Freshwater Climate Risk Index for Biodiversity (FW-CRIB): Using Climate Change Vulnerability and Risk Assessments (CCVA/CCRA) to Guide Freshwater Management in Canada's Maritime Provinces

By

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Table of Contents

List of Tables **iv**

List of Figures **v**

Abstract **x**

List of Abbreviations **xi**

Acknowledgements **xiii**

Chapter 1. Introduction **1**

1.1 Impacts of climate change on freshwater ecosystems and the humans that rely on them 1

1.2 Current freshwater management and protection initiatives.. 2

1.3 FW-CRIB structure 4

Chapter 2. FW-CRIB Methods **7**

2.1 Watershed and species selection 7

2.2 Component and index selection and rationale 11

2.3 Input data 13

2.4 Sensitivity component calculations.. 15

2.4.1 S1-Thermal safety margin *16*

2.4.2 S2-Ecosystem disruption *17*

2.4.3 S3-Conservation status *19*

2.4.4 S4-Watershed health index *19*

2.5 Exposure component calculations.. 21

2.5.1 E1-Climate change velocity *22*

2.5.2 E2-Magnitude of precipitation change *23*

2.5.3 E3-Projected time of thermal niche emergence *24*

2.5.4 E4-Projected habitat loss *24*

2.6 Adaptive capacity component calculations.. 25

2.6.1 AC1-Geographic area availability *25*

2.6.2 AC2-Thermal habitat variability *26*

2.6.3 AC3-Barriers to connectivity *27*

2.6.4 AC4-Maximum body length *28*

2.7 Overall vulnerability calculations 29

2.8 Transformations to risk 30

Chapter 3. FW-CRIB Results of Study Area **35**

3.1 Summary of results 36

3.1.1 Ecosystem-level *36*

3.1.1.1 Overall vulnerability and risk levels 36
3.1.1.2 Sensitivity component 38
3.1.1.2.1 S2-Ecosystem disruption index 39
3.1.1.2.2 S4-Watershed health index 40
3.1.1.3 Exposure component 41
3.1.1.3.1 E1-Climate change velocity 42
3.1.1.3.2 E2-Magnitude of precipitation variance 44
3.1.1.4 Adaptive capacity component 46
3.1.1.4.1 AC1-Geographic area 48
3.1.1.4.2 AC3-Barriers to connectivity 49
3.1.2 Species-specific results 50
3.1.2.1 Overall species vulnerability and risk 50
3.1.3.1 S1-Thermal safety margin 52
3.1.3.3 S3-Population status 54
3.1.4.3 E3-Time of thermal niche emergence results 56
3.1.4.4 E4-Projected habitat loss results 68
3.1.5.2 AC2-Thermal habitat variability results 69
Chapter 4. Discussion **60**
4.1 Further improvement of the framework 61
4.2 Caveats 64
4.3 Reproducible and open access methods 66
Chapter 5. Applications **66**
5.1 Subject matter experts 66
5.2 Management applications 68
5.2 Socio-economic and cultural impact mitigation/response 69
Chapter 6. Recommendations and conclusion **69**
References **72**
Appendices **82**

List of Tables

Table 1 Species included in the FW-CRIB framework, COSEWIC statuses, provincial distribution, and rationale for inclusion. 10

Table 2 List of indices included in Boyce et al.'s marine CRIB, and adaptations to FW-CRIB. Black text indicates common indices; red text indicates indices included in the marine CRIB that were removed for the FW-CRIB; orange text indicates indices that were similar in ecological theory, but modified for the FW environment, blue text indicates an index that was moved from its component; and green text indicates a new index. 12

Table 3 Thresholds for each index included in this study and rationale for selection. 31

List of Figures

Figure 1 Map of primary watersheds across Nova Scotia, New Brunswick, and Prince Edward Island. Watershed numbers correspond to names found in Appendix A. 8

Figure 2 Species temperature tolerances of those included and not included within this study. Temperature tolerances of 44 species not included in this study, versus 14 included in this study 18

Figure 3 Correlation matrix of cumulative impact parameters on overall watershed health index (WSHI). 21

Figure 4 Linear regressions for percentage of agriculture and impervious surfaces in relation to WSHI scores. Green lines indicate low risk thresholds as found in the literature, red lines indicate high risk thresholds as found in the literature. 32

Figure 5 Barriers to connectivity index score plotted against the weighted density of barriers per km of river logistic regression outputs. Green indicates low risk, yellow is medium, orange is high, and red is critical. 34

Figure 6 Map of study area coloured by overall vulnerability scores from 0-1, averaged across species for each watershed under three different RCP models (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 37

Figure 7 Map of study area coloured by ecosystem-level risk scores, averaged across species, for each watershed, under three RCPs (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 37

Figure 8 Vulnerability scores for species and RCPs, averaged across watersheds. Background colouring indicates associated risk levels (green = low, yellow = medium, orange = high, red = critical). 38

Figure 9 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by sensitivity component scores from 0-1 for each RCP (2.6, 4.5, and 8.5). 39

Figure 10 Map of study area coloured by watershed specific, ecosystem disruption index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 40

Figure 11 Map of study area coloured by ecosystem disruption index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 40

Figure 12 Map of study area coloured by WSHI scores from 0-1, as scaled by global maxima; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 40

Figure 13 Map of study area coloured by WSHI scores from 0-0.3, as scaled by local maxima, to increase visibility; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 40

Figure 14 Map of study area coloured by WSHI risk levels; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 41

Figure 15 Map of study area coloured by exposure component scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 42

Figure 16 Map of study area coloured by climate change velocity scores from 0-1 for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 43

Figure 17 Map of study area coloured by climate change velocity scores from 0-0.3 for each RCP (2.6, 4.5, 8.5), as scaled by local maxima, to increase visibility; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 43

Figure 18 Map of study area coloured by climate change velocity risk levels for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 44

Figure 19 Map of study area coloured by magnitude of variance in precipitation scores from 0-1 for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 45

Figure 20 Map of study area coloured by magnitude of variance in precipitation from 0-0.13 for each RCP (2.6, 4.5, 8.5), as scaled by local maxima, to increase visibility; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 45

Figure 21 Map of study area coloured by magnitude of precipitation variance risk levels for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 46

Figure 22 Map of study area coloured by adaptive capacity component scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 47

Figure 23 Map of study area coloured by geographic area scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 48

Figure 24 Map of study area coloured by geographic area risk levels; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 48

Figure 25 Map of study area coloured by barriers to connectivity index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 49

Figure 26 Map of study area coloured by barriers to connectivity index risk levels; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 49

Figure 27 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic salmon (Salmo salar) overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5). 51

Figure 28 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic salmon (Salmo salar) overall risk levels for each of three RCPs (2.6, 4.5, 8.5). 51

Figure 29 Map of study area coloured by striped bass (Morone saxatilis) overall vulnerability scores for each watershed across three RCPs (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 52

Figure 30 Map of study area coloured by striped bass (Morone saxatilis) overall risk levels for each watershed across three RCPs (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 52

Figure 31 Map of study area coloured by Atlantic salmon (Salmo salar) thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 53

Figure 32 Map of study area coloured by Atlantic salmon (Salmo salar) thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 53

Figure 33 Map of study area coloured by striped bass (Morone saxatilis) thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 54

Figure 34 Map of study area coloured by striped bass (Morone saxatilis) thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 54

Figure 35 Map of study area coloured by Atlantic salmon (Salmo salar) population status index scores from 0-1. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1. 56

Figure 36 Map of study area coloured by striped bass (Morone saxatilis) population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1. 56

Figure 37 Map of study area coloured by Atlantic salmon (Salmo salar) time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 57

Figure 38 Map of study area coloured by Atlantic salmon (Salmo salar) time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 57

Figure 39 Map of study area coloured by striped bass (Morone saxatilis) time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 68

Figure 40 Map of study area coloured by striped bass (Morone saxatilis) time of emergence risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 68

Figure 41 Map of study area coloured by Atlantic salmon (Salmo salar) habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 69

Figure 42 Map of study area coloured by striped bass (Morone saxatilis) habitat loss by 2100 index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 69

Figure 43 Map of study area coloured by Atlantic salmon (Salmo salar) thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 59

Figure 44 Map of study area coloured by Atlantic salmon (Salmo salar) thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 59

Figure 45 Map of study area coloured by striped bass (Morone saxatilis) thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 60

Figure 46 Map of study area coloured by striped bass (Morone saxatilis) thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. 60

Figure 47 Jam board brainstorm with the freshwater committee to identify potential management applicability for FW-CRIB results. 67

Abstract

Climate change is occurring globally, impacting the distribution and fitness of organisms and the potential for ecosystems to provide vital services to human societies. In freshwater ecosystems across the globe, increasing variability and frequency of extremes in precipitation and subsequent water flows, as well as rising trends in water temperature are being observed. To effectively manage freshwater populations, policy measures must be implemented with climate projections in mind. Fisheries and Oceans Canada has recently committed and invested in, in alignment with United Nations Sustainable Goal 13, to combat climate change and its impacts on aquatic ecosystems to ensure climate-resilient aquatic ecosystem management. An essential step in this process is to identify the species and ecosystems that are most vulnerable to climate change to support decision-making for conservation and/or restoration. The Freshwater Climate Risk Index for Biodiversity (FW-CRIB), composed of climate change vulnerability (CCVAs) and risk (CCRAs) assessments can support climate adaptation efforts by helping to understand how climate risk manifests and what actions could help mitigate it. These assessments look at 12 indices across three components (adapting methods from Boyce et al.'s (2022) marine CRIB): exposure of a species in a watershed to future threats, current sensitivities faced by the species in a watershed, and the species' presence, or lack of, adaptive traits. Results included generally higher risk levels in New Brunswick watersheds, with most species only showing high risk levels under RCP 8.5. Atlantic salmon (*Salmo salar*) exhibited the highest overall vulnerabilities in the Saint John River Basin watershed under RCP 8.5. Using the open-access and reproducible framework developed through the FW-CRIB as applied in this study can be used to inform provincial and federal policy, and community-level decisions, providing meaningful guidance for predictive management tools.

Keywords: Climate change vulnerability assessments, climate change risk assessments, freshwater management, species at risk, climate change projections

List of Abbreviations

°C – Degrees Celsius

AC1 – Adaptive Capacity index one; Geographic area

AC2 – Adaptive Capacity index two; Thermal habitat variability

AC3 – Adaptive Capacity index three; Barriers to connectivity

AC4 – Adaptive Capacity index four; Maximum body length

CABD - Canadian Aquatic Barrier Database

CBD - Convention on Biological Diversity

CCCS - Canada Centre for Climate Services

CCRA - Climate Change Risk Assessment

CCVA - Climate Change Vulnerability Assessment

cm – Centimetre

CMIP5 - Coupled Model Intercomparison Project Phase 5

CMIP6 - Coupled Model Intercomparison Project Phase 6

COP - Convention of Parties

COSEWIC - Committee on the Status of Endangered Wildlife in Canada

CRIB - Climate Risk Index for Biodiversity

DFO – Fisheries and Oceans Canada

E1 – Exposure index one; Climate change velocity

E2 – Exposure index two; Magnitude of precipitation change

E3 – Exposure index three; Time of thermal niche emergence

E4 – Exposure index four; Projected habitat loss

EBSA - Ecologically and Biologically Significant Area

ECCC - Environment and Climate Change Canada

ESA – Ecologically Significant Area

FW - Freshwater

IUCN - International Union for Conservation of Nature

km – Kilometre

KMGBF - Kunming-Montreal Global Biodiversity Framework

LFA - Lobster Fishing Area

NCC - Nature Conservancy of Canada

RCP - Representative Concentration Pathways

S1 – Sensitivity index one; Thermal safety margin

S2 – Sensitivity index two; Ecosystem disruption

S3 – Sensitivity index three; Population status

S4 – Sensitivity index four; Watershed health index

SARA - *Species at Risk Act*

ToE – Time of Emergence

TSM – Thermal Safety Margin

UN – United Nations

VoCC – Velocity of Climate Change

WSHI - Watershed Health Index

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Chapter 1. Introduction

1.1 Impacts of climate change on freshwater ecosystems and the humans that rely on them

Climate change has emerged at the forefront of global issues, impacting the distribution and fitness of organisms, and the associated potential for ecosystems to provide vital services to human societies (Field et al. 2014; Du Pontavice et al. 2020). Habitat destruction, alteration, exploitation, pollution, and nutrient deposition from anthropogenic stressors can exacerbate detrimental effects of climate change and reduce the resilience of a natural habitat to its impacts (Halpern et al. 2019). Globally, freshwater ecosystems are particularly threatened, due to an increase in variability and frequency of precipitation extremes, subsequent water flows, and rising temperature trends (Jonsson and Jonsson 2009; Thistle and Caissie 2013; Sloat et al. 2017). This vulnerability affects resident freshwater species' risk disproportionately when compared to marine species due to greater habitat specificity, sensitive life stages, physical restrictions for migration and dispersal capacity, and proximity of freshwater bodies to human activity (Pörtner and Peck 2010; Closs et al. 2016; Comte and Olden 2017; Liu et al. 2017).

Freshwater ecosystem services are essential to human society. Biodiverse and abundant freshwater areas are essential in maintaining healthy human communities (Harmon et al. 2018). Wilson and Carpenter (1999) estimated the economic value attached to these services in the United States; they assessed goods and activities such as fishing, swimming, transportation, drinking water, irrigation, electricity, aesthetic and ecosystem-based activities, as well as other prevalent indices. Their results estimated potential economic losses from one lake's continued degradation to be upwards of US$87,500 per year across the analyzed services (Wilson and Carpenter 1999). In a Canadian context, the study states the inherent challenges of estimating economic value of freshwater ecosystems but demonstrates the importance of doing so under the continued degradation of lakes, rivers, and streams. Their results highlight the importance of ecosystem conservation for environmentally-focused and economic-growth minded decision makers alike. The maintained health and diversity of freshwater ecosystems promotes quality of life for those who interact with the area and must be prioritized moving forward.

In the Canadian context, freshwater environments have played vital roles for human development and society for centuries. With the largest freshwater area in the world, Indigenous Peoples and Canadians have used and continue to use these ecosystems to support their lifestyles, cultures, and livelihoods. Indigenous Peoples in Canada have used freshwater bodies and the species within them for food, social, and ceremonial purposes for time immemorial (Alexander et al. 2021). In 1999, after Donald Marshall Jr.'s case was concluded in the Supreme Court of Canada, Indigenous People's right to fish for a moderate commercial livelihood was recognized, expanding Indigenous inherent rights to a commercial setting (Alexander et al. 2021). Indigenous People in Canada have existed in harmony with freshwater ecosystems for as long as humans have inhabited the land, and as such, the government has a duty to protect these environments and promote continuous, sustainable use of Canadian inland waters under the public trust doctrine. With climate change, predicting how and when communities' resource availability changes is imperative to minimize food, social, ceremonial, and livelihood impacts.

1.2 Current freshwater management and protection initiatives

Currently, management in the freshwater environment excludes climate projections, and employs restoration efforts around watersheds based on areas of high usage or significance, rather than on areas resistant to climate change effects (Du Toit and Pollard 2019). Typically employing recreational angling restrictions, habitat restoration, and restocking efforts, coupled with the only recent joining of conservation and management ideologies, these management methods leave room for uncertainty regarding their efficacy (Winfield 2016). This investment of time, resources, and effort into areas of potentially high vulnerability to detrimental climate change effects is a risk that managers currently face. An essential step to address this gap is to identify the species and ecosystems that are most and least vulnerable to climate change to support decision-making for conservation and/or restoration.

In 2021, Fisheries and Oceans Canada has committed, aligning with the United Nations Sustainable Development Goal 13 (United Nations 2023), to expand climate vulnerability-based research to better inform aquatic conservation management and planning, and to invest in research and protection of areas with high carbon storage potential (Prime Minister of Canada 2021). At the most recent United Nations Convention on Biological Diversity (UN CBD) Convention of Parties (COP) in 2023, the Kunming Montreal Global Biodiversity Framework (KMGBF) was established, with Canada as a signing party. The KMGBF outlined four goals for 2050 and 23 targets for 2030, with marine and terrestrial protection included as main topics of global concern (UN CBD 2022). Target three mandates 30% protection of terrestrial and inland water and of marine coastal areas, with special notice given to places of ecological significance (UN CBD 2022). With 20% of the world's fresh, inland water, and the longest coastline of any country in the world, Canada's commitment to the KMGBF targets is monumental. These commitments to protection, however, must be well informed to produce meaningful and sustainable management decisions.

The UN CBD initiatives present an opportunity to close gaps within Canadian conservation legislation and policy. Stated earlier, the gaps that Canadian policy makers must address revolve around the ability to endure future climate conditions. Although global policy is pushing for immediate carbon emission mitigation strategies, the detrimental effects that have already been put into motion must be prepared for. This study looks at three different climate projection models to provide insight on what effects are occurring, what the primary drivers behind high vulnerability areas are, and where and when risk will be highest. The Representative Concentration Pathways (RCPs) included in this study are 2.6, 4.5, and 8.5, as developed by the International Panel on Climate Change (IPCC) and put forth in their Fifth Assessment Report (AR5) (Climate Watch 2023). RCP 2.6 assumes the most proactive climate change mitigation strategies across the globe, as well as small constant net negative emissions after 2100, acting as an optimistic best-case scenario (Climate Watch 2023). RCP 4.5 assumes aggressive yet realistic climate change mitigation strategies and acts as a mid-point climate predictor model for this study. The worst-case scenario for climate change and carbon emissions included in this study is RCP 8.5, which includes emissions and concentrations of the full suite of greenhouse gasses, aerosols, and chemically active gasses, with carbon dioxide concentrations only stabilizing after 2250 (Climate Watch 2023). By employing these three RCP models within this study's framework, the importance of immediate and aggressive climate action and response is highlighted.

1.3 FW-CRIB structure

Climate change vulnerability and climate change risk assessments (CCVA and CCRA, respectively) can support climate adaptation efforts by advancing knowledge on how climate risk manifests and what actions could help mitigate it (reviewed in Pacifici et al. 2015; De Los Ríos et al. 2018; Foden et al. 2019). CCVAs and CCRAs can answer key questions such as which species and ecosystems are most vulnerable to climate impacts, as well as the timing, location, and magnitude of such impacts. By employing multiple climate projections, these assessments can support scenario planning exercises to understand the risk reduction achieved through emissions mitigation. However, many CCVAs and CCRAs are not well suited to aid in these situations. Past assessments have lacked spatial data, been qualitative, non-reproducible, or been challenging to interpret and communicate results (Boyce et al. 2022). Furthermore, most assessments developed for use in freshwater ecosystems have depended on expert knowledge, which lengthens the time needed to complete the assessment, reduces their potential for reproduction, and introduces potential errors due to subjectivity, human error, and bias (Boyce et al. 2022). Most have not employed fine-scale ecological data regarding population structure, spawning site fidelity, and climate variability, which are necessary to inform local management (Small-Lorenz et al. 2013). In order for appropriate local management of aquatic resources to proceed, these assessments require the use of local-scale data and a standardized, quantitative approach.

The marine climate risk index for biodiversity (CRIB) was recently developed (Boyce et al. 2022). The CRIB framework is a quantitative, spatially explicit, and reproducible two-step CCVA and CCRA process, quantifying vulnerability (i.e., CCVA), and translating these vulnerabilities to risks (i.e., CCRA) for individual species and ecosystems under different greenhouse gas emissions scenarios (i.e., RCP 2.6, 4.5, 8.5) (Boyce et al. 2022). The approach captures unique but generalized species responses to climate change and is flexible, having been implemented globally to ~25,000 species and regionally across the northwest Atlantic to ~2,000 species. The CRIB considers cumulative impacts of anthropogenic stressors, and includes globally-relevant and internationally-accepted vulnerability components (Field et al. 2014; De Los Ríos et al. 2018): *Exposure* (representing the magnitude and rate of change expected in the environment surrounding the species of interest), *Sensitivity* (representing the likelihood of the species of interest being negatively impacted by anticipated climate change given physiological tolerance, the presence of other stressors, current population status, and projected disruption to the surrounding ecosystem structure), and *Adaptive Capacity* (representing opportunities within the environment and the species' life history to avoid or adapt to environmental change).

In this study, the Boyce et al. (2022) CRIB was adapted to evaluate the vulnerability and climate risk of six diadromous and eight freshwater species of ecological, commercial, and/or cultural importance to climate change and other anthropogenic stressors under three emissions scenarios, within all primary watersheds across Nova Scotia, New Brunswick, and Prince Edward Island, Canada. Diadromous species are those that inhabit both freshwater and saltwater during different stages of their life cycles. For the purposes of this study, vulnerability and risk were only calculated for the periods in which the species inhabit freshwater. Similarly to the marine CRIB, the freshwater climate risk index for biodiversity (FW-CRIB) framework is composed of two parts: the CCVA and the CCRA. The CCVA provides vulnerability scores from zero to one, while the CCRA provides a risk level; low, medium, high or critical.

Resulting vulnerability scores and risk categorizations can help to understand key questions, such as which species and ecosystems are most vulnerable to climate impacts, as well as the timing, location, and magnitude of such impacts. Specific applications in which the FW-CRIB may be used to inform freshwater management include: identification of areas to support increased protection (e.g. ecologically significant areas (ESAs), *Species at Risk Act* (SARA) critical habitat identification and recovery planning), fisheries management decisions, regulatory reviews of projects under the *Fisheries Act*, and conservation and recovery planning. With recent initiatives, need for action and protection, and gaps associated with past vulnerability assessments as outlined in this section, the FW-CRIB was applied to the Canadian maritime provinces to provide the tools and results needed by freshwater managers to make climate-smart decisions.

Chapter 2. FW-CRIB Methods

2.1 Watershed and species selection

The FW-CRIB framework was adapted from Boyce et al.'s 2022 marine CRIB and applied to 14 species of interest to derive climate vulnerability scores for each species, specific to primary watersheds in the Canadian provinces of New Brunswick, Nova Scotia, and Prince Edward Island. Primary resolution (rather than secondary or tertiary) for the 64 watershed delineations was chosen based on data availability, generalization of the method, and application to management (Figure 1; Appendix 1). Freshwater habitat data is not comprehensive, and it was found that data at the primary watershed level was most accessible across all indices. Generalization of the method was maximized at the primary watershed level, referring to the ability of the methods to be reproduced in any given area within Canada or even globally. Finally, as confirmed through consultations with local freshwater managers, management applications were relevant at the primary watershed level.

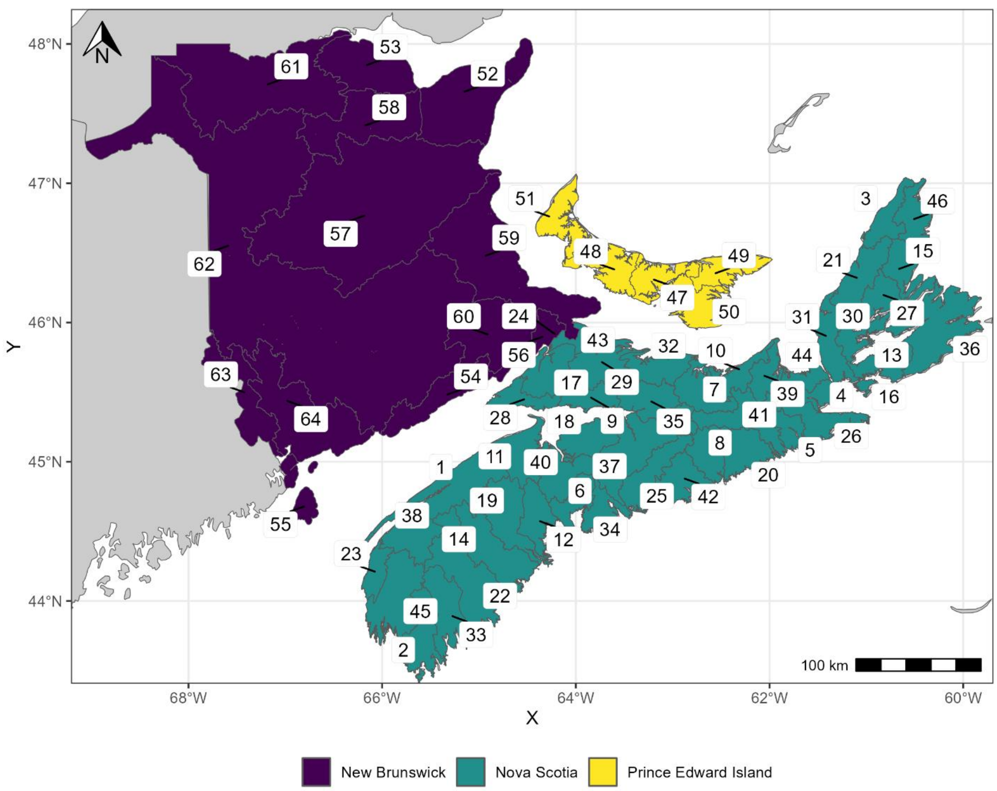


Figure 1 Map of primary watersheds across Nova Scotia, New Brunswick, and Prince Edward Island. Watershed numbers correspond to names found in (Appendix 1).

Fourteen freshwater and diadromous species were chosen according to their cultural, ecological, and economic significance, as well as their populations statuses according to assessments conducted by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and the SARA schedule 1 listings (Table 1). Species were also chosen based on data availability of thermal tolerance limits from the literature. These species include: American shad (*Alosa sapidissima*), Atlantic sturgeon (*Acipenser oxyrhynchus*), banded killifish (*Fundulus diaphanus*), brook floater (*Alasmidonta varicosa*), Lake Utopia rainbow smelt (small and large-bodied populations) (*Osmerus mordax*), shortnose sturgeon (*Acipenser brevirostrum*), yellow lampmussel (*Lampsilis cariosa*), Atlantic salmon (*Salmo salar*), Atlantic whitefish (*Coregonus* *huntsmani*), striped bass (*Morone saxatilis*), American eel (*Anguilla rostrata*), brook trout (*Salvelinus fontinalis*), and alewife (*Alosa pseudoharengus*) (Table 1). Using the FW-CRIB, species were assessed to find which were most vulnerable to climate change in Nova Scotia, New Brunswick, and Prince Edward Island, and in which primary watersheds they are most at-risk. Given the characterization of climate exposure, sensitivity, and adaptive capacity indices, this assessment also provides insight into the relative influence of projected climate change, when compared to other place-based stressors (e.g., clear-cutting, dams, impermeable surfaces, etc.).

Table 1 Species included in the FW-CRIB framework, COSEWIC statuses, provincial distribution, and rationale for inclusion.

Common Name	Scientific Name	Population	COSEWIC Status	COSEWIC Index	Provinces of Occurrence	Rationale for Inclusion	Status Source
Alewife	*Alosa pseudoharengus*		Candidate species	0.25	NS, NB, PEI	Significant forage fish	Wild Species
American eel	*Anguilla rostrata*		Threatened	0.75	NS, NB, PEI	COSEWIC status, significant commercial fishery, significant cultural fish	COSEWIC report, 2012
American shad	*Alosa sapidissima*		Candidate species	0.25	NS, NB, PEI		COSEWIC
Atlantic salmon	*Salmo salar*	Gaspe-Southern Gulf	Threatened	0.75	NS, NB, PEI	COSEWIC status, SARA status (inner Bay of Fundy), significant cultural fish	COSEWIC report, 2010
		Eastern Cape Breton	Endangered	1	NS		
		Southern Upland	Endangered	1	NS		
		Inner Bay of Fundy	Endangered	1	NS, NB		
		Outer Bay of Fundy	Endangered	1	NS, NB		
Atlantic sturgeon	*Acipenser oxyrhynchus*	St. Lawrence	Threatened	0.75	NB	COSEWIC status	COSEWIC report, 2011
		Maritimes	Threatened	0.75	NS, NB		
Atlantic whitefish	*Coregonus huntsmani*		Endangered	1	NS	COSEWIC status, endemism	COSEWIC report, 2010
Banded killifish	*Fundulus diaphanus*	Mainland Maritimes	Not at risk	0	NS, NB, PEI	COSEWIC status in Newfoundland, significant forage fish	Wild Species
Brook floater	*Alasmidonta varicose*		Special concern	0.5	NS, NB	COSEWIC status, endemism, SARA status	SARA Management Plan, 2018
Brook trout	*Salvelinus fontinalis*		Candidate species	0.25	NS, NB, PEI	Significant recreational fishery, significant cultural fish, at risk from non-native species	Wild Species
Lake Utopia small-bodied Rainbow smelt	*Osmerus mordax*	Lake Utopia	Threatened	0.75	NB	COSEWIC status, endemism, SARA status	COSEWIC report, 2018
Lake Utopia large-bodied Rainbow smelt	*Osmerus mordax*	Lake Utopia	Threatened	0.75	NB	COSEWIC status, endemism, SARA status	COSEWIC report, 2018
Shortnose sturgeon	*Acipenser brevirostrum*		Special concern	0.5	NS, NB	COSEWIC status, endemism	COSEWIC report, 2015
Striped bass	*Morone saxatilis*	Southern Gulf of St. Lawrence	Special concern	0.5	NS, NB, PEI	COSEWIC status	COSEWIC report, 2012
		Bay of Fundy	Endangered	0.75	NS, NB		
Yellow lampmussel	*Lampsilis cariosa*		Special concern	0.5	NS, NB	COSEWIC status, endemism, SARA status	COSEWIC report, 2010

2.2 Component and index selection and rationale

The components of climate change vulnerability (sensitivity, exposure, and adaptive capacity), as stated earlier, are not exclusive to defining vulnerability in the aquatic context, and are relevant across all ecosystems (e.g., terrestrial, freshwater, and marine) (Field et al. 2014). Some specific indices included within each component, however, are ecosystem-specific (e.g. freshwater). An example of a freshwater-specific index that cannot be translated to a marine or terrestrial landscape is the watershed health index (WSHI), which is comprