Potential for Establishment of Quagga Mussel based on calcium concentrations and adjusted for unsuitable temperatures.

3.3.2.2. Potential for Invasion

Like Zebra Mussel, southeastern Ontario, the southern portions of the Prairie provinces, Quebec south of the St. Lawrence River, and several discrete areas in the Maritime provinces have the highest Potential for Invasion of Quagga Mussel across Canada using the calcium-based model (Figure 19).

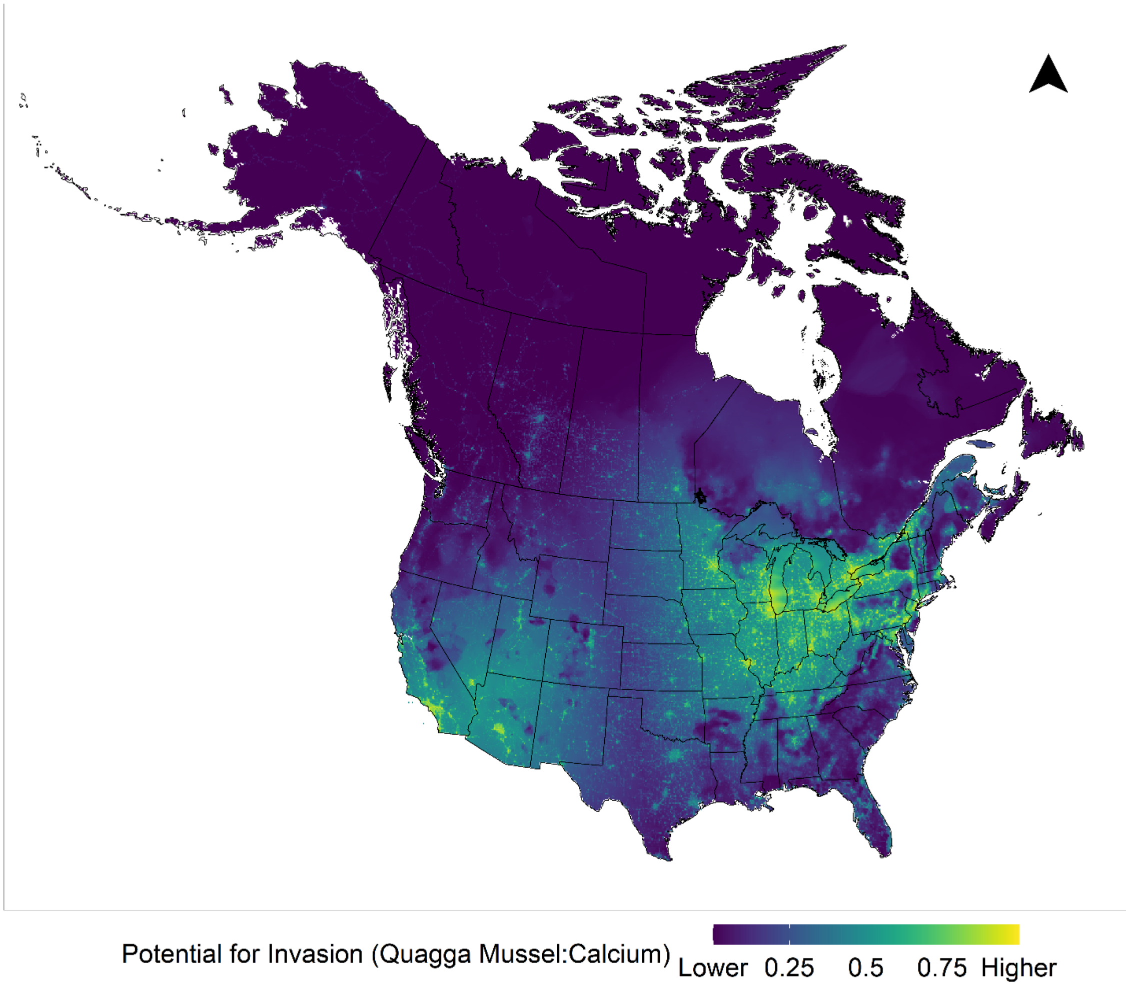

Figure 19. Potential for Invasion of Quagga Mussel in North America based on the Potential for Introduction and Establishment (calcium-based model).

3.3.2.3. Ecological Risk

Generally, the Ecological Risk for Quagga Mussel using the calcium-based model across Canada was Low (Figure 20). Moderate risk areas include most of Ontario, southern and central Manitoba through the Nelson River, southern Alberta and Saskatchewan, Quebec (particularly south of the St Lawrence Estuary), and the Maritime provinces (particularly New Brunswick and Prince Edward Island). The High risk areas were located along the Laurentian-Great Lakes system corresponding to the current known distribution of this species. Small, discrete areas of High risk also exist in the Fredericton area of New Brunswick and in the Winnipeg area of Manitoba. Unlike Zebra Mussel, areas below the temperature threshold which are likely of very low risk, were generally restricted to the Arctic Archipelago. Ecological Risk is presented at regional extents with the grid cell resolution in Appendix C (Figures C1-C5) and the maximum and mode for Ecological Risk per sub-drainage are presented below (Figure 21).

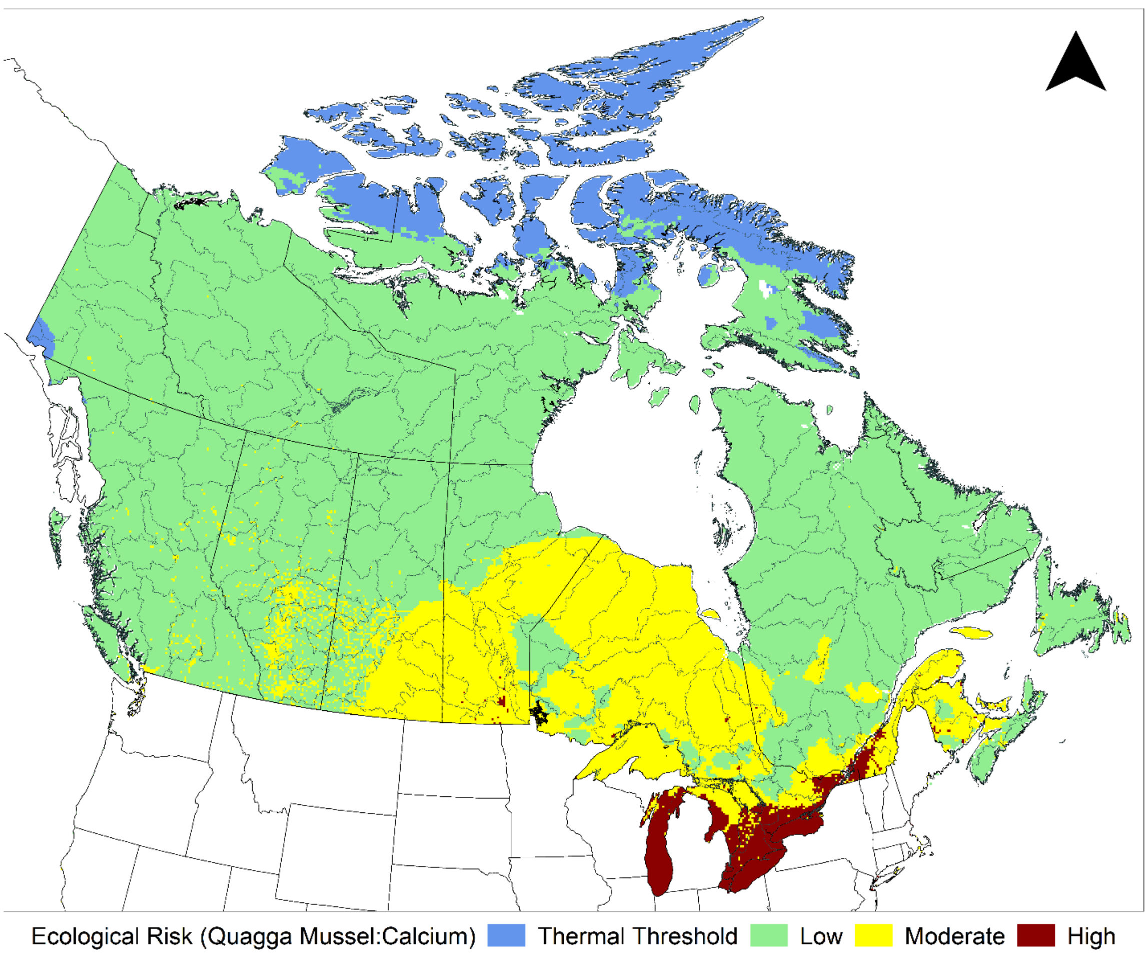

Figure 20. Quagga Mussel Ecological Risk in Canada using the calcium-based model. Risk is based on the Potential for Invasion and Ecological Impacts. Sub-drainages (grey lines) are overlaid on the map.

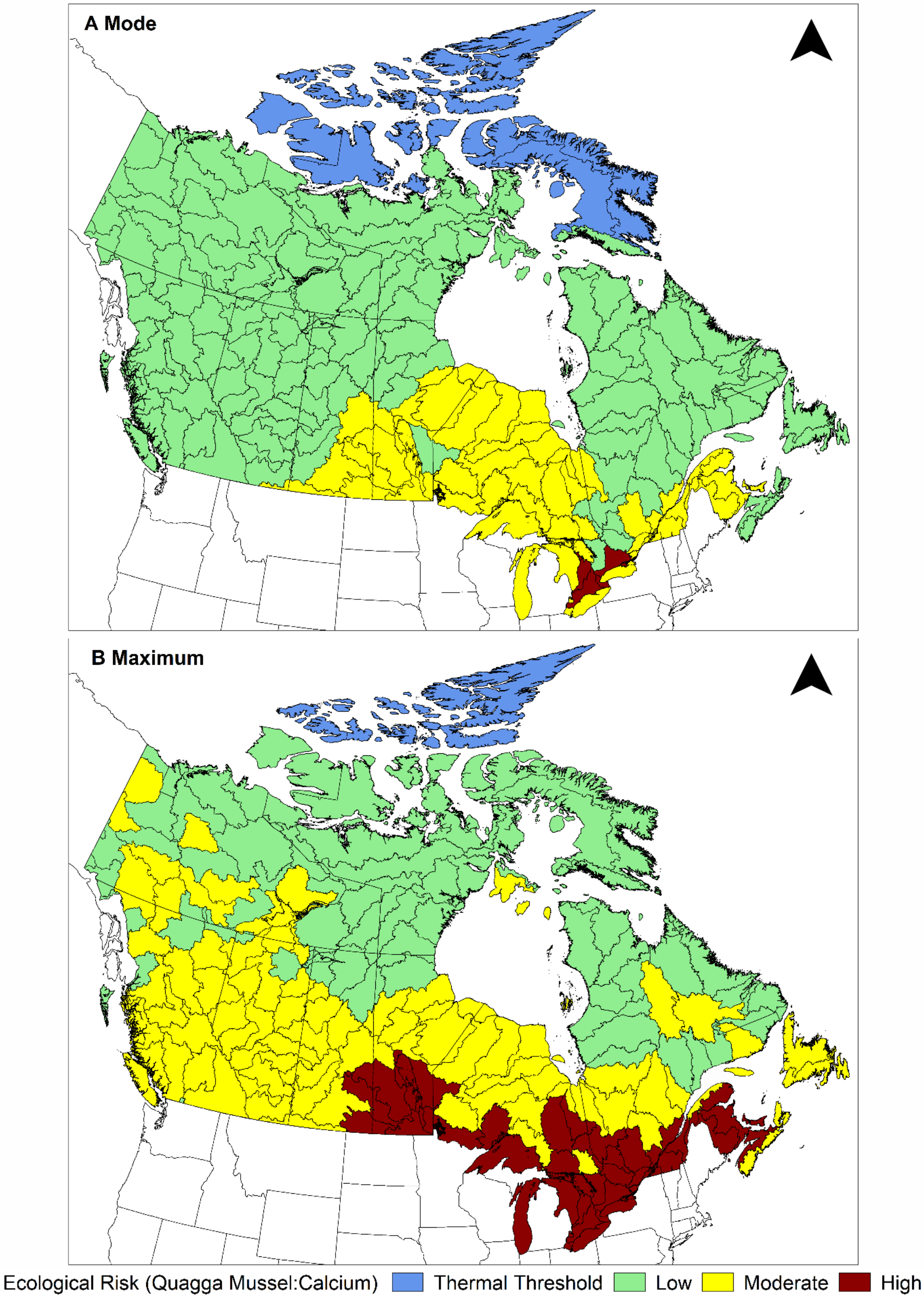

Figure 21. Mode (A) and maximum (B) Quagga Mussel Ecological Risk per Sub-drainage in Canada based on the Calcium-based model. Note that sub-drainage 020 (Great Lakes and St. Lawrence) does include both freshwater and marine habitat, however marine habitat is unsuitable for both species and thus the risk should be applied to only freshwater portions of the sub-drainage.

3.3.3. MaxEnt-based Modelling

3.3.3.1. Potential For Establishment

The MaxEnt model for Quagga Mussel also provides a more restricted geographic area of highly suitable habitat compared to the calcium-based model (Figure 22). Highest values for Canada were located through the Laurentian-Great Lakes system and southern Ontario, which corresponds to the current distribution of the species within North America. The Okanagan Valley region of southern British Columbia as well as the most southern areas of Alberta exhibited patches of higher suitability. The remainder of Canada had relatively lower habitat suitability.

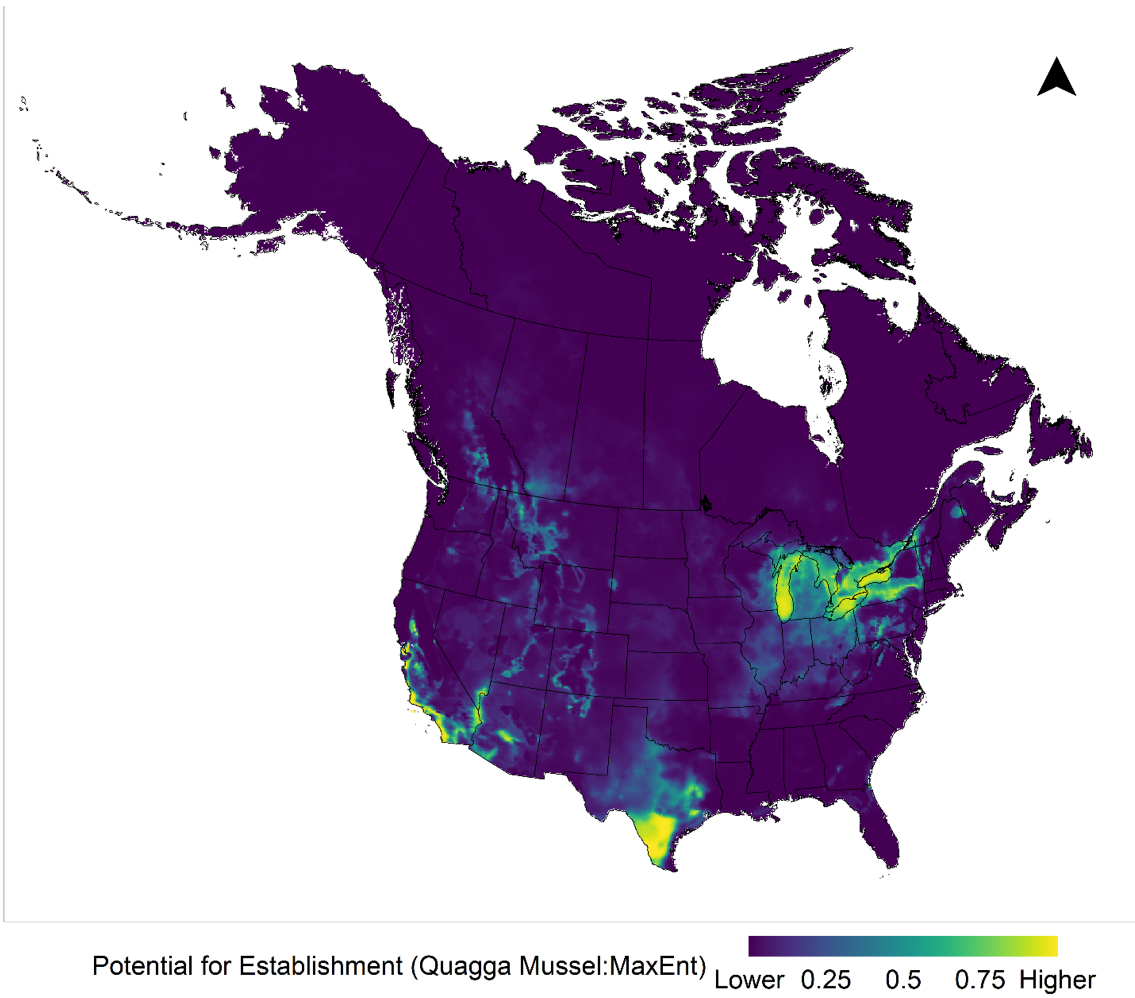

Figure 22. Potential for Establishment of Quagga Mussel using the MaxEnt habitat suitability model and adjusted for unsuitable temperatures.

3.3.3.2. Potential for Invasion

The Potential for Invasion of Quagga Mussel generally mirrors the current known distribution of this species (Figure 23) with the highest values around the Laurentian-Great Lakes system and southern Ontario. The Potential for Invasion in the rest of Canada was determined to be lower.

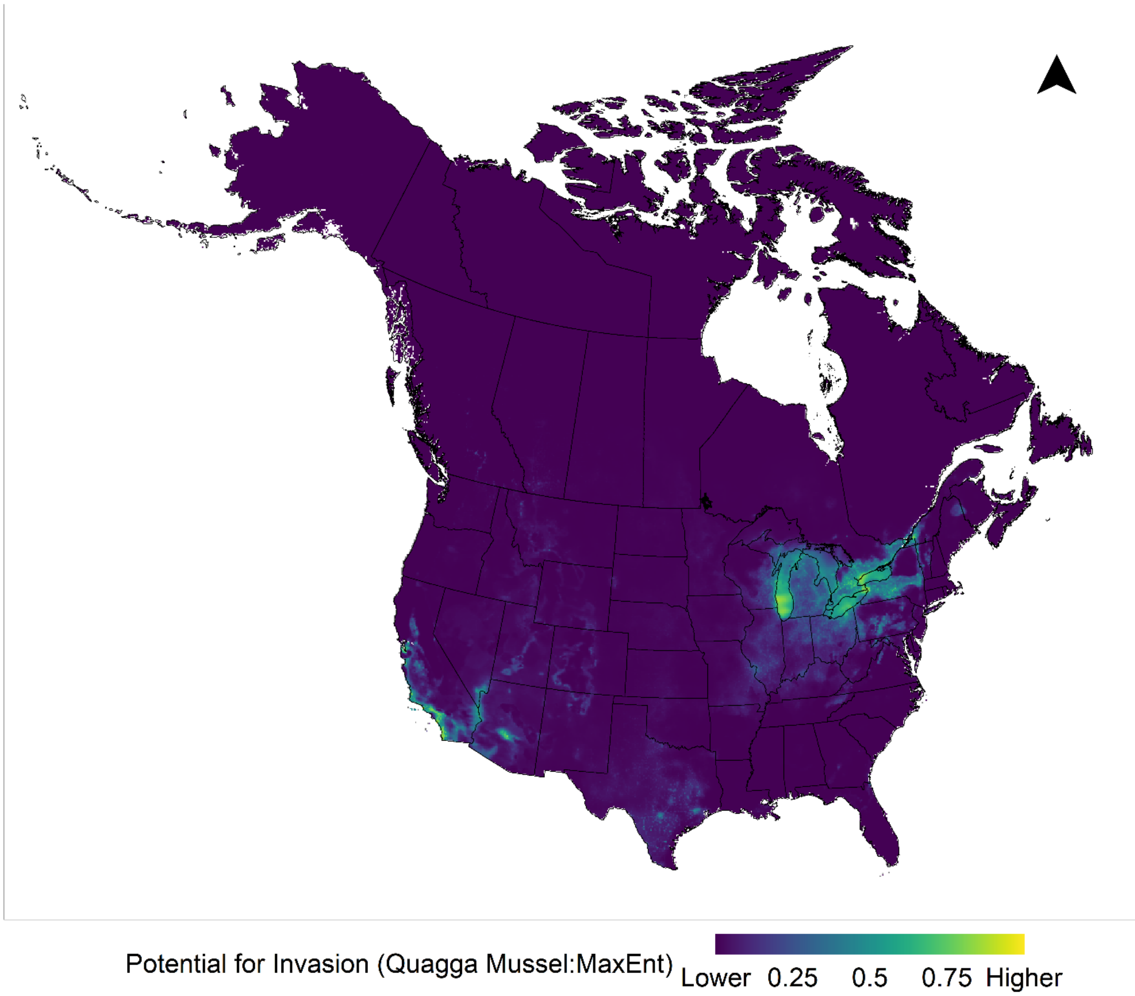

Figure 23. Potential for Invasion of Quagga Mussel in North America based on the Potential for Introduction and Establishment (MaxEnt habitat suitability model).

3.3.3.3. Ecological Risk

Due to the relatively low habitat suitability identified by the MaxEnt model, the Ecological Risk for most of Canada was Low for Quagga Mussel (Figure 24). Small discrete areas of Moderate risk are found in southern Alberta and British Columbia as well as Quebec and New Brunswick. The Laurentian-Great Lakes system, which corresponds to the current distribution of this species, contains both Moderate and High Ecological Risk areas. Ecological Risk is presented at regional extents with the grid cell resolution in Appendix C (Figures C1-C5) and the maximum and mode for Ecological Risk per sub-drainage are presented below (Figure 25).

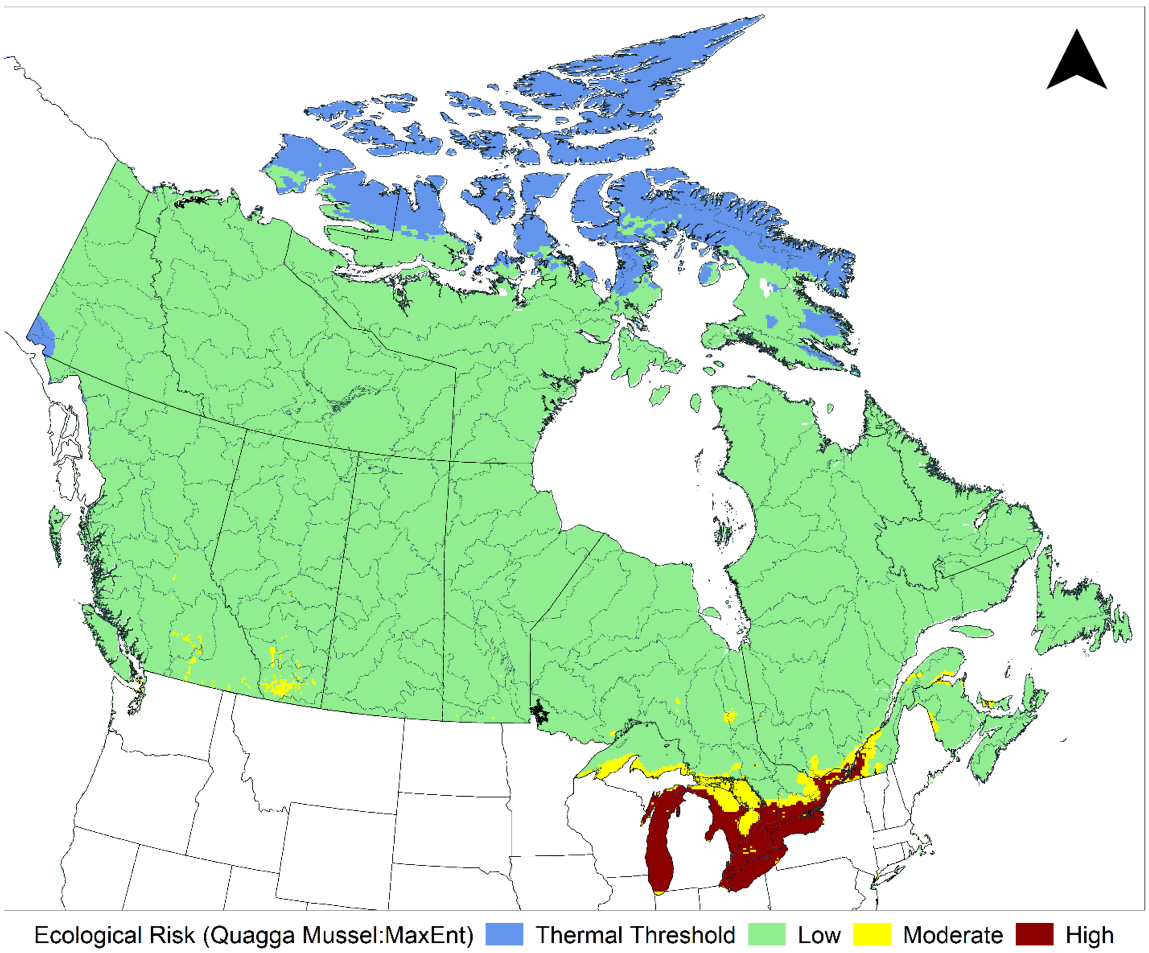

Figure 24. Quagga Mussel Ecological Risk in Canada using the MaxEnt habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts. Sub-drainages (grey lines) are overlaid on the map.

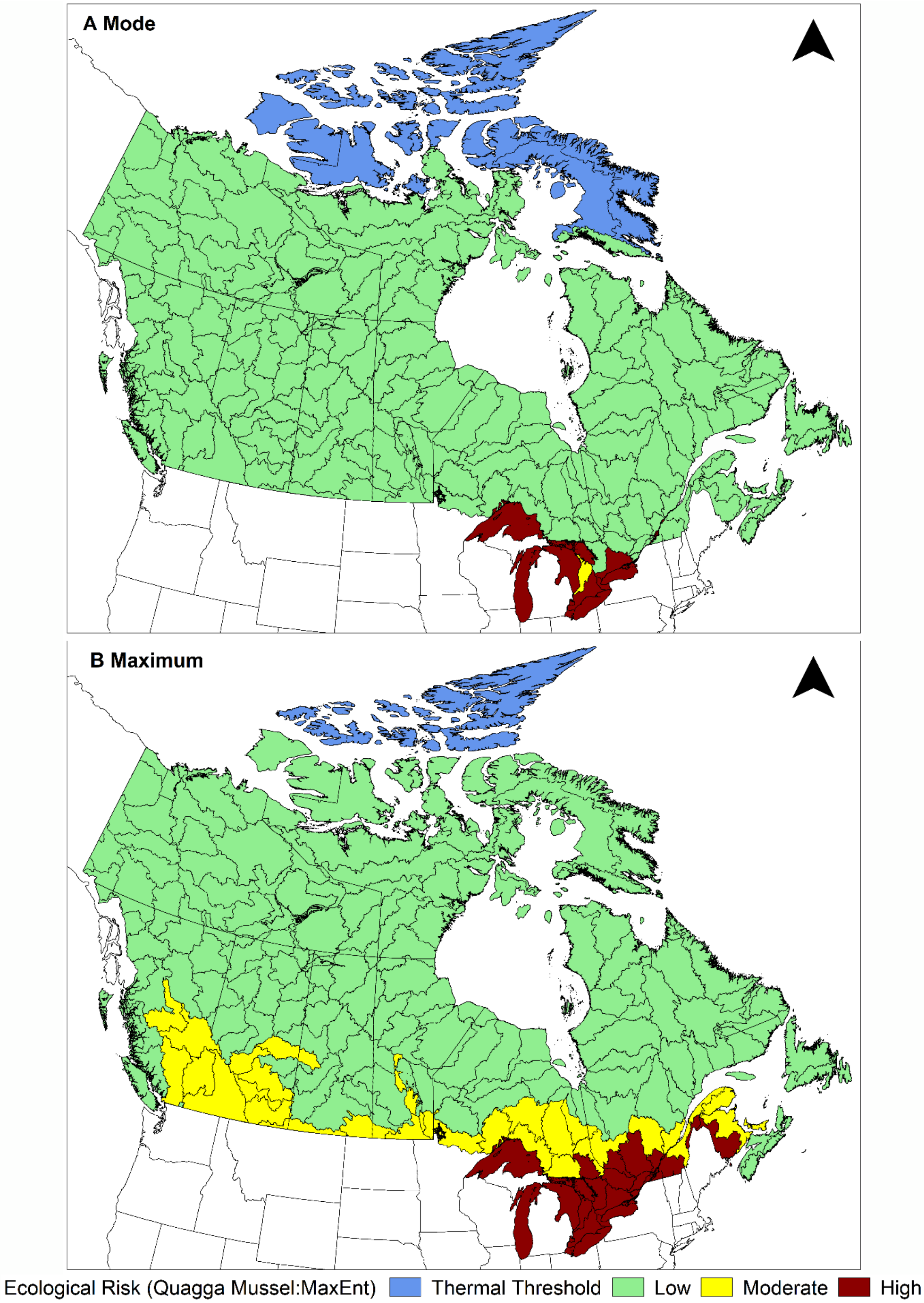

Figure 25. Mode (A) and maximum (B) Quagga Mussel Ecological Risk per Sub-drainage in Canada based on the MaxEnt habitat suitability model. Note that sub-drainage 020 (Great Lakes and St. Lawrence) does include both freshwater and marine habitat, however marine habitat is unsuitable for both species and thus the risk should be applied to only freshwater portions of the sub-drainage.

4. DISCUSSION

4.1. EFFICACY OF THE RISK ASSESSMENT PROCEDURES

While the resulting assessment follows similar steps to the 2012 risk assessment (Therriault et al. 2013) by deriving Ecological Risk through the various steps of the invasion process, the present assessment has significantly greater spatial resolution (9,260 × 9,260 m compared to sub-drainage) and improved data layers used to calculate the various components of risk, including updated species occurrence records and new environmental variables at the national scale. Where the previous assessment used proximity of watersheds to invaded systems as a proxy of connectivity (i.e., potential for downstream drift), the Potential for Introduction in the present assessment now incorporates a quantitative metric of propagule pressure (Human Footprint Index) combined with connectivity based on the cumulative distribution of recreational boater travelling distances. The Potential for Establishment is now based on two habitat suitability scenarios – a calcium-based model similar to what was used in the first assessment (with a correction for temperature limitations), and a MaxEnt habitat suitability model which directly incorporates a variety of environmental data including temperature and water chemistry variables such as calcium concentrations. Finally, the resolution of the data provides more information on the spatial variability in risk values compared to the previous assessment where the resolution was at the sub-drainage level. While the steps of the process are similar, these differences in the development of the components of invasion are fundamentally different from the previous assessment and provide an estimation of the ecological risk posed by these two invasive mussel species to Canadian freshwater ecosystems at a higher resolution.

The use of calcium as a predictor alone may not account for the full suite of environmental variables but as exemplified in the predictor variables of the MaxEnt habitat suitability models, it provides an important predictor of suitable habitat for both dreissenid species. Further, Whittier et al. (2008) defined risk based on calcium concentrations as follows: very low (< 12 mg/L), low (12–20 mg/L), moderate (20–28 mg/L), and high (> 28 mg/L) with the idea that greater calcium concentrations would support larger dreissenid populations as a metric of risk. The calcium-based model for Zebra and Quagga Mussel establishment in the present assessment gave comparable results to those reported by Whittier et al. (2008), with lower risk areas in most of the southeast and western portions of the Pacific Northwest (within the shared extent).

There are numerous approaches available in species distribution modelling using species occurrence data and environmental variables (see review by Elith et al. 2006). When only presence data is available, MaxEnt has been shown to be among the top-performing models used for predicting areas of suitable habitat (see recent review of Valavi et al. 2022). Several authors have previously developed risk assessments for dreissenid mussels in North America. Drake and Bossenbroek (2004) developed an early assessment of Zebra Mussel habitat using a GARP (genetic algorithm for rule-set production) model for the United States of America. Although they used an older data set with a model that pre-dates MaxEnt, their results were comparable to those presented here in that their predicted areas of suitable habitat were consistent with areas of known occurrences (e.g., eastern United States of America) and showed climatic variables and bedrock geology (likely correlated with calcium) were important for identifying suitable Zebra Mussel habitat.

More recent dreissenid habitat assessments have been applied to Zebra or Quagga Mussel in North America using MaxEnt (Gallardo et al. 2013, Quinn et al. 2014, Barnes and Patino 2020). There are two key differences between past MaxEnt approaches and those in the current study. First, past studies used global distributions to develop predictions for North America. In general, models that have been calibrated to include the native range in Europe perform poorly at predicting suitable habitat in North America. For example, Gallardo et al. (2013) noted that

Zebra Mussel occupies different ecological niches in Europe and North America as this species has repeatedly demonstrated the ability to adapt to new environmental conditions. Although some of this adaptive potential is undoubtedly genetic, this alone is not sufficient to account for the differences observed between populations in Europe and North America. Second, past studies identified calcium limitation as a key factor for dreissenid habitat but, due to data limitations, their models could only include geological surrogates (Gallardo et al. 2013, Quinn et al. 2014) or excluded calcium entirely (Barnes and Patino 2020). The models produced by Barnes and Patino (2020) used global occurrence data for Zebra and Quagga Mussel and did not have a continuous global layer of calcium that could be incorporated as a predictive variable in their models. This may account for the resulting assessment of Quagga Mussel invasion risk in Texas not identifying western Texas as an area of potentially suitable habitat. Both the calcium-based and MaxEnt habitat suitability models in the present study predicted suitable habitat for Quagga Mussel in Texas which is supported by the recent and first detection of Quagga Mussel in the state at the International Amistad Reservoir in the Rio Grande basin in 2022 (Texas Parks and Wildlife Department 2022). This highlights the importance of the environmental variables used for model predictions and that the calcium layer may have refined model predictions in contrast to previous studies.

4.2. MODEL DIFFERENCES IN ECOLOGICAL RISK

Overall, there was generally consensus between the resulting Ecological Risk values for both establishment models across Canada. The biggest deviations in Ecological Risk between the two scenarios for establishment varied for both species. For Zebra Mussel, the MaxEnt-based model resulted in greater Ecological Risk predominantly through patches of Eastern Canada, the Rocky Mountains of British Columbia, and the northern Prairie provinces in to southern Nunavut and Northwest Territories (Figure 26A). The calcium-based model resulted in greater Ecological Risk predominantly through patches in northern Alberta and southern Northwest Territories. In both cases most of these patches correspond with a difference between Low and Moderate Ecological Risk. For Quagga Mussel, the calcium-based model showed considerably higher risk throughout the southern Prairie Provinces, Ontario, Quebec south of the Saint Lawrence Estuary, and the Maritime Provinces (Figure 26B). The MaxEnt-based-model tended to agree or resulted in lower Ecological Risk than the calcium-based model. Again, these differences correspond predominantly with a difference between Low and Moderate Ecological Risk. It is important to recall that both models evaluate habitat suitability (Potential for Establishment) using different sets of predictor variables and thus yielding different predictions. Generally, habitat suitability modelling is used to describe the distribution of a species and assumes the modelled niche space is fully represented by the input data. For invasive species which are non-native (by definition) and potentially still spreading, the current distribution (and niche) may not be fully realized thus is likely to be underestimating the true niche being modelled. Thus, while this model can be very useful to identify uninvaded regions which exhibit similar environmental conditions to currently invaded systems, caution should be exercised as areas identified as lower suitability with this approach cannot be assumed to be incapable of supporting an invasive species. However, calcium is not the only factor that influences the distribution of these two mussel species and thus caution must also be exercised when assessing the Potential for Invasion based on this metric alone. Although a temperature threshold was applied, there are undoubtedly other factors affecting an invasion outcome.

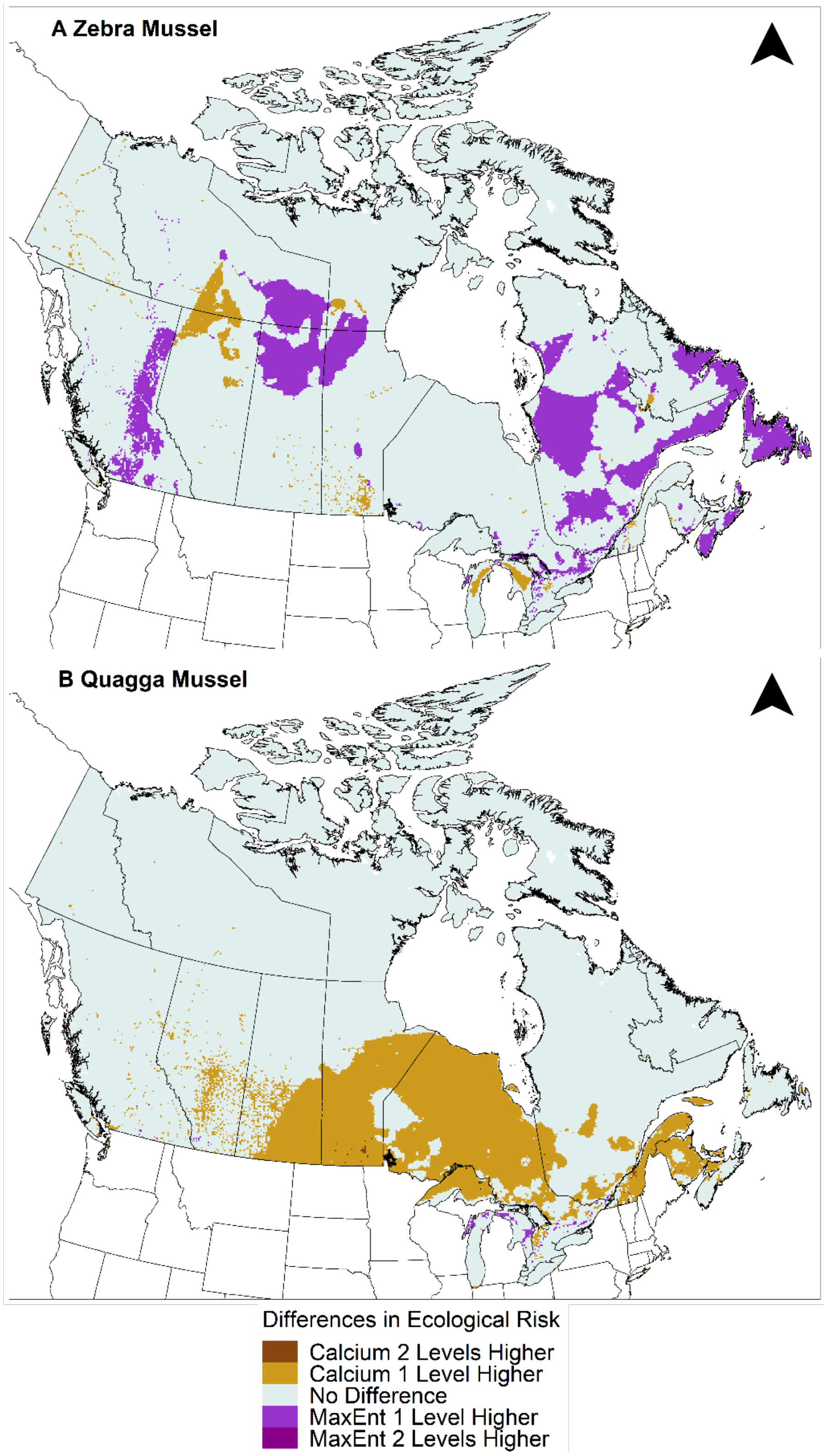

Figure 26. Differences in Ecological Risk of Zebra (A) and Quagga (B) Mussel between the calcium-based and MaxEnt habitat suitability models. Colours indicate where Ecological Risk levels were greater for calcium-based model (Browns), were consistent between models (Light blue), or were greater for the MaxEnt habitat suitability model (Purples).

4.3. UNCERTAINTY AND FUTURE DIRECTIONS

The current risk assessment used a robust and scientifically defensible process to characterize the Ecological Risk posed by Zebra and Quagga Mussel in Canada. There are, however, several areas of uncertainty which, with further refinement of data and the addition of new metrics, could improve the accuracy of resulting models. For example, Potential for Introduction was based on connectivity (proximity to invaded habitats) and human activity as proxies for propagule pressure. Given the importance of recreational boating to the spread of these species, geospatial information such as location or size of boat launches or the amount and types of boating activity could provide a more accurate estimation of dreissenid propagule pressure across the Canadian landscape. Metrics such as those discussed above were only found at local scales but would need to be developed at a national scale to be incorporated in future assessments. Similarly, other invasion vectors such as contaminated aquarium moss balls could be more explicitly considered using the actual geospatial locations of retail outlets selling aquarium livestock. The weighting of metrics for different vectors should reflect their relative contribution to the Potential for Introduction and although there are other vectors that were not explicitly modelled here there is little doubt that the relative contribution of recreational boating to overall propagule pressure would greatly exceed that of contaminated aquarium moss balls. It is also important to note that the connectivity metric used only incorporates dispersal from invaded systems (sources) but does not incorporate spatial variability in the attractiveness of areas to recreational boaters (likelihood of areas to be sinks). The development of such a metric at a national scale would further improve future estimates of spatial variability in propagule pressure.

In the present study, based largely on a significant volume of scientific literature, a score of Very High for Ecological Impacts was applied. However, while it is likely the impacts are on the higher end of this scale, it also is likely that they vary spatially. Ideally, this metric would be based on a full impact analysis, characterizing the different types of impacts noted for dreissenid mussels (see above) in a spatially explicit way and would increase the potential discrimination among levels of impact in a more quantitative way. Alternatively, a national scale assessment of general habitat vulnerability, identifying areas of greater sensitivity to disturbance such as an invasion could be employed to provide greater differentiation and potentially be used in conjunction with (or incorporate) current information on distributions of species listed under the *Species at Risk Act*.

There may be other variables that influence actual distributions of Zebra and Quagga Mussel which were not included as predictor variables in this risk assessment. Some may currently lack the coverage to generate spatial data layers equivalent to the calcium and pH layers developed in this assessment. For example, some chlorophyll *a* records were assembled along with calcium and pH but poor coverage in space and time prevented meaningful spatial interpolation. While such data are not yet readily available for spatial analyses, future inclusion could improve predictions of habitat suitability. Similarly, *in situ* measurements of water temperature would negate the need for proxies such as air temperature and be much more reflective of the conditions Zebra and Quagga Mussel are encountering. There may also be differences in environmental tolerances within a species depending on whether populations represent different ecotypes that could further refine predictor variables (as exemplified in multiple marine species; e.g., Stanley et al. 2018) however, there is no current data to indicate that species represent different ecotypes.

For the data that was used in the current assessment, being conducted at the national scale, there is uncertainty among multiple sources of data used. Some regions such as the Arctic, in particular Nunavut, the Northwest Territories, Yukon, and Alaska were data-poor, resulting in a higher degree of uncertainty for calcium and pH interpolations. In addition, the results and predictions of the models are highly dependent on the scale used in the input data, in this case ~100 km^2. While this resolution can identify habitat differences at the scale of individual watersheds, it prevents resolving the land-water boundaries of fine-scale aquatic features such as tributaries and ponds which would require higher-resolution data. Prioritizing efforts to generate higher resolution environmental data would improve the resolution of future assessment while also creating data layers that could be used for similar assessments for other species.

Another area of uncertainty is the weighting of the various components of an invasion. Without an understanding of the relative importance of each metric to the associated component and each component to the overall likelihood of invasion, it is difficult to determine how each metric should be weighted. For instance, when calculating the Potential for Introduction, the Human Footprint Index and connectivity metric were given equal weighting. However, it is unknown whether one metric contributes more to the chance of an introduction into novel habitats. Presently, there are no independent data sets available with which to validate the weighting of each component, nor the two models used for the Potential for Establishment. Continual monitoring of future expansions could yield the occurrence data necessary to improve future iterations, not only to inform the relative importance of the various metrics but to validate the model and improve the accuracy of the predictions.

The overall Ecological Risk was determined by combining the Potential for Invasion with the Ecological Impacts using a heat matrix (Table 6) with each having various elements of uncertainty. However, the specific categories used to determine overall risk (i.e., the color-coded categories) have inherent risk tolerance implications such that there are several ways to determine the overall risk categories for any assessment. Given substantial documented impacts linking dreissenid invasions to Very High Ecological Impacts, it is reasonable to assume High overall risk even with slightly lower Potential for Introduction which is consistent with the previous assessment for these species (Therriault et al. 2013). However, it is also probable that other assessments may opt for a different scheme for determining overall risk posed by an invader. Even if quantitative data were available for both the Potential for Invasion and Ecological Impacts (which was not the case here) there would still be uncertainty in how best to combine these values given that the relationship between these two components and overall risk remain unknown for all invaders. That said, there was high agreement between locations of higher overall risk and the current distribution of these dreissenid mussels where impacts have been documented and in retrospect some areas identified as higher risk in Therriault et al. (2013) did become invaded in years following that assessment.

5. CONCLUSIONS

The Ecological Risk posed by Zebra Mussel was highest for the Laurentian-Great Lakes area, Manitoba, and New Brunswick regardless of the model used (i.e., calcium-based or MaxEnt) with both highlighting elevated risk to the Maritime Provinces (which was outside the geographic scope of the previous assessment and thus not assessed). Also, the calcium-based model identified higher risk areas in Saskatchewan and Alberta. The Ecological Risk posed by Quagga Mussel also was greatest for the Laurentian-Great Lakes area, but higher risk areas were more constrained relative to Zebra Mussel. Southern British Columbia and Alberta had elevated risk regardless of the model while the calcium-based model identified High risk areas in New

Brunswick and Manitoba. To aid managers in using the data provided in this report, a summary of the data products is shown in Figure 27. These can be downloaded from the Open Government data portal or the Federal Geospatial Platform. It is important to recognize that the Ecological Risk values presented are not absolute, and areas of Low risk do not necessarily indicate an inability of dreissenid mussels to be introduced, establish, or to impact these systems but rather indicates that the risk of ecological impacts due to invasion are lower relative to higher risk areas. It is also important to recognize that there is no indication that the invasion in North America is complete, and that the current distribution represents the fully realized known distribution of these two species. There is therefore a continual need to refine the data inputs and procedures to integrate the various components of risk as the invasion unfolds. Thus, the risk assessment will need to be updated regularly to reflect the new distributions of each dreissenid species which would change the Potential for Introduction by altering the metric of connectivity. It would also require MaxEnt habitat suitability models to be retrained using the new distribution, which could refine the input parameters to reflect more closely the full suite of habitats suitable for establishment. To facilitate these successive updates, a national database of geo-referenced water quality data and AIS occurrences for Canadian aquatic ecosystems (marine, estuarine, and freshwater) is much needed.

ECOLOGICAL RISK

- Ecological Risk incorporates all steps of the invasion process
- Given that Ecological impacts are Very High across all of Canada, the final determination of Ecological Risk represents differences in the Potential for Invasion
- The current distributions of Zebra and Quagga Mussel (Fig. 3) are in Moderate and High Ecological Risk areas
- Low Ecological Risk does not mean no risk

GRID CELL RESOLUTION MAPS

Provide the most detailed maps (~ 100 km^2)

Zebra Mussel		Quagga Mussel	
Calcium	MaxEnt	Calcium	MaxEnt
Fig. 11	Fig. 15	Fig. 20	Fig. 24

*See appendices for regional extents

SUB-DRAINAGE MAPS

Mode and maximum values per sub-drainage

Zebra Mussel		Quagga Mussel	
Calcium	MaxEnt	Calcium	MaxEnt
Fig. 12	Fig. 16	Fig. 21	Fig. 25

*See appendices for tables

INTERMEDIATE PRODUCTS

For select steps of the invasion process

POTENTIAL FOR INVASION

Introduction and Establishement

Zebra Mussel		Quagga Mussel	
Calcium	MaxEnt	Calcium	MaxEnt
Fig. 10	Fig. 14	Fig. 19	Fig. 23

POTENTIAL FOR INTRODUCTION

HFI (Fig. 5) and Connectivity (Fig. 6)

Zebra Mussel	Quagga Mussel
Fig. 8	Fig. 17

Human Footprint Index: proxy for human influence
Connectivity: proxy for movement from invaded sites

POTENTIAL FOR ESTABLISHMENT

Suitable habitat maps

Zebra Mussel		Quagga Mussel	
Calcium	MaxEnt	Calcium	MaxEnt
Fig. 9	Fig. 13	Fig. 18	Fig. 22

Calcium model: based on calcium thresholds
MaxEnt model: based on environmental variables

Figure 27. Summary of the data products produced by the 2022 risk assessment for Zebra and Quagga Mussel in Canada and which can be downloaded from the Open Government data portal or the Federal Geospatial Platform.

6. ACKNOWLEDGEMENTS

We wish to thank those that provided Zebra and Quagga Mussel data: Amy Benson (United States Geological Survey), Annick Drouin and Olivier Morissette (Ministère de l'Envrionment, de la Lutte contre les changemets climatiques, de la Faune et des Parcs), Laureen Janusz and Jeff Long (Natural Resources and Northern Development, Government of Manitoba). We also thank those that provided environmental data: Sarah Forté (Crown-Indigenous Relations and Northern Affairs Canada), Kivalliq Inuit Association, Victoria Millette (Water Security Agency of Saskatchewan), Marie Ducharme, Cameron Sinclair and Nicole Novodvrosky (Department of Environment, Government of Yukon), Daniel Rheault (Environment, Climate, and Parks, Government of Manitoba), Jason LeBlanc (Department of Fisheries and Aquaculture, Government of Nova Scotia), Cindy Chu (Ontario Ministry of Natural Resources & Forestry), Mario Bérubé and Manon Ouellet (Ministère de l'Environnement et de la Lutte contre les changements climatiques, Gouvernement du Québec), Annick Drouin and Sylvie Normand (Ministère des Forêts, de la Faune et des Parcs, Gouvernement du Québec), Julie Grenier (Conseil de gouvernance de l'eau des bassins versants de la rivière Saint-François), Robin Staples (Environment and Natural Resources, Government of the Northwest Territories), Tanya Johnston, Mary Raven, Nelda Craig, Justin Shead, Dean Jeffries, Leif-Matthias Herborg, and others who provided data for the 2012 risk assessment. Kurt Menke (Septima) provided excellent support for GIS analyses. We acknowledge funding from DFO Science's Aquatic Invasive Species (AIS) program. We also thank the CSAS Steering Committee and meeting participants who provided useful comments and advice.

7. REFERENCES

Antoniades, D., Douglas, M.S.V., and Smol, J.P. 2003a. Comparative physical and chemical limnology of two Canadian High Arctic regions: Alert (Ellesmere Island, NU) and Mould Bay (Prince Patrick Island, NWT). Arch. Hydrobiol. 158:485-516.

Antoniades, D., Douglas, M. S. V., and Smol, J. P. 2003b. The physical and chemical limnology of 24 ponds and one lake from Isachsen, Ellef Ringnes Island, Canadian High Arctic. International Review of Hydrobiology, 88:519-538.

Barnes, M.A., and Patiño, R. 2020. Predicting suitable habitat for dreissenid Mussel invasion in Texas based on climatic and lake physical characteristics. Manag. Biol. Invasions 11(1):63-79.

Benson, A.J., Raikow, D., Larson, J., Fusaro, A., Bogdanoff, A.K., and Elgin, A. 2022. *Dreissena polymorpha* (Pallas, 1771): U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL, Revision Date: 4/27/2022. [online] [accessed 27 May 2022].

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R.U., and Richardson, D.M. 2011. A proposed unified framework for biological invasions. Trends Ecol. Evol. 26:333-339.

Buchan, L.A.J., and Padilla, D.K. 1999. Estimating the probability of long-distance overland dispersal of invading aquatic species. Ecol. Appl. 9(1):254-265.

De Cicco, L.A., Hirsch, R.M., Lorenz, D., and Watkins, W.D. 2018. dataRetrieval: R packages for discovering and retrieving water data available from Federal hydrologic web services.

Carlsson, N.O.L., Bustamante, H., Strayer, D.L., and Pace, M.L. 2011. Biotic resistance on the increase: native predators structure invasive zebra mussel populations. Freshw. Biol. 56(8):1630-1637.

Chan, F.C., Drake, D.A.R., and Therriault, T.W. 2021. The Risk of Introducing Live Organisms by the Aquarium, Water Garden, and Seafood Trades in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/036.

Clavero, M., and García-Berthou, E. 2005. Invasive species are a leading cause of animal extinctions. Trends Ecol. Evol. 20(3):110.

Cohen, A.N., and Weinstein, A. 2001. Zebra Mussel‟s Calcium Threshold and Implications for its Potential Distribution in North America. Richmond, CA: San Francisco Estuary Institute.

Collins, S.M., Yuan, S., Tan, P.N., Oliver, S.K., Lapierre, J.F., Cheruvelil, K.S., Fergus, C.E., Skaff, N.K.,Stachelek, J., Wagner, T., and Soranno, P.A. 2019. Winter precipitation and summer temperature predict lake water quality at macroscales. Water Resour. Res. 55:2708-2721.

COSEWIC 2021. Committee on the Status of Endangered Wildlife in Canada. [online] [accessed 15 March 2022].

Depew, D.C., Krutzelmann, E., Watchorn, K.E., Caskenette, A., and Enders, E.C. 2021. The distribution, density, and biomass of the zebra mussel (*Dreissena polymorpha*) on natural substrates in Lake Winnipeg 2017-2019. J. Great Lakes Res. 47(3): 556-566.

DFO. 2013a. Science advice from the risk assessment of three dreissenid mussels (*Dreissena polymorpha*, *Dreissena rostriformis bugensis*, and *Mytilopsis leucophaeata*) in Canadian freshwater ecosystems. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/082.

DFO. 2013b. Proceedings of the National Risk Assessment of Zebra Mussel, Quagga Mussel and Dark Falsemussel, March 27-28, 2012. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2012/059.

DFO. 2021a. Invasive mussels found in Moss Ball products in Canada. News Release, March 11, 2021.

Dominguez Almela, V., Nolan, E.T., Winter, E.R., and Britton, J.R. 2022. Dietary contributions of the alien zebra mussel *Dreissena polymorpha* in British freshwater fish suggest low biological resistance to their invasion. Hydrobiologia 849:2253-2265.

Dove, R. and Wallis, M. 1981. Studies on aquatic macrophytes part XXXIV. The 1980 aquatic quarantine project. APD Bulletin 17. Province of British Columbia Ministry of Environment, Victoria, British Columbia, Canada.

Drake, D.A.R. 2017. Overland spread of aquatic invasive species among freshwater ecosystems due to recreational boating in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/031. Vi + 38 p.

Drake, J.M. and Bossenbroek, J.M. 2004. The potential distribution of zebra mussels in the United States. BioScience, 54, 931–941.

Drake, D.A.R., Bailey, S.A., and N.E. and Mandrak, N.E. 2017. Ecological Risk Assessment of Recreational Boating as a Pathway for the Secondary Spread of Aquatic Invasive Species in the Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/030. V + 85 p.

Elith, J.H., Graham, C.P., Anderson, R., Dudík, M., Ferrier, S., Guisan, A.J., Hijmans, R., Huettmann, F.R., Leathwick, J., Lehmann, A., and Li, J. 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography. 29:129-151.

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., and Yates, C.J. 2011. A statistical explanation of MaxEnt for ecologists. Divers. Distrib. 17(1):43-57.

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

Filazzola, A., Mahdiyan, O., Shuvo, A., Ewins, C., Moslenko, L., Sadid, T., Blagrave K., Imrit, M. A., Gray, D. K., Quinlan, R., O'Reilly, C. M., and Sharma, S. 2020. A database of chlorophyll and water chemistry in freshwater lakes. Scientific Data. 7:310.

Gallardo, B. and Aldridge, D.C. 2013. The 'dirty dozen': socio-economic factors amplify the invasion potential of 12 high-risk aquatic invasive species in Great Britain and Ireland. J. Appl. Ecol. 50:757-766.

Gallardo, B., P.S.E. zu Ermgassen, and Aldridge, D.C. 2013. Invasion ratcheting in the zebra mussel (*Dreissena polymorpha*) and the ability of native and invaded ranges to predict its global distribution. J. Biogeogr. (40)12:2274-2284.

Gallardo, B., Zieritz, A., and Aldridge, D.C. 2015. The importance of the human footprint in shaping the global distribution of terrestrial, freshwater and marine invaders. PLoS ONE 10:e0125801.

Gallardo, B., Clavero, M., Sanchez, M.I., and Vilà, M. 2016. Global ecological impacts of invasives species in aquatic ecosystems. Global Change Biology 22:151-163.

Garton, D.W., R. McMahon, A.M. Stoeckmann, T.F. Nalepa, and Schloesser, D.W. 2013. Limiting environmental factors and competitive interactions between zebra mussels and quagga mussels in North America. Quagga and zebra mussels: biology, impacts, and control. 331-334.

Gillis, P.L. and Mackie, G.L. 1994. Impact of the zebra mussel, *Dreissena polymorpha*, on populations of Unionidae (Bivalvia) in lake St. Clair. Can. J. Zool. 72:1260-1271.

Hebert, P.D.N., Muncaster, B.W, and Mackie, G.L. 1989. Ecological and Genetic Studies on *Dreissena polymorpha* (Pallas): a New Mollusc in the Great Lakes. Can. J. Fish. Aquat. Sci. 46(9):1587-1591.

Higgins, S.N. 2014. Meta-Analysis of Dreissenid Effects on Freshwater Ecosystems. In: Nalepa, T.F. and D.W. Schloesser (eds.), Quagga and Zebra mussels: Biology, Impacts, and Control, 2nd ed. CRC Press, Boca Raton, FL., pp. 487-494.

Higgins, S.N., and Vander Zanden, M.J. 2010. What a difference a species makes: A meta-analysis of dreissenid mussel impacts on freshwater ecosystems. Ecol. Monogr. 80(2):179-196.

Higgins, S.N., Malkin, S.Y., Howell, E.T., Guildford, S.J., Campbell, L., Hiriart-Baer, V., and Hecky, R.E. 2008. An ecological review of *Cladophora glomerata* (Chlorophyta) in the Laurentian Great Lakes. J. Phycol. 44:839-854.

Higgins, S.N., M.J. Vander Zanden, L.N. Joppa, and Vadeboncoeur, Y. 2011. The effect of dreissenid invasions on chlorophyll and the chlorophyll: total phosphorus ratio in north-temperate lakes. Can. J. Fis.h Aquat. Sci. 68:319-329.

Hijmans, R. J., S. Phillips, J. Leathwick, J. Elith, and Hijmans, M.R.J. 2017. Package "dismo." Circles 9.

Hijmans, R. J. 2021. Raster: Geographic Data Analysis and Modelling. R package version 3.4-13.

Hijmans, R.J., Charles, K., Williams, E., and Vennes, C. 2021. geosphere: Spherical Trigonometry. R package version 1.5-14.

Hincks, S.S. and Mackie, G.L. 1997. Effects of pH, calcium, alkalinity, hardness, and chlorophyll on the survival, growth, and reproductive success of zebra mussels (*Dreissena polymorpha*) in Ontario Lakes. Can. J. Fish. Aquat. Sci. 54:2049–2057.

Johnson, L.E. and Carlton, J.T. 1996. Post-Establishment Spread in Large-Scale Invasions: Dispersal Mechanisms of the Zebra Mussel *Dreissena Polymorpha*. Ecology 77(6):1686-1690.

Johnson, L.E. and Padilla, D.K. 1996.Geographic spread of exotic species: Ecological lessons and opportunities from the invasion of the zebra mussel *Dreissena polymorpha*. Biol. Conserv. (78)1–2:23-33.

Johnstone, I.M., Coffey, B.T., and Howard-Williams, C. 1985. The role of recreational boat traffic in interlake dispersal of macrophytes: A New Zealand case study. J. Environ. Manage. 20: 263-279.

Jones, L.A. and Ricciardi, A. 2005. Influence of physiochemical factors on the distribution and biomass of invasive mussels (*Dreissena polymorpha* and *Dreissena bugensis*) in the St. Lawrence River. Can. J. Fish. Aquat. Sci. 62:1953–62.

Joynt, E. H. and Wolfe, A.P. 2001. Paleoenvironmental inference models from sediment diatom assemblages in Baffin Island lakes (Nunavut, Canada) and reconstruction of summer water temperature. Can. J. Fish. Aquat. Sci. 58:1222-1243.

Karatayev, A.Y., Burlakova, L.E., and Padilla, D.K. 2002. Impacts of zebra mussels on aquatic communities and their role as ecosystem engineers. In: Leppäkoski E., Gollasch S., Olenin S. (eds) Invasive Aquatic Species of Europe, Distribution, Impacts, and Management. Springer, Dordrecht.

Karatayev, A.Y., Burlakova, L.E., Mastitsky, S.E., and Padilla, D.K. 2015. Predicting the spread of aquatic invaders: insight from 200 years of invasion by zebra mussels. Ecol. Appl. 25(2):430-440.

Kass J.M., Muscarella, R., Galante, P.J., Bohl, C.L., Pinilla-Buitrago, G.E., Boria, R.A., Soley-Guardia, M., and Anderson, R.P. 2021. ENMeval 2.0: Redesigned for customizable and reproducible modelling of species' niches and distributions. Methods Ecol. Evol. 12(9):1602-8.

Knoll, L.B, Sarnelle, O., Hamilton, S.K., Kissman, C.E.H., Wilson, A.E., Rose, J.B., and Morgan, M.R. 2008. Invasive zebra mussels (*Dreissena polymorpha*) increase cyanobacterial toxin concentrations in low-nutrient lakes. Can. J. Fish. Aquat. Sci. 65(3):448-455.

L'actualité, 2021. Des moules zébrées observées pour la première fois dans le lac Massawippi. News release, October 22, 2021.

Liu, C., Berry, P. M., Dawson, T. P., and Person, R.G. 2005. Selecting thresholds of occurrence in the Predictions of Species Distribution. Ecography 28:385–393.

Liu X, G.Z., Ke, Z., Wang, S., and Li, Y.   2011. Increasing Potential Risk of a Global Aquatic Invader in Europe in contrast to other continents under future climate change. PLOS ONE 6(3): e18429.

Mackie, G. L. and Schloesser, D.W. 1996. Comparative biology of zebra mussels in Europe and North America: an overview. Amer. Zool. 36:244-158.

Mackie, G. L. and Claudi, R. 2010. Monitoring and control of macrofouling mollusks in freshwater systems, Second Edition. CRC Press, Boca Raton, FL. 508 pp.

Mandrekar, J. N. 2010. Receiver operating characteristic curve in diagnostic test assessment. J. Thorac. Oncol. 5:1315-1316.

McDowell, W.G., Benson, A.J., and Beyers, J.E. 2014. Climate controls the distribution of a widespread invasive species: implications for future range expansion. Freshwater Biol. 59:847-857.

McMahon, R.F. 1996. The physiological ecology of the zebra mussel, *Dreissena polymorpha*, in North America and Europe. Am. Zool. 36:339-363.

Mellina, E. and Rasmussen, J.B. 1994. Patterns in the distribution and abundance of zebra mussel (*Dreissena polymorpha*) in rivers and lakes in relation to substrate and other physiochemical factors. Can. J. Fish. Aquat. Sci. 51:1024-1036.

Merow, C., Smith, M. J., and Silander, J.A.. 2013. A practical guide to MaxEnt for modelling species' distributions: What it does, and why inputs and settings matter. Ecography, 36: 1058–1069.

Mills, E.L., Casselman, J.M., Dermott, R., Fitzsimons, J.D., Gal, G., Holeck, K.T., Hoyle, J.A., Johannsson, O.E., Landry, B.F., Makarewicz, J.C., Millard, E.S., Munawar, I.F., Munawar, M., O'Gorman, R., Owens, R.W., Rudstan, L.G., Schaner, T., and Stewart, T.J.. 2003. Lake Ontario: food web dynamics in a changing ecosystem (1970-2000). Can. J. Fish. Aquat. Sci. 60:471-490.

Michelutti, N., Douglas, M. S. V., Lear, D. R. S., and Smol, J.P. 2002a. Physical and chemical limnology of 34 ultra-oligotrophic lakes and ponds near Wynniatt Bay, Victoria Island, Arctic Canada. Hydrobiologia, 482:1-13.

Michelutti, N., Douglas, M.S.V., Muir, D.C.G., Wang, X., and Smol, J.P. 2002b. Limnological characteristics of 38 lakes and ponds on Axel Heiberg Island, High Arctic Canada. Int. Rev. Hydrobiol. 87:385-399.

Mollot, G., Pantel, J.H., and Romanuk, T.N. 2017. The effects of invasive species on the decline in species richness: a global meta-analysis. Adv. Ecol. Res. 56:61-83.

Morrison, H. 2004. Canadian Acid Deposition Science Assessment. Meteorological Service of Canada, 479 p.

Naimi, B., Hamm, N., Groen, T., Skidmore, A., and Toxopeus, A. 2014. Where is positional uncertainty a problem for species distribution modelling. Ecography 37:191–203.

Nakano, D. and Strayer, D.L. 2014. Biofouling animals in fresh water: biology, impacts, and ecosystem engineering. Front. Ecol. Environ. 12(3):167-175.

Natural Resources Canada. 2016, "Atlas of Canada 1,000,000 National Frameworks Data, Hydrology - Fundamental Drainage Areas", 10.5203/ze9g-4t83, Canadian Watershed Information Network, V1.

Neary B.P. and Leach, J.H. 1992. Mapping the potential spread of the zebra mussel (*Dreissena polymorpha*) in Ontario. Can. J. Fish. Aquat. Sci. 49:406–15.

Nephin, J., Gregr, E. J., St. Germain, C., Field, C., and Finney, J.L. 2020. Development of a Species Distribution Modelling Framework and its Application to Twelve Species on Canada's Pacific Coast. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/004.

Orlova, M.I., Muirhead, J.R., Antonov, P.I., Shcherbina, G.K., Starobogatov, Y.I., Biochino, G.I., Therriault, T.W., and McIsaac, H.J. 2004. Range expansion of quagga mussels *Dreissena rostriformis bugensis* in the Volga River and Caspian Sea basin. Aquat. Ecol. 38:561–573.

Orlova, M.I., Therriault, T.W., Antonov, P.I., and Shcherbina, G.K. 2005. Invasion ecology of quagga mussels (*Dreissena rostriformis bugensis*): a review of evolutionary and phylogenetic impacts. Aquat. Ecol. 39:401–418.

Pebesma, E.J. 2004. Multivariable geostatistics in S: the gstat package. Comput Geosci 30:683-691.

Pebesma, E. 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal 10(1):439-446.

Pebesma, E.J. and Bivand, R.S. 2005. Classes and methods for spatial data in R. R News, 5(2): 9-13.

Peyer, S.M., Hermanson, J.C., and Lee, C.E. 2010. Developmental plasticity of shell morphology of quagga mussels from shallow and deep-water habitats of the Great Lakes. J. Exp. Biol. 213:2601-2609.

Phillips, S.J. 2005. A brief tutorial on MaxEnt. [online] [accessed 5 June 2021].

Phillips, S. J., Anderson, R. P., and Schapire, R. E. 2006. Maximum entropy modelling of species geographic distributions. Ecol. Model. 190:231-259.

Phillips, S. J., Dudik, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., and Ferrier, S. 2009. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. Ecol. Appl. 19:181–197.

Picard, I. and Doyon, S. 2018. Vérification de la présence de moules zébrées dans la baie de Magog au lac Memphrémagog et première évaluation de l'état de la situation. Étude réalisée pour Memphrémagog Conservation inc. (MCI). 11 p.

Pienitz, R., Smol, J. P., and Lean, D.R.S. 1997. Physical and chemical limnology of 24 lakes located between Yellowknife and Contowoyto Lake, Northwest Territories (Canada). Can. J. Fish. Aquat. Sci. 54:347-358.

Pollux, B.J.A., van der Velde, G., and bij de Vaate, A. 2010. A perspective on global spread of Dreissena polymorpha: a review on possibilities and limitations. In: Van der Velde, G., Rajagopal, S., and Bij de Vaate, A. (eds). The Zebra Mussel in Europe. Backhuys Publishers, Leiden/Margraf Publishers, Weikersheim, pp 45-58.

Quinn, A., Gallardo, B., and Aldridge, D.C. 2014. Quantifying the ecological niche overlap between two interacting invasive species: the zebra mussel (*Dreissena polymorpha*) and the quagga mussel (*Dreissena rostriformis bugensis*). Aquatic Conserv.: Mar. Freshw. Ecosyst. 24:324-337.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raikow, D.F., Sarnelle, O.,Wilson, A.E., and Hamilton, S.K. 2004. Dominance of the noxious Cyanobacterium *Microcystis aeruginosa* in low-nutrient lakes is associated with exotic zebra mussels. Limnol. Oceanogr. 49:482-487.

Ram, J.L., Karim, A.S., Banno, F., and Kashian, D.R. 2011. Invading the invaders: reproductive and other mechanisms mediating the displacement of zebra mussels by quagga mussels. Invertebr. Reprod. Dev. 56:1, 21-32.

Ramcharan, C.W., Padilla, D.K., and Dodson, S.I. 1992. Models to predict potential occurrence and density of the zebra mussel, *Dreissena polymorpha*. Can. J. Fish. Aquat. Sci. 49(12):2611-2620.

Ricciardi, A. 2006. Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Divers. Distrib. 12: 425-433.

Ricciardi, A. and Whoriskey, F.G. 2004. Exotic species replacement: shifting dominance of dreissenid mussels in the Soulanges Canal, upper St. Lawrence River, Canada. J. N. Am. Benthol. Soc. 23(3):507–514.

Ricciardi, A., Whoriskey, F.G., and Rasmussen, J.B. 1996. Impact of the Dreissena invasion on native unionid bivalves in the upper St. Lawrence River. Can. J. Fish. Aquat. Sci. 53: 1434-1444.

Ricciardi, A., Neves, R.J., and Rasmussen, J.B. 1998. Impending extinctions of North American freshwater mussels (Unionoida) following the zebra mussel (*Dreissena polymorpha*) invasion. J. Animal Ecol. 67(4): 613-619.

Roe, S.L. and MacIsaac, H.J. 1997. Deepwater population structure and reproductive state of quagga mussels (*Dreissena bugensis*) in Lake Erie. Can. J. Fish. Aquat. Sci. 54(10):2428-2433.

Rühland, K.M., Smol J.P., Wang X., and Muir, D.C.G. 2003. Limnological characteristics of 56 lakes in the Central Canadian Arctic Treeline Region. J. Limnol. 62:9-27.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M. and Wall, D.H. 2000. Biodiversity - Global biodiversity scenarios for the year 2100. Science 287:1770-1774.

Schloesser, D.W., Kovalak, W.P., Longton, G.D., Ohnesorg, K.L., and Smithee, R.D. 1998. Impact of Zebra and Quagga Mussels (*Dreissena* spp.) on Freshwater Unionids (Bivalvia: Unionidae) in the Detroit River of the Great Lakes. Am. Midl. Nat. 140(2): 299-313.

Son, M.O. 2007. Native range of the zebra mussel and quagga mussel and new data on their invasions within the Ponto-Caspian region. Aquat. Invasions 2: 169–179.

South, A. 2017. rnaturalearth: World Map Data from Natural Earth. R package version 0.1.0.

Srivastava, V., Lafond, V., and Griess, V. 2019. Species distribution models (SDM): applications, benefits and challenges in invasive species management. CAB Reviews Perspectives in Agriculture Veterinary Science Nutrition and Natural Resources. 14. 1-13. 10.1079/PAVSNNR201914020.

Stanley, R.R.E, DiBacco, C., Lowen, B., Beiko, R.G., Jeffery, N.W., Van Wyngaarden, M., Bentzen, P., Brickman, D., Benestan, L., Bernatchez, L., Johnson, C., Snelgrove, P.V.R., Wang, Z., Wringle, B.F., Bradbury, and Bradbury, I.R. 2018. A climate-associated multispecies cryptic cline in the northwest Atlantic. Sci. Adv. 4(3):eaaq0929:1-7.

Stefan, H.G. and Preud'homme, E.B. 1993. Stream temperature estimation from air temperature. J. Am. Water Resour. As. 29, 27–45.

Strayer, D.L. 1991. Projected distribution of the zebra mussel, *Dreissena polymorpha*, in North America. Can. J. Fish. Aquat. Sci. 48: 1389–95.

Strayer, D.L., Powell, J., Ambrose, P., Smith, L.C., Pace, M.L., and Fischer, D.T. 1996. Arrival, spread, and early dynamics of a zebra mussel (*Dreissena polymorpha*) population in the Hudson River Estuary. Can. J. Fish. Aquat. Sci. 53: 1143-1149.

Texas Parks and Wildlife Department. 2022. Quagga mussels detected for the first time in Texas Reservoir. News release, February 2, 2022.

Therriault, T. W., and Herborg, L-M 2008. A qualitative biological risk assessment for vase tunicate *Ciona intestinalis* in Canadian waters: using expert knowledge. ICES J. Mar. Sci. 65:781-787.

Therriault, T.W., Docker, M.F., Orlova, M.I., Heath, D.D., and MacIsaac, H.J. 2004. Molecular resolution of the family Dreissenidae (Mollusca: Bivalvia) with emphasis on Ponto-Caspian species, including first report of *Mytilopsis leucophaeata* in the Black Sea basin. Mol. Phylogenet. Evol. 30(3):479-489.

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

van der Velde, G., Rajagopal, S., and bij de Vaate, A. (eds.) 2010. The Zebra Mussel in Europe. Backhuys Publishers, Leiden/Margraf Publishers, Weikersheim, pp.

Venables, W. N. and Ripley, B. D. 2002. Modern Applied Statistics with S. Springer, New York.

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., Levy, M.A., and Watson, J. E. 2016. Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nature Communications 7:12558.

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., Levy, M.A., and Watson, J. E. 2018. Last of the Wild Project, Version 3 (LWP-3): 2009 Human Footprint, 2018 Release. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Valavi, R., Guillera-Arroita, G., Lahoz-Monfort, J.J., and Elith, J. 2022. Predictive performance of presence-only species distribution models: a benchmark study with reproducible code. Ecol. Monogr. 92(1):e01486:1-27.

Weyhenmeyer,G.A., Hartmann, J., Hessen, D.O., Kopácek, J., Hejzlar, J., Jacquet, S., Hamilton, S.K., Verburg, P.,Leach, T.H., Schmid, M., Flaim, G., Nõges, T., Nõges, P., Wentzky, V.C., Rogora, M., Rusak, J.A., Kosten, S., Paterson, A.M., Teubner, K., Higgins, S.N., Lawrence, G., Kangur, K., Kokorite, I., Cerasino, L., Funk, C., Harvey, R., Moatar, F., de Wit, H.A., and Zechmeister, T. 2019. Widespread diminishing effects on calcium in freshwaters. Scientific Reports, 9:10450.

Whittier, T.R., Ringold, R.L., Herlihy, A.T., and Pierson, S.M. 2008. A calcium-based invasion risk assessment for zebra and quagga mussels (*Dreissena* spp). Front. Ecol. Environ. 6:180-184.

Wilson, A. E., Gossiaux, D. C., Höök, T. O., Berry, J. P., Landrum, P. F., Dyble, J., and Guildford, S.J. 2008. Evaluation of the human health threat associated with the hepatotoxin microcystin in the muscle and liver tissues of yellow perch (*Perca flavescens*). Can. J. Fish. Aquat. Sci. 65(7):1487-1497.

U.S. Geological Survey, 2021. Nonindigenous Aquatic Species Database, Gainesville, FL. Data provided by Amy Benson, February 10, 2021.

APPENDIX A. DATA SOURCES

Table A1. List of data sources for Zebra Mussel and Quagga Mussel records used in the risk assessment. ZM: Zebra Mussel, QM: Quagga Mussel.

Source	Geographic Coverage	Years	Number of Data Points (n)	
			ZM	QM
U.S. Geological Survey 2021	United States of America and some sites in Ontario, Quebec, and Manitoba	1986-2021	8184	1357
Depew et al. 2021	Lake Winnipeg, Manitoba	2017-2019	51	-
Memphémagog Conservation Inc.	Lake Memphremagog, Quebec	2018-2020	55	-
Ministère des Forêts, de la Faune et des Parcs	Quebec	1995-2020	405	11
Manitoba Government	Manitoba	2013-2021	42	-

Table A2. Sources for calcium concentration and pH data used for the spatially interpolated calcium and pH layers. Note that the number of sites used to generate the final interpolated rasters is not the total number of sites (n) below, since some sites occur in multiple data sources.

Source	Geographic Coverage	Years	Number of Sites (n)	
			Ca	**pH**
Environment Alberta	AB	2000-2020	284	302
BC Environmental monitoring system	BC	2000-2020	2915	4178
Manitoba Water Stewardship	MB	2000-2011	382	158
Government of Manitoba	MB	2011-2018	127	664
Government of New Brunswick, Department of Environment and Local Government	NB	2000-2020	829	664
Government of Newfoundland and Labrador	NL	2019-2020	-	29
Government of Nova Scotia	NS	2002-2017	-	5
Kivalliq Inuit Association, Crown-Indigenous Relations and Northern Affairs Canada	NU	2004-2020	56	55
Joynt and Wolfe 2001	NU	1995	-	56
Antoniades et al. 2003a, 2003b	NU, NT	1996-2000	84	84
Michelutti et al. 2002a, 2002b	NU, NT	1997-1998	37	37
Rühland et al. 2003	NU, NT	1996/1998	56	56
Pienitz et al. 1997	NT	1991	24	24
Government of the Northwest Territories	NT	1982-2021	97	97
Ontario Ministry of the Environment (Dorset Environmental Science Center)	ON	2008, 2009	175	182
Government of Canada, Environment and Climate Change Canada, Great Lakes water quality monitoring and surveillance data	ON	2000-2018	4172	4357
Ontario Ministry of Natural Resources & Forestry	ON	2008-2017	1341	1352
Ontario Stream Water Quality Monitoring Network	ON	2000-2019	543	595
Department of Environment, Energy and Climate Action	PEI	2001-2020	72	219
Ministère des Forêts, de la Faune et des Parcs	QC	2012	3108	3095
Ministère de l'Environnement et de la Lutte contre les changements climatiques	QC	2005-2020	1058	594
Ministère des Forêts, de la Faune et des Parcs Ministère de l'Environnement et de la Lutte contre les changements	QC	2001-2020	155	561

Source	Geographic Coverage	Years	Number of Sites (n)	
			Ca	pH
climatiques, Conseil de gouvernance de l'eau des bassins versants de la rivière Saint-François				
Ministère de l'Environnement et de la Lutte contre les changements climatiques, Atlas de l'eau	QC	2005-2019	1058	-
Government of Saskatchewan	SK	2000-2010	151	148
Water Security Agency, Saskatchewan	SK	2010-2020	683	454
Government of Saskatchewan Primary Station Water Quality	SK	2000-2020	-	22
Government of Yukon, Environment Department	YT	2010-2021	325	343
USGS, Yukon River Inter-Tribal Watershed Council, Indigenous Observation Network	YT, Alaska	2009-2014	84	91
Morrison 2004	All Provinces	1983-2010	4377	-
Filazzola et al. 2020	North of 50° N	1998-2014	-	152
Atlantic DataStream	NB, NS, PEI, NL	2000-2020	557	2238
Mackenzie DataStream	AB, BC, NT, YT	2000-2018	484	722
Government of Canada, Environment and Climate Change Canada, National long-term water quality monitoring data	Canada + some USA	2000-2019	282	282
Government of Canada, Environment and Climate Change Canada, Water quality in Canadian rivers	Canada	2002-2018	-	267
National Water Quality Monitoring Council, Water Quality Portal*	USA	2000-2021	46589	127079

*The number of sites for the Water Quality Portal data excludes single-record and single-date sites.

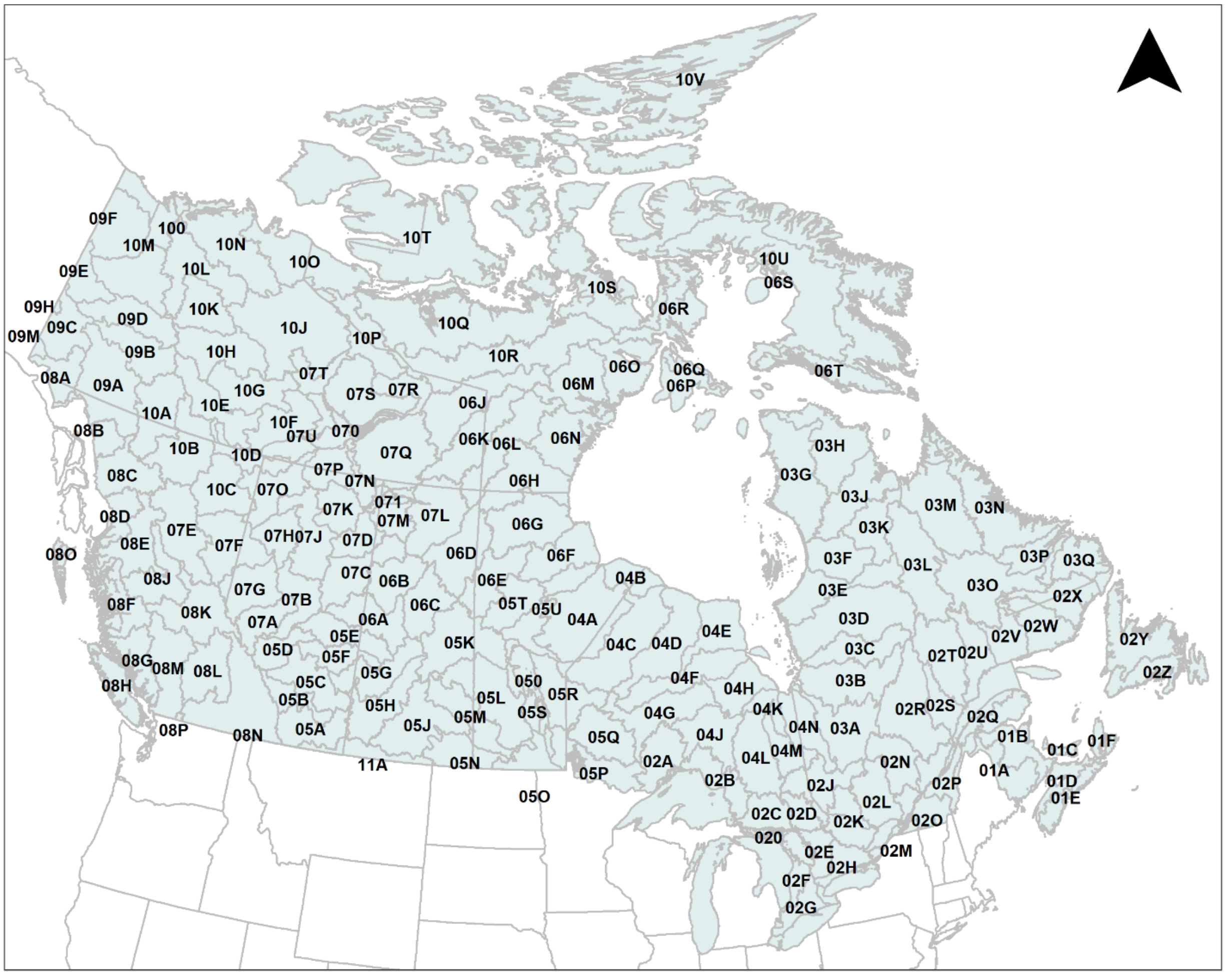

Figure A1. Sub-drainage designations. Codes relate to the data presented in Tables B1 and C1. Source: Atlas of Canada 1,000.000 National Frameworks Data, Natural Resources Canada (2016).

APPENDIX B. ZEBRA MUSSEL ECOLOGICAL RISK; SUMMARY AND REGIONAL EXTENTS

Table B1. Summary of Ecological Risk (mode and maximum) by sub-drainage for Zebra Mussel using the calcium-based and MaxEnt habitat suitability model. Sub-drainage designation codes are displayed in Figure A1.

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
NB and QC	01A	Saint John and Southern Bay of Fundy (N.B.)	Moderate	High	Moderate	High
NB and QC	01B	Gulf of St. Lawrence and Northern Bay of Fundy (N.B.)	Moderate	High	Moderate	High
PE	01C	Prince Edward Island	Moderate	High	Moderate	High
NS	01D	Bay of Fundy and Gulf of St. Lawrence (N.S.)	Moderate	High	Moderate	High
NS	01E	Southeastern Atlantic Ocean (N.S.)	Low	Moderate	Moderate	High
NS	01F	Cape Breton Island	Moderate	Moderate	Moderate	Moderate
QC and ON	020	Great Lakes and St. Lawrence	High	High	Moderate	High
ON	02A	Northwestern Lake Superior	Moderate	High	Moderate	High
ON	02B	Northeastern Lake Superior	Moderate	Moderate	Moderate	Moderate
ON	02C	Northern Lake Huron	Moderate	High	Moderate	High
ON	02D	Wanipitai and French (Ont.)	Moderate	Moderate	Moderate	High
ON	02E	Eastern Georgian Bay	Moderate	High	Moderate	High
ON	02F	Eastern Lake Huron	High	High	High	High
ON	02G	Northern Lake Erie	High	High	High	High
ON	02H	Lake Ontario and Niagara Peninsula	High	High	High	High
QC and ON	02J	Upper Ottawa	Moderate	High	Moderate	Moderate
QC and ON	02K	Central Ottawa	Moderate	High	Moderate	High

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
QC and ON	02L	Lower Ottawa	Moderate	High	Moderate	High
QC and ON	02M	Upper St. Lawrence	Moderate	High	Moderate	High
QC	02N	Saint-Maurice	Low	Moderate	Moderate	High
QC	02O	Central St. Lawrence	Moderate	High	Moderate	High
QC	02P	Lower St. Lawrence	Moderate	High	Moderate	High
NB and QC	02Q	Northern Gaspé Peninsula	Moderate	Moderate	Moderate	High
QC	02R	Saguenay	Low	Moderate	Moderate	Moderate
QC	02S	Betsiamites - Coast	Low	Moderate	Moderate	Moderate
QC	02T	Manicouagan and aux Outardes	Low	Moderate	Low	Moderate
QC	02U	Moisie and St. Lawrence Estuary	Low	Moderate	Low	Moderate
NL and QC	02V	Gulf of St. Lawrence - Romaine	Low	Low	Low	Moderate
NL and QC	02W	Gulf of St. Lawrence - Natashquan	Low	Moderate	Moderate	Moderate
NL and QC	02X	Petit Mécatina and Strait of Belle Isle	Low	Low	Low	Moderate
NL	02Y	Northern Newfoundland	Low	Moderate	Moderate	Moderate
NL	02Z	Southern Newfoundland	Low	Moderate	Moderate	Moderate
QC	03A	Nottaway - Coast	Moderate	Moderate	Moderate	Moderate
QC and NU	03B	Broadback and Rupert	Low	Moderate	Moderate	Moderate
QC	03C	Eastmain	Low	Low	Moderate	Moderate
QC and NU	03D	La Grande - Coast	Low	Moderate	Moderate	Moderate
QC and NU	03E	Grande rivière de la Baleine - Coast	Moderate	Moderate	Moderate	Moderate
QC and NU	03F	Eastern Hudson Bay	Moderate	Moderate	Moderate	Moderate
QC and NU	03G	Northeastern Hudson Bay	Thermal Threshold	Low	Thermal Threshold	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
QC and NU	03H	Western Ungava Bay	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
QC and NU	03J	Aux Feuilles - Coast	Thermal Threshold	Moderate	Thermal Threshold	Moderate
QC	03K	Koksoak	Moderate	Moderate	Moderate	Moderate
QC	03L	Caniapiscau	Low	Moderate	Moderate	Moderate
NL, QC, and NU	03M	Eastern Ungava Bay	Thermal Threshold	Low	Thermal Threshold	Moderate
NL, QC, and NU	03N	Northern Labrador	Thermal Threshold	Low	Thermal Threshold	Moderate
NL	03O	Churchill (Nfld.)	Low	Moderate	Low	Moderate
NL	03P	Central Labrador	Low	Low	Moderate	Moderate
NL	03Q	Southern Labrador	Low	Low	Moderate	Moderate
ON and MB	04A	Hayes (Man.)	Moderate	Moderate	Moderate	Moderate
ON and MB	04B	Southwestern Hudson Bay	Moderate	Moderate	Moderate	Moderate
ON and MB	04C	Severn	Moderate	Moderate	Moderate	Moderate
ON	04D	Winisk - Coast	Moderate	Moderate	Moderate	Moderate
ON and NU	04E	Ekwan - Coast	Moderate	Moderate	Moderate	Moderate
ON and NU	04F	Attawapiskat - Coast	Moderate	Moderate	Moderate	Moderate
ON	04G	Upper Albany	Moderate	Moderate	Moderate	Moderate
ON and NU	04H	Lower Albany - Coast	Moderate	Moderate	Moderate	Moderate
ON	04J	Kenogami	Moderate	High	Moderate	Moderate
ON	04K	Moose (Ont.)	Moderate	Moderate	Moderate	Moderate
ON	04L	Missinaibi-Mattagami	Moderate	High	Moderate	Moderate
QC and ON	04M	Abitibi	Moderate	High	Moderate	Moderate
QC and ON	04N	Harricanaw - Coast	Moderate	Moderate	Moderate	Moderate
MB	050	Lake Winnepeg	Moderate	High	Moderate	High
SK and AB	05A	Upper South Saskatchewan	Moderate	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
AB	05B	Bow	Moderate	High	Moderate	Moderate
SK and AB	05C	Red Deer	Moderate	High	Moderate	Moderate
AB	05D	Upper North Saskatchewan	Moderate	High	Moderate	Moderate
SK and AB	05E	Central North Saskatchewan	Moderate	High	Moderate	Moderate
SK and AB	05F	Battle	Moderate	High	Moderate	Moderate
SK and AB	05G	Lower North Saskatchewan	Moderate	High	Moderate	Moderate
SK and AB	05H	Lower South Saskatchewan	Moderate	High	Moderate	Moderate
MB and SK	05J	Qu'Appelle	Moderate	High	Moderate	Moderate
MB and SK	05K	Saskatchewan	Moderate	High	Moderate	Moderate
MB and SK	05L	Lake Winnipegosis and Lake Manitoba	Moderate	High	Moderate	Moderate
MB and SK	05M	Assiniboine	Moderate	High	Moderate	Moderate
MB and SK	05N	Souris	Moderate	High	Moderate	Moderate
MB	05O	Red	Moderate	High	Moderate	High
ON and MB	05P	Winnipeg	Moderate	High	Moderate	Moderate
ON	05Q	English	Moderate	Moderate	Moderate	Moderate
ON and MB	05R	Eastern Lake Winnipeg	Moderate	High	Moderate	High
MB	05S	Western Lake Winnipeg	Moderate	High	Moderate	High
MB	05T	Grass and Burntwood	Moderate	High	Moderate	Moderate
MB	05U	Nelson	Moderate	High	Moderate	Moderate
SK and AB	06A	Beaver (Alta.-Sask.)	Moderate	Moderate	Moderate	Moderate
SK and AB	06B	Upper Churchill (Man.)	Moderate	Moderate	Moderate	Moderate
SK	06C	Central Churchill (Man.) - Upper	Moderate	Moderate	Moderate	Moderate
MB and SK	06D	Reindeer	Low	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
MB and SK	06E	Central Churchill (Man.) - Lower	Moderate	High	Moderate	Moderate
MB and NU	06F	Lower Churchill (Man.)	Moderate	Moderate	Moderate	Moderate
MB and NU	06G	Seal - Coast	Moderate	Moderate	Moderate	Moderate
MB, SK, NU	06H	Western Hudson Bay - Southern	Low	Moderate	Moderate	Moderate
NT and NU	06J	Thelon	Low	Low	Low	Moderate
NT and NU	06K	Dubawnt	Low	Moderate	Moderate	Moderate
MB, SK, NT, and NU	06L	Kazan	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NU	06M	Chesterfield Inlet	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06N	Western Hudson Bay - Central	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NU	06O	Western Hudson Bay - Northern	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06P	Hudson Bay - Southampton Island	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NU	06Q	Foxe Basin - Southampton Island	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06R	Foxe Basin - Melville Peninsula	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06S	Foxe Basin - Baffin Island	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06T	Hudson Strait - Baffin and Southampton Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT	070	Great Slave Lake	Moderate	Moderate	Moderate	Moderate
SK and AB	071	Lake Athabasca	Moderate	Moderate	Moderate	Moderate
AB	07A	Upper Athabasca	Moderate	Moderate	Moderate	Moderate
AB	07B	Central Athabasca - Upper	Moderate	Moderate	Moderate	Moderate
SK and AB	07C	Central Athabasca - Lower	Moderate	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
SK and AB	07D	Lower Athabasca	Moderate	Moderate	Moderate	Moderate
BC	07E	Williston Lake	Low	Moderate	Low	Moderate
AB and BC	07F	Upper Peace	Low	Moderate	Moderate	Moderate
AB and BC	07G	Smoky	Moderate	Moderate	Moderate	Moderate
AB	07H	Central Peace - Upper	Moderate	Moderate	Moderate	Moderate
AB	07J	Central Peace - Lower	Moderate	Moderate	Moderate	Moderate
AB	07K	Lower Peace	Moderate	Moderate	Moderate	Moderate
SK and NT	07L	Fond-du-Lac	Low	Moderate	Moderate	Moderate
SK and AB	07M	Lake Athabasca - Shores	Low	Moderate	Moderate	Moderate
AB, NT	07N	Slave	Moderate	Moderate	Moderate	Moderate
AB, BC, and NT	07O	Hay	Moderate	Moderate	Low	Moderate
AB and NT	07P	Southern Great Slave Lake	Moderate	Moderate	Low	Moderate
SK, AB, and NT	07Q	Great Slave Lake - East Arm South Shore	Low	Moderate	Moderate	Moderate
NT	07R	Lockhart	Low	Low	Low	Moderate
NT	07S	Northeastern Great Slave Lake	Low	Moderate	Low	Moderate
NT	07T	Marian	Low	Moderate	Low	Moderate
AB, BC, and NT	07U	Western Great Slave Lake	Moderate	Moderate	Low	Moderate
BC and YT	08A	Alsek	Thermal Threshold	Moderate	Thermal Threshold	Moderate
BC	08B	Northern Coastal Waters of B.C.	Thermal Threshold	Moderate	Thermal Threshold	Moderate
BC	08C	Stikine - Coast	Thermal Threshold	Moderate	Thermal Threshold	Moderate
BC	08D	Nass - Coast	Low	Moderate	Low	Moderate
BC	08E	Skeena - Coast	Low	Moderate	Low	Moderate
BC	08F	Central Coastal Waters of B.C.	Low	Moderate	Low	Moderate
BC	08G	Southern Coastal Waters of B.C.	Low	Moderate	Low	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
BC	08H	Vancouver Island	Low	Moderate	Low	Moderate
BC	08J	Nechako	Low	Moderate	Low	Moderate
BC	08K	Upper Fraser	Low	Moderate	Moderate	Moderate
BC	08L	Thompson	Low	Moderate	Moderate	Moderate
BC	08M	Lower Fraser	Low	Moderate	Low	Moderate
BC	08N	Columbia - U.S.A.	Moderate	Moderate	Moderate	Moderate
BC	08O	Queen Charlotte Islands	Low	Low	Low	Low
BC	08P	Skagit	Low	Moderate	Moderate	Moderate
BC and YT	09A	Headwaters Yukon	Low	Moderate	Low	Low
YT	09B	Pelly	Low	Moderate	Low	Low
YT	09C	Upper Yukon	Low	Moderate	Low	Low
YT	09D	Stewart	Low	Moderate	Low	Low
YT	09E	Central Yukon	Low	Moderate	Low	Low
YT	09F	Porcupine	Low	Moderate	Low	Moderate
YT	09H	Tanana	Thermal Threshold	Moderate	Thermal Threshold	Low
YT	09M	Copper	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NT	100	Mackenzie River Delta (Main Channel)	Low	Moderate	Low	Moderate
BC, YT	10A	Upper Liard	Low	Moderate	Low	Moderate
BC and YT	10B	Central Liard	Low	Moderate	Low	Moderate
AB and BC	10C	Fort Nelson	Low	Moderate	Low	Moderate
AB, BC, YT, and NT	10D	Central Liard - Petitot	Low	Moderate	Low	Moderate
NT	10E	Lower Liard	Low	Moderate	Low	Moderate
NT	10F	Upper Mackenzie - Mills Lake	Low	Moderate	Low	Moderate
NT	10G	Upper Mackenzie - Camsell Bend	Low	Moderate	Low	Moderate
NT	10H	Central Mackenzie - Blackwater Lake	Low	Moderate	Low	Moderate
NT and NU	10J	Great Bear	Low	Moderate	Low	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
NT	10K	Central Mackenzie - The Ramparts	Low	Moderate	Low	Moderate
NT	10L	Lower Mackenzie	Low	Moderate	Low	Moderate
YT and NT	10M	Peel and Southwestern Beaufort Sea	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NT	10N	Southern Beaufort Sea	Low	Low	Low	Low
NT and NU	10O	Amundsen Gulf	Thermal Threshold	Low	Thermal Threshold	Low
NT and NU	10P	Coppermine	Thermal Threshold	Low	Thermal Threshold	Low
NU	10Q	Coronation Gulf - Queen Maud Gulf	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT and NU	10R	Back	Thermal Threshold	Low	Thermal Threshold	Low
NU	10S	Gulf of Boothia	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT and NU	10T	Southern Arctic Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	10U	Baffin Island - Arctic Drainage	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT and NU	10V	Northern Arctic Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
SK and AB	11A	Missouri	Moderate	Moderate	Moderate	Moderate

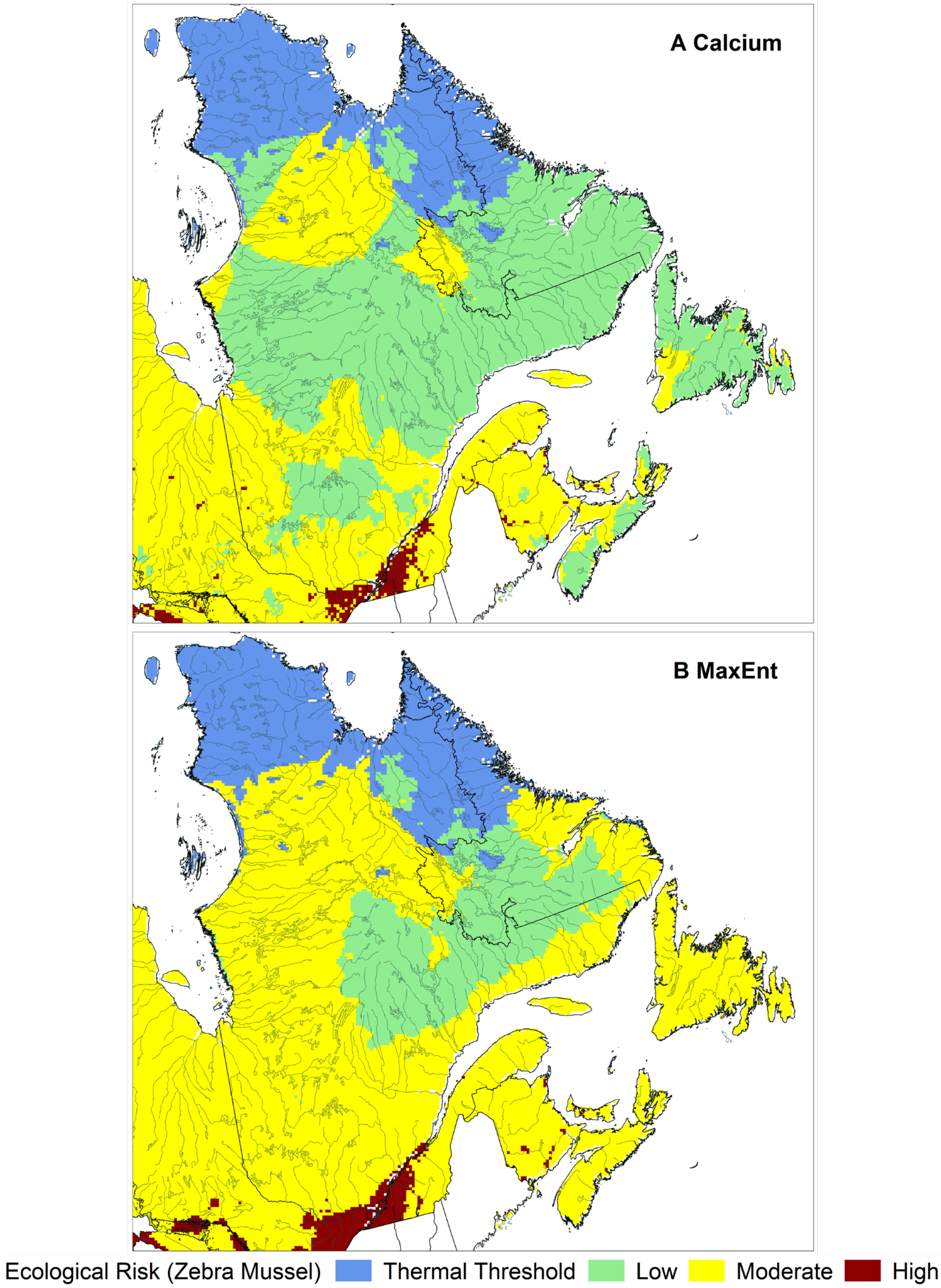

Figure B1. Zebra Mussel Ecological Risk in Quebec and Atlantic Canada using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

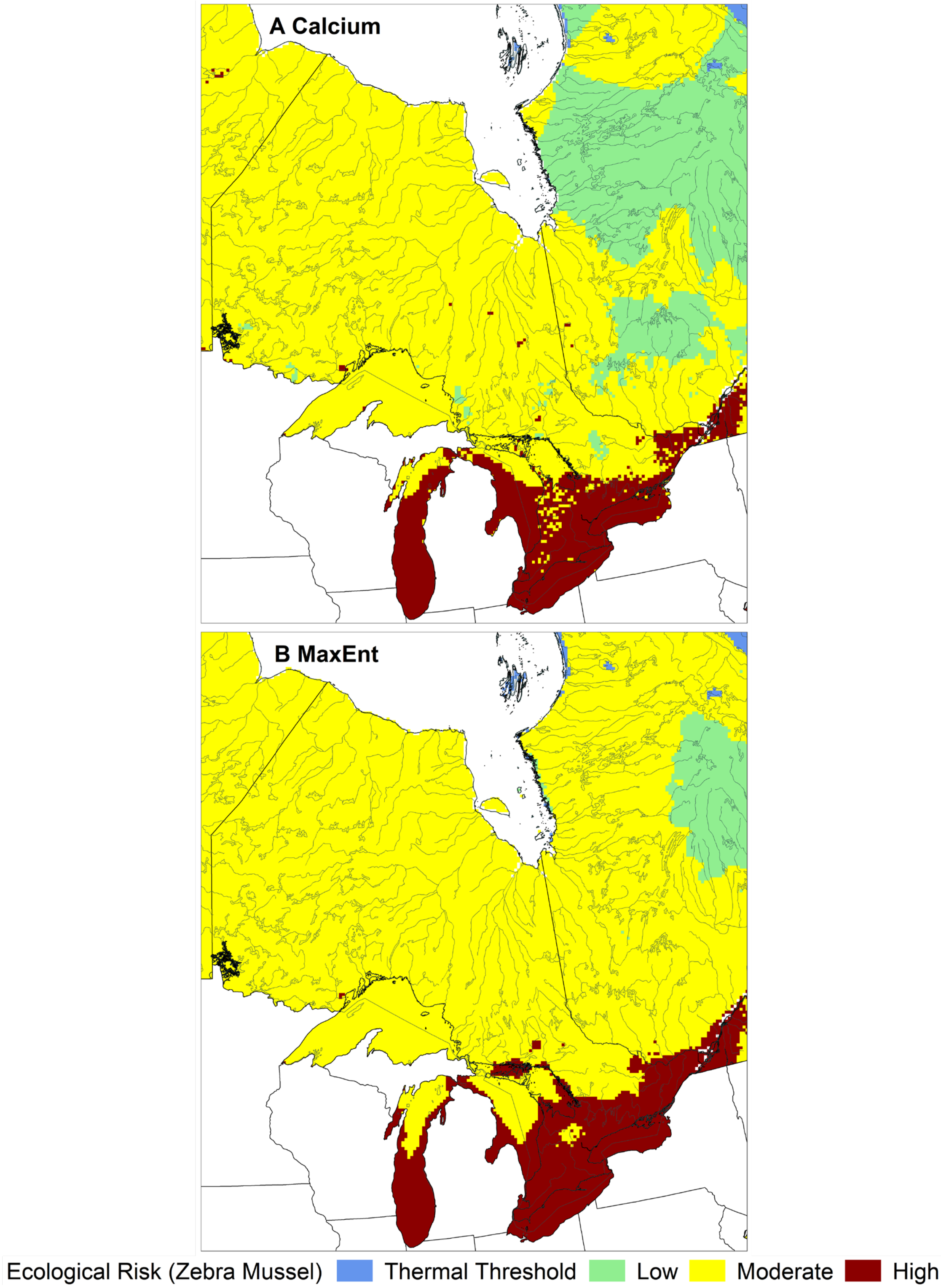

Figure B2. Zebra Mussel Ecological Risk in Ontario and the Great Lakes using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

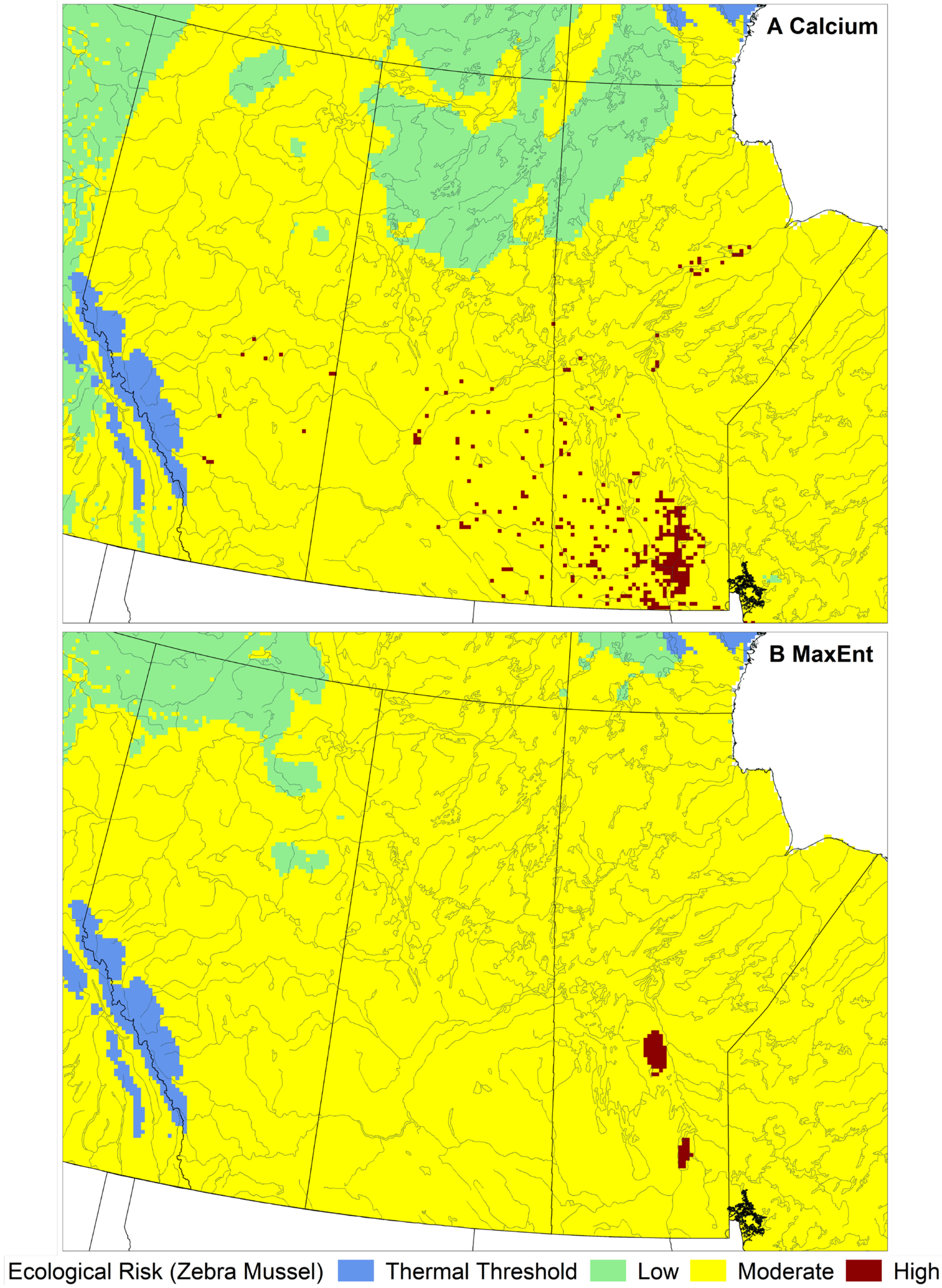

Figure B3. Zebra Mussel Ecological Risk in the Prairie Provinces using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

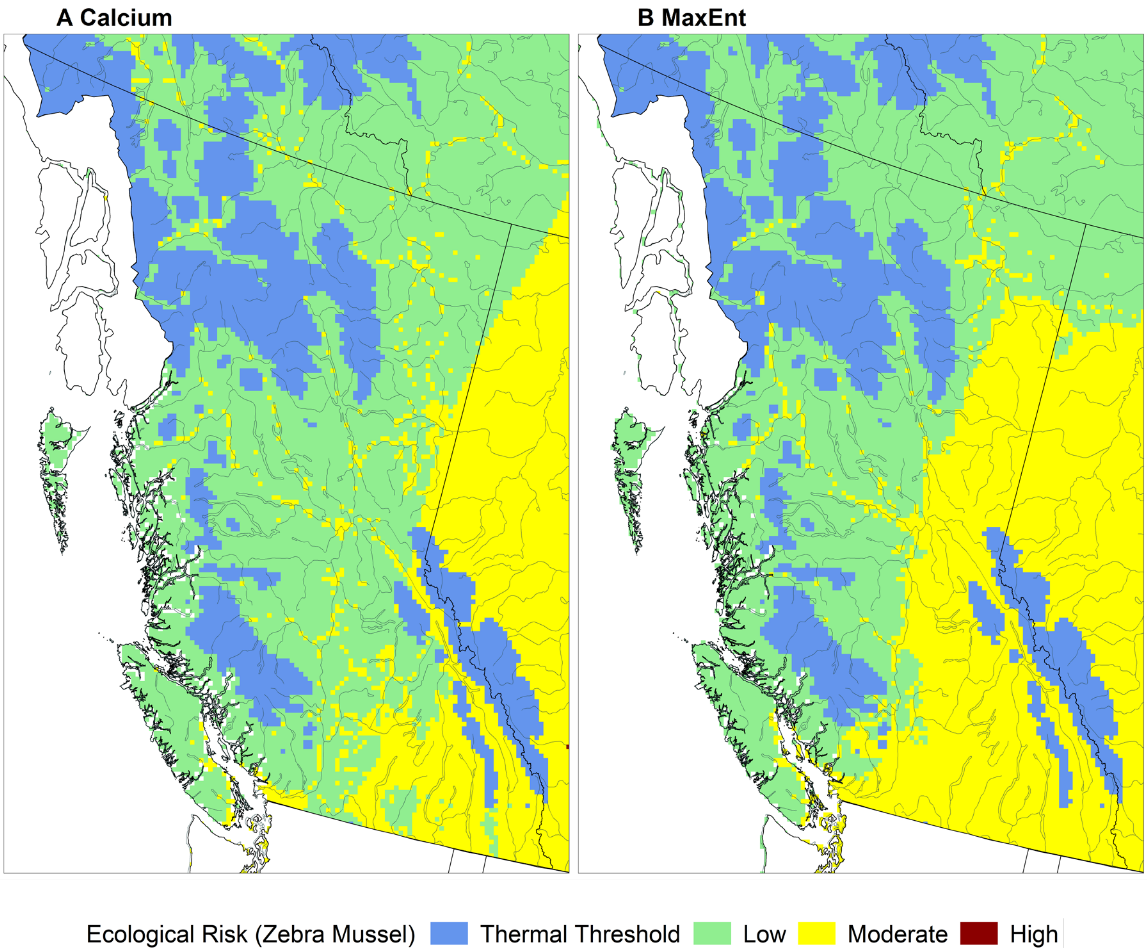

Figure B4. Zebra Mussel Ecological Risk in British Columbia using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

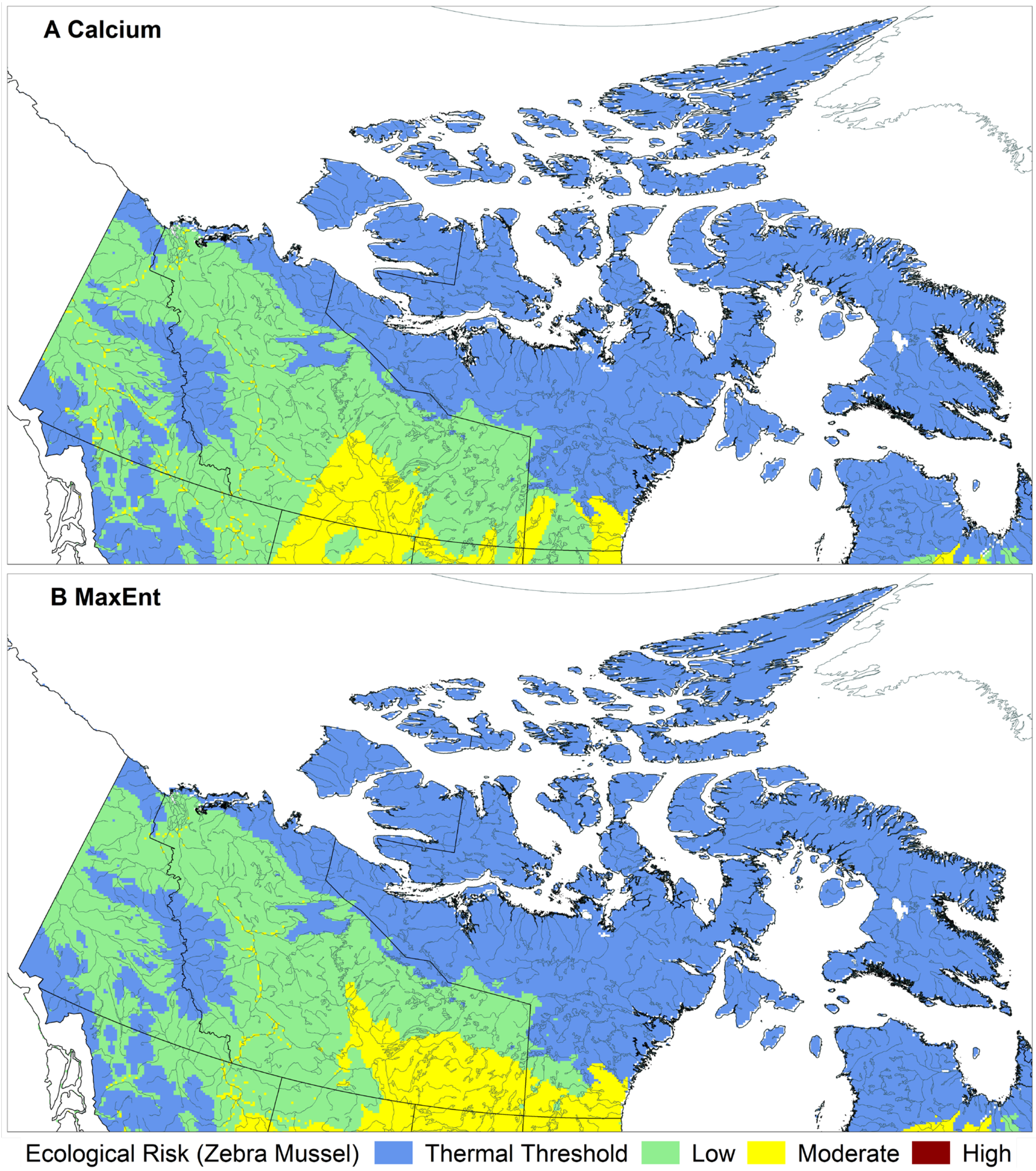

Figure B5. Zebra Mussel Ecological Risk in the Territories using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

APPENDIX C. QUAGGA MUSSEL ECOLOGICAL RISK; SUMMARY AND REGIONAL EXTENTS

Table C1. Summary of Ecological Risk (mode and maximum) by sub-drainage for Quagga Mussel using the calcium-based and MaxEnt habitat suitability model. Sub-drainage designation codes are displayed in Figure A1.

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
NB and QC	01A	Saint John and Southern Bay of Fundy (N.B.)	Moderate	High	Low	High
NB and QC	01B	Gulf of St. Lawrence and Northern Bay of Fundy (N.B.)	Moderate	High	Low	Moderate
PE	01C	Prince Edward Island	Moderate	High	Low	Moderate
NS	01D	Bay of Fundy and Gulf of St. Lawrence (N.S.)	Low	High	Low	Low
NS	01E	Southeastern Atlantic Ocean (N.S.)	Low	Moderate	Low	Low
NS	01F	Cape Breton Island	Low	Moderate	Low	Low
QC and ON	020	Great Lakes and St. Lawrence	Moderate	High	High	High
ON	02A	Northwestern Lake Superior	Moderate	High	Low	Moderate
ON	02B	Northeastern Lake Superior	Moderate	Moderate	Low	Moderate
ON	02C	Northern Lake Huron	Moderate	High	Low	Moderate
ON	02D	Wanipitai and French (Ont.)	Moderate	Moderate	Low	High
ON	02E	Eastern Georgian Bay	Low	High	Low	High
ON	02F	Eastern Lake Huron	High	High	Moderate	High
ON	02G	Northern Lake Erie	High	High	High	High
ON	02H	Lake Ontario and Niagara Peninsula	High	High	High	High
QC and ON	02J	Upper Ottawa	Low	High	Low	Moderate
QC and ON	02K	Central Ottawa	Low	High	Low	High
QC and ON	02L	Lower Ottawa	Moderate	High	Low	High

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
QC and ON	02M	Upper St. Lawrence	Moderate	High	Low	High
QC	02N	Saint-Maurice	Low	Moderate	Low	Moderate
QC	02O	Central St. Lawrence	Moderate	High	Low	High
QC	02P	Lower St. Lawrence	Moderate	High	Low	Moderate
NB and QC	02Q	Northern Gaspé Peninsula	Moderate	Moderate	Low	Moderate
QC	02R	Saguenay	Low	Moderate	Low	Low
QC	02S	Betsiamites - Coast	Low	Moderate	Low	Low
QC	02T	Manicouagan and aux Outardes	Low	Low	Low	Low
QC	02U	Moisie and St. Lawrence Estuary	Low	Low	Low	Low
NL and QC	02V	Gulf of St. Lawrence - Romaine	Low	Low	Low	Low
NL and QC	02W	Gulf of St. Lawrence - Natashquan	Low	Moderate	Low	Low
NL and QC	02X	Petit Mécatina and Strait of Belle Isle	Low	Low	Low	Low
NL	02Y	Northern Newfoundland	Low	Moderate	Low	Low
NL	02Z	Southern Newfoundland	Low	Moderate	Low	Low
QC	03A	Nottaway - Coast	Low	Moderate	Low	Low
QC and NU	03B	Broadback and Rupert	Low	Moderate	Low	Low
QC	03C	Eastmain	Low	Low	Low	Low
QC and NU	03D	La Grande - Coast	Low	Low	Low	Low
QC and NU	03E	Grande rivière de la Baleine - Coast	Low	Low	Low	Low
QC and NU	03F	Eastern Hudson Bay	Low	Low	Low	Low
QC and NU	03G	Northeastern Hudson Bay	Low	Low	Low	Low
QC and NU	03H	Western Ungava Bay	Low	Low	Low	Low
QC and NU	03J	Aux Feuilles - Coast	Low	Low	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
QC	03K	Koksoak	Low	Low	Low	Low
QC	03L	Caniapiscau	Low	Moderate	Low	Low
NL, QC, and NU	03M	Eastern Ungava Bay	Low	Low	Low	Low
NL, QC, and NU	03N	Northern Labrador	Low	Low	Low	Low
NL	03O	Churchill (Nfld.)	Low	Moderate	Low	Low
NL	03P	Central Labrador	Low	Low	Low	Low
NL	03Q	Southern Labrador	Low	Low	Low	Low
ON and MB	04A	Hayes (Man.)	Moderate	Moderate	Low	Low
ON and MB	04B	Southwestern Hudson Bay	Moderate	Moderate	Low	Low
ON and MB	04C	Severn	Moderate	Moderate	Low	Low
ON	04D	Winisk - Coast	Moderate	Moderate	Low	Low
ON and NU	04E	Ekwan - Coast	Moderate	Moderate	Low	Low
ON and NU	04F	Attawapiskat - Coast	Moderate	Moderate	Low	Low
ON	04G	Upper Albany	Moderate	Moderate	Low	Low
ON and NU	04H	Lower Albany - Coast	Moderate	Moderate	Low	Low
ON	04J	Kenogami	Moderate	Moderate	Low	Moderate
ON	04K	Moose (Ont.)	Moderate	Moderate	Low	Low
ON	04L	Missinaibi-Mattagami	Moderate	High	Low	Moderate
QC and ON	04M	Abitibi	Moderate	High	Low	Moderate
QC and ON	04N	Harricanaw - Coast	Moderate	Moderate	Low	Low
MB	050	Lake Winnepeg	Moderate	High	Low	Low
SK and AB	05A	Upper South Saskatchewan	Low	Moderate	Low	Moderate
AB	05B	Bow	Low	Moderate	Low	Moderate
SK and AB	05C	Red Deer	Low	Moderate	Low	Moderate
AB	05D	Upper North Saskatchewan	Low	Moderate	Low	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
SK and AB	05E	Central North Saskatchewan	Low	Moderate	Low	Moderate
SK and AB	05F	Battle	Low	Moderate	Low	Low
SK and AB	05G	Lower North Saskatchewan	Low	Moderate	Low	Low
SK and AB	05H	Lower South Saskatchewan	Low	Moderate	Low	Low
MB and SK	05J	Qu'Appelle	Moderate	Moderate	Low	Low
MB and SK	05K	Saskatchewan	Moderate	Moderate	Low	Low
MB and SK	05L	Lake Winnipegosis and Lake Manitoba	Moderate	High	Low	Low
MB and SK	05M	Assiniboine	Moderate	High	Low	Low
MB and SK	05N	Souris	Moderate	High	Low	Moderate
MB	05O	Red	Moderate	High	Low	Moderate
ON and MB	05P	Winnipeg	Moderate	High	Low	Moderate
ON	05Q	English	Moderate	Moderate	Low	Low
ON and MB	05R	Eastern Lake Winnipeg	Low	High	Low	Low
MB	05S	Western Lake Winnipeg	Moderate	High	Low	Moderate
MB	05T	Grass and Burntwood	Low	Moderate	Low	Low
MB	05U	Nelson	Moderate	Moderate	Low	Low
SK and AB	06A	Beaver (Alta.-Sask.)	Low	Moderate	Low	Low
SK and AB	06B	Upper Churchill (Man.)	Low	Moderate	Low	Low
SK	06C	Central Churchill (Man.) - Upper	Low	Moderate	Low	Low
MB and SK	06D	Reindeer	Low	Low	Low	Low
MB and SK	06E	Central Churchill (Man.) - Lower	Low	Moderate	Low	Low
MB and NU	06F	Lower Churchill (Man.)	Low	Moderate	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
MB and NU	06G	Seal - Coast	Low	Low	Low	Low
MB, SK, NU	06H	Western Hudson Bay - Southern	Low	Low	Low	Low
NT and NU	06J	Thelon	Low	Low	Low	Low
NT and NU	06K	Dubawnt	Low	Low	Low	Low
MB, SK, NT, and NU	06L	Kazan	Low	Low	Low	Low
NU	06M	Chesterfield Inlet	Low	Low	Low	Low
NU	06N	Western Hudson Bay - Central	Low	Low	Low	Low
NU	06O	Western Hudson Bay - Northern	Low	Low	Low	Low
NU	06P	Hudson Bay - Southampton Island	Low	Moderate	Low	Low
NU	06Q	Foxe Basin - Southampton Island	Low	Low	Low	Low
NU	06R	Foxe Basin - Melville Peninsula	Low	Low	Low	Low
NU	06S	Foxe Basin - Baffin Island	Thermal Threshold	Low	Thermal Threshold	Low
NU	06T	Hudson Strait - Baffin and Southampton Islands	Low	Low	Low	Low
NT	070	Great Slave Lake	Low	Moderate	Low	Low
SK and AB	071	Lake Athabasca	Low	Low	Low	Low
AB	07A	Upper Athabasca	Low	Moderate	Low	Low
AB	07B	Central Athabasca - Upper	Low	Moderate	Low	Low
SK and AB	07C	Central Athabasca - Lower	Low	Moderate	Low	Low
SK and AB	07D	Lower Athabasca	Low	Moderate	Low	Low
BC	07E	Williston Lake	Low	Moderate	Low	Low
AB and BC	07F	Upper Peace	Low	Moderate	Low	Low
AB and BC	07G	Smoky	Low	Moderate	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
AB	07H	Central Peace - Upper	Low	Moderate	Low	Low
AB	07J	Central Peace - Lower	Low	Moderate	Low	Low
AB	07K	Lower Peace	Low	Low	Low	Low
SK and NT	07L	Fond-du-Lac	Low	Low	Low	Low
SK and AB	07M	Lake Athabasca - Shores	Low	Low	Low	Low
AB, NT	07N	Slave	Low	Moderate	Low	Low
AB, BC, and NT	07O	Hay	Low	Moderate	Low	Low
AB and NT	07P	Southern Great Slave Lake	Low	Moderate	Low	Low
SK, AB, and NT	07Q	Great Slave Lake - East Arm South Shore	Low	Low	Low	Low
NT	07R	Lockhart	Low	Low	Low	Low
NT	07S	Northeastern Great Slave Lake	Low	Moderate	Low	Low
NT	07T	Marian	Low	Low	Low	Low
AB, BC, and NT	07U	Western Great Slave Lake	Low	Moderate	Low	Low
BC and YT	08A	Alsek	Low	Low	Low	Low
BC	08B	Northern Coastal Waters of B.C.	Low	Low	Low	Low
BC	08C	Stikine - Coast	Low	Moderate	Low	Low
BC	08D	Nass - Coast	Low	Low	Low	Low
BC	08E	Skeena - Coast	Low	Moderate	Low	Low
BC	08F	Central Coastal Waters of B.C.	Low	Moderate	Low	Low
BC	08G	Southern Coastal Waters of B.C.	Low	Moderate	Low	Low
BC	08H	Vancouver Island	Low	Moderate	Low	Low
BC	08J	Nechako	Low	Moderate	Low	Moderate
BC	08K	Upper Fraser	Low	Moderate	Low	Moderate
BC	08L	Thompson	Low	Moderate	Low	Moderate
BC	08M	Lower Fraser	Low	Moderate	Low	Moderate
BC	08N	Columbia - U.S.A.	Low	Moderate	Low	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
BC	08O	Queen Charlotte Islands	Low	Low	Low	Low
BC	08P	Skagit	Low	Low	Low	Low
BC and YT	09A	Headwaters Yukon	Low	Moderate	Low	Low
YT	09B	Pelly	Low	Moderate	Low	Low
YT	09C	Upper Yukon	Low	Low	Low	Low
YT	09D	Stewart	Low	Low	Low	Low
YT	09E	Central Yukon	Low	Moderate	Low	Low
YT	09F	Porcupine	Low	Moderate	Low	Low
YT	09H	Tanana	Low	Low	Low	Low
YT	09M	Copper	Low	Low	Low	Low
NT	100	Mackenzie River Delta (Main Channel)	Low	Low	Low	Low
BC, YT	10A	Upper Liard	Low	Moderate	Low	Low
BC and YT	10B	Central Liard	Low	Low	Low	Low
AB and BC	10C	Fort Nelson	Low	Moderate	Low	Low
AB, BC, YT, and NT	10D	Central Liard - Petitot	Low	Low	Low	Low
NT	10E	Lower Liard	Low	Moderate	Low	Low
NT	10F	Upper Mackenzie - Mills Lake	Low	Low	Low	Low
NT	10G	Upper Mackenzie - Camsell Bend	Low	Moderate	Low	Low
NT	10H	Central Mackenzie - Blackwater Lake	Low	Low	Low	Low
NT and NU	10J	Great Bear	Low	Low	Low	Low
NT	10K	Central Mackenzie - The Ramparts	Low	Moderate	Low	Low
NT	10L	Lower Mackenzie	Low	Low	Low	Low
YT and NT	10M	Peel and Southwestern Beaufort Sea	Low	Low	Low	Low
NT	10N	Southern Beaufort Sea	Low	Low	Low	Low
NT and NU	10O	Amundsen Gulf	Low	Low	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt model	
			Mode	Max	Mode	Max
NT and NU	10P	Coppermine	Low	Low	Low	Low
NU	10Q	Coronation Gulf - Queen Maud Gulf	Low	Low	Low	Low
NT and NU	10R	Back	Low	Low	Low	Low
NU	10S	Gulf of Boothia	Low	Low	Low	Low
NT and NU	10T	Southern Arctic Islands	Thermal Threshold	Low	Thermal Threshold	Low
NU	10U	Baffin Island - Arctic Drainage	Thermal Threshold	Low	Thermal Threshold	Low
NT and NU	10V	Northern Arctic Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
SK and AB	11A	Missouri	Moderate	Moderate	Low	Moderate

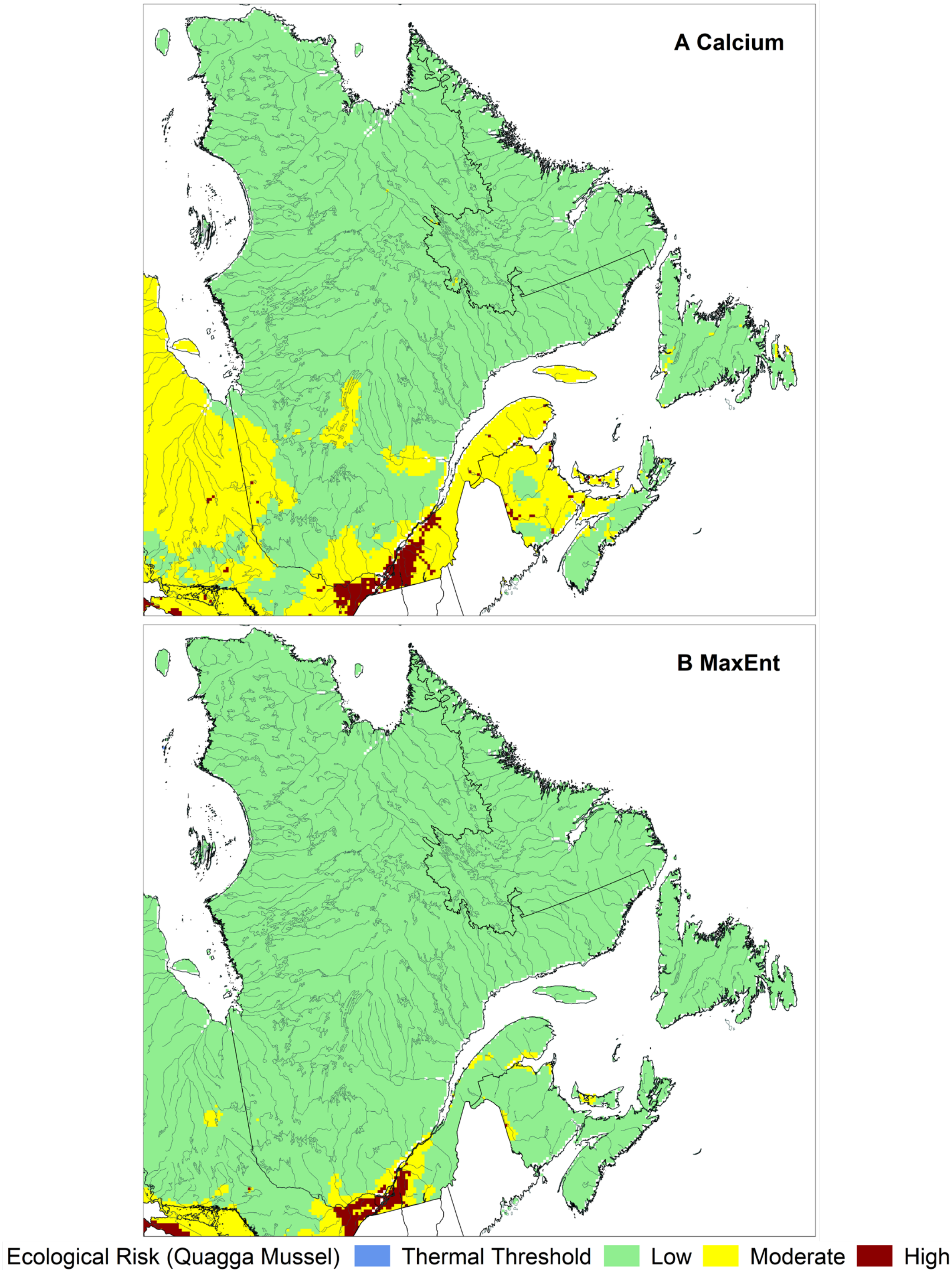

Figure C1. Quagga Mussel Ecological Risk in Quebec and Atlantic Canada using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

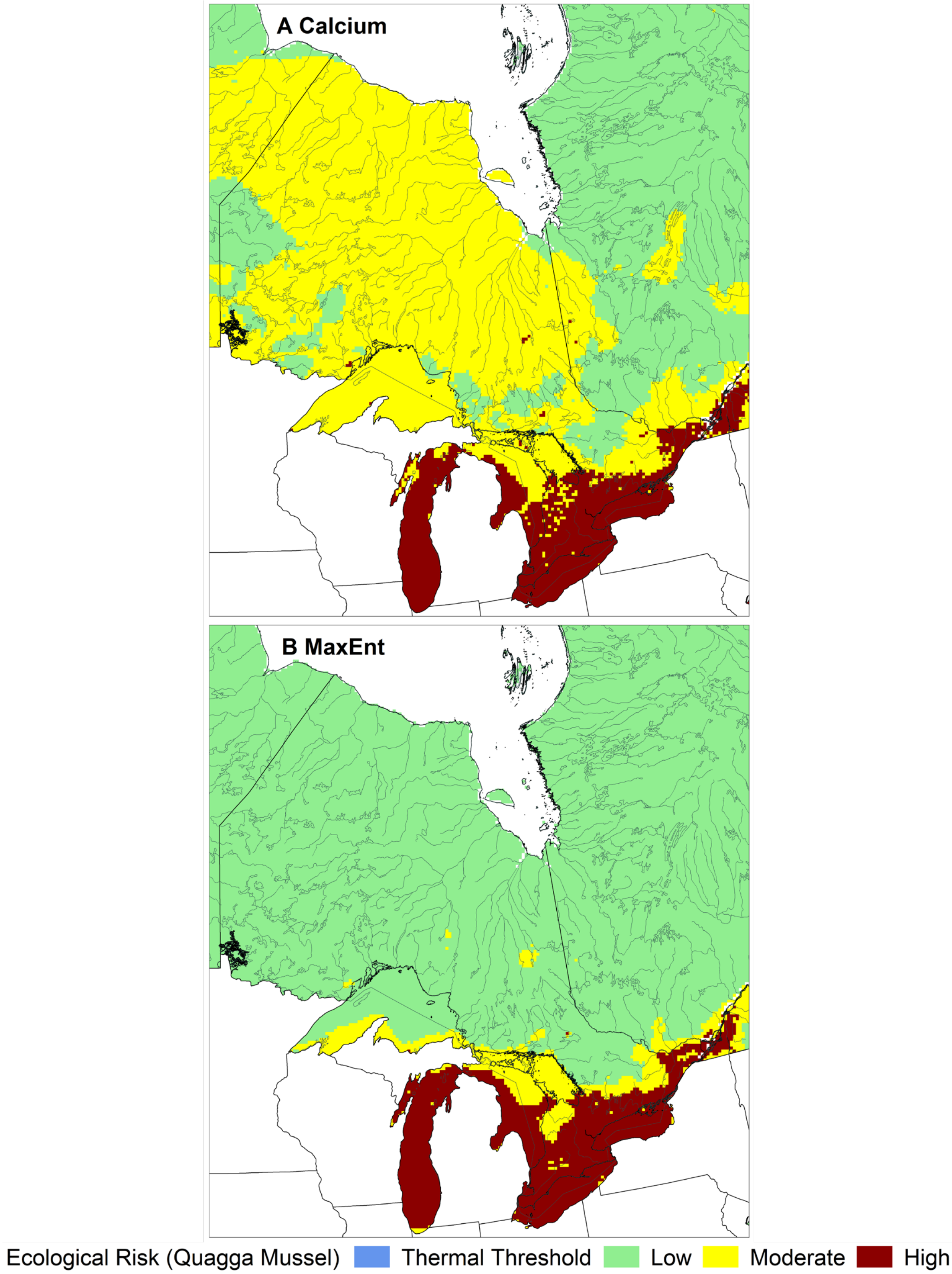

Figure C2. Quagga Mussel Ecological Risk in Ontario and the Great Lakes using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

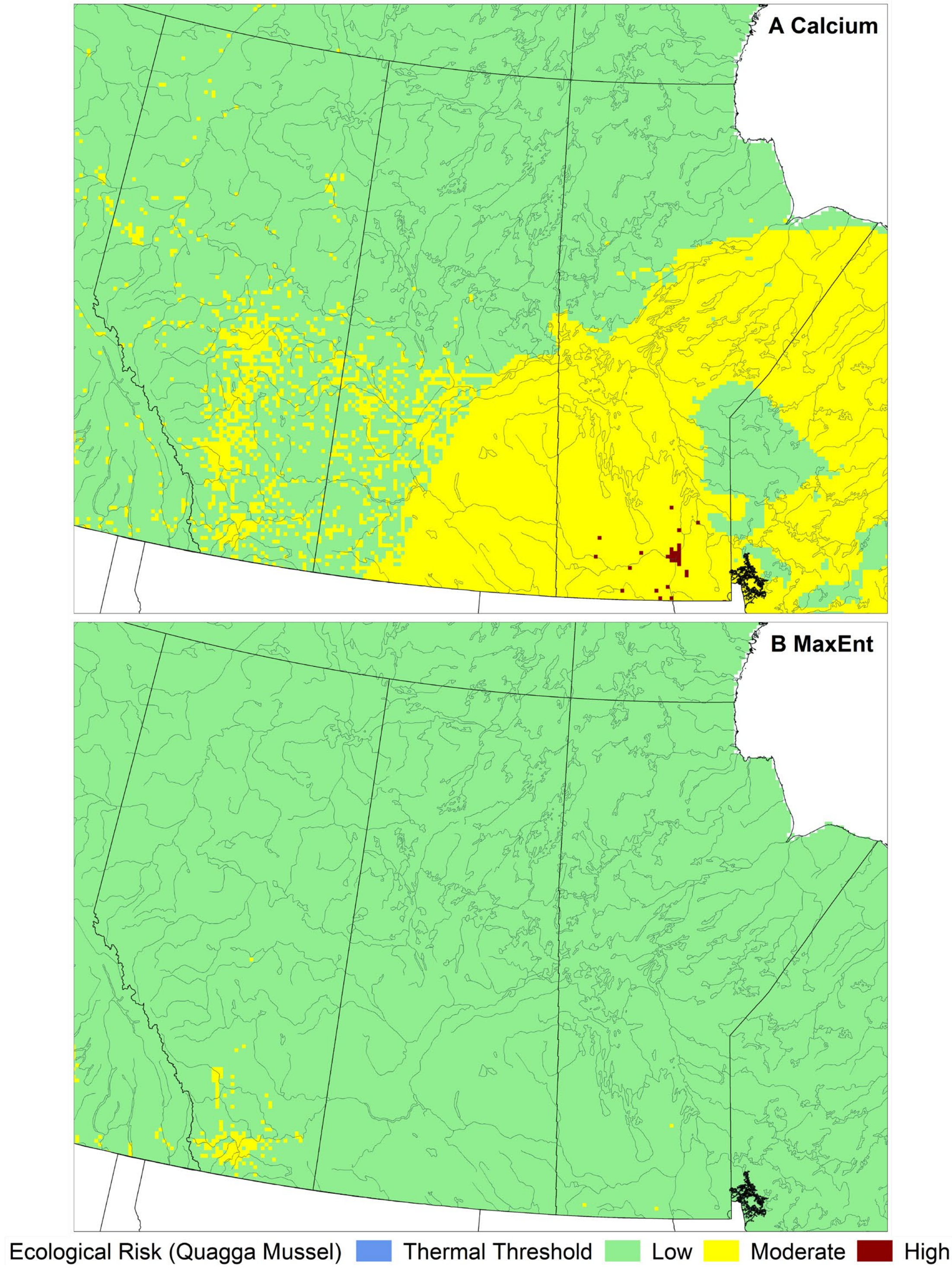

Figure C3. Quagga Mussel Ecological Risk in the Prairie Provinces using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

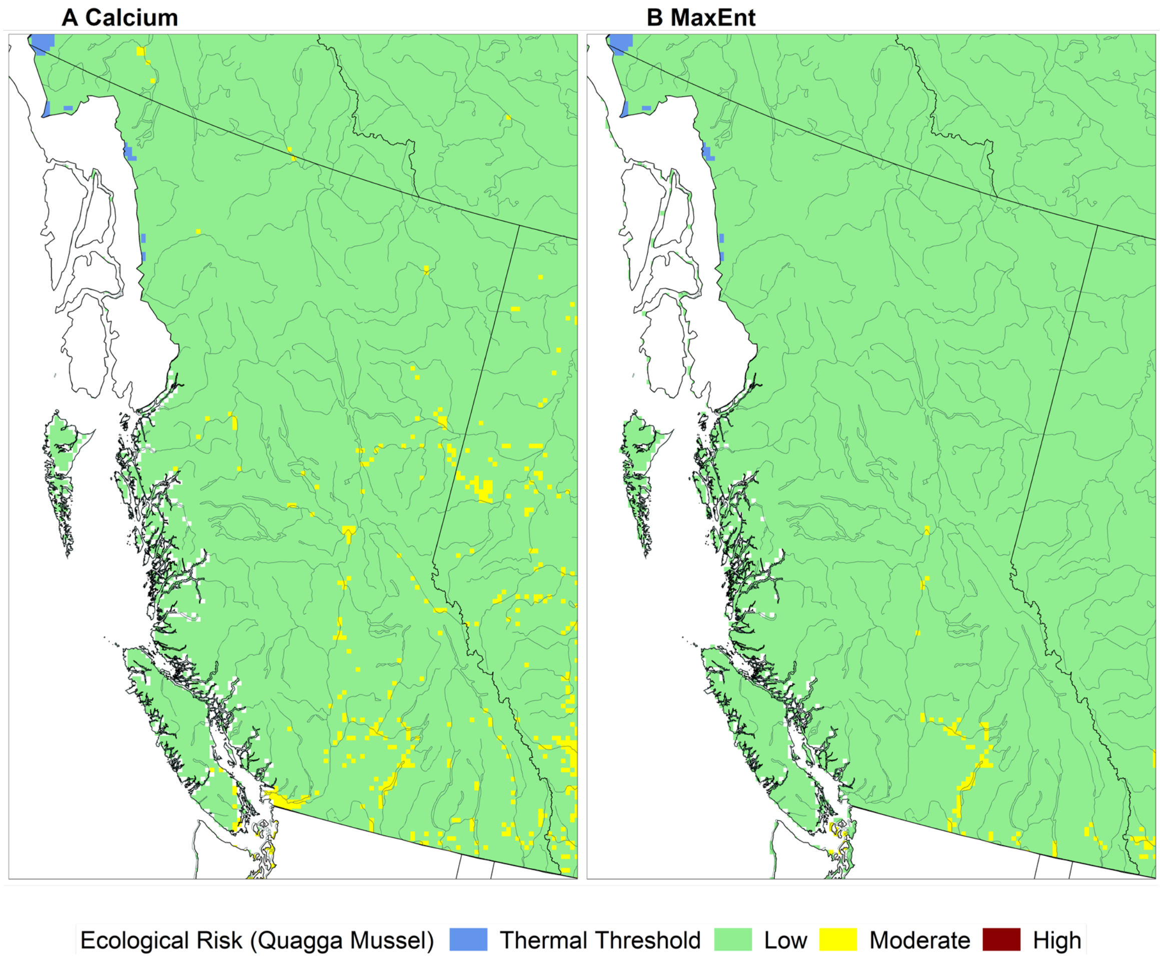

Figure C4. Quagga Mussel Ecological Risk in British Columbia using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.

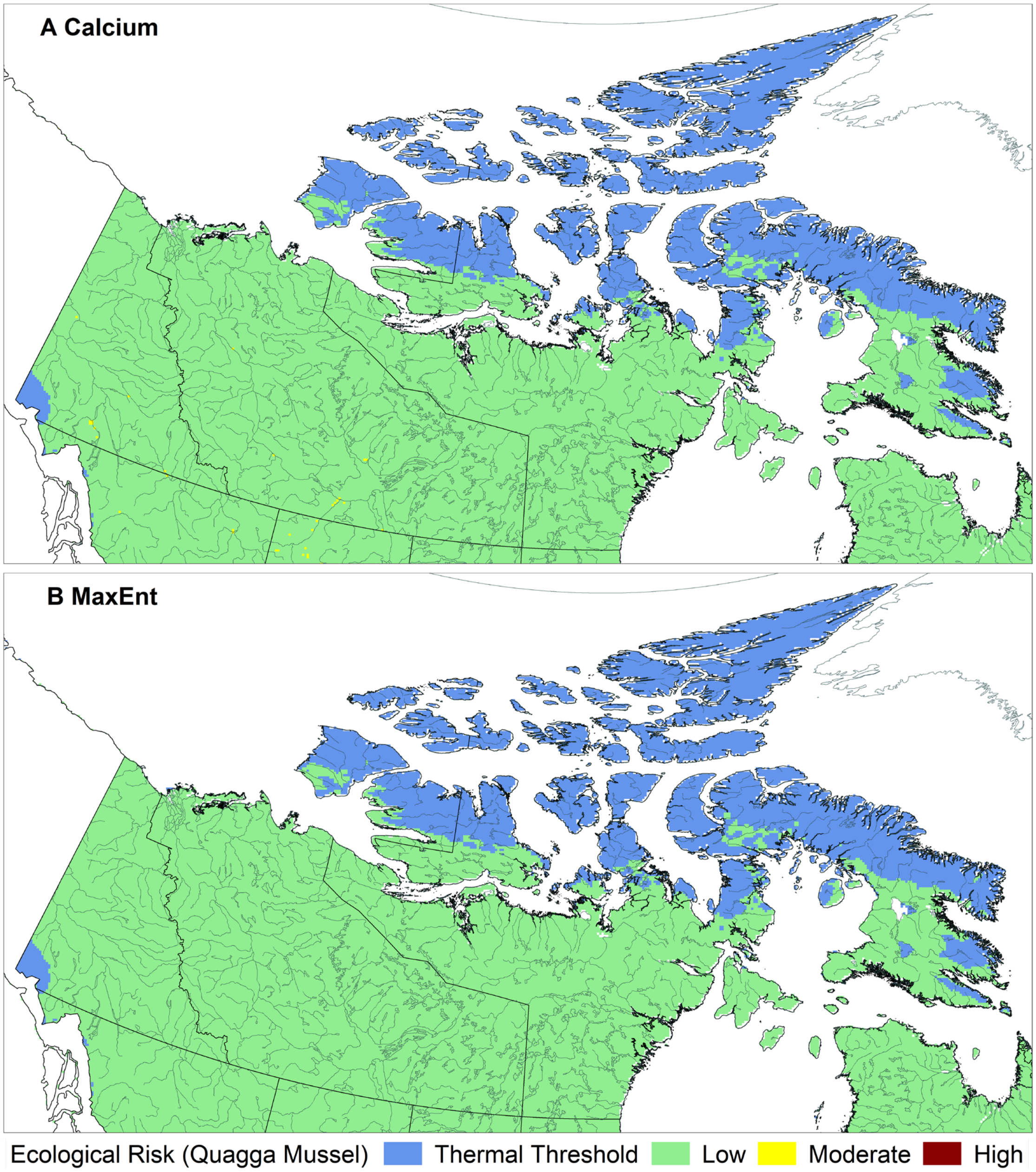

Figure C5. Quagga Mussel Ecological Risk in the Territories using the Calcium (A) and MaxEnt (B) habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts.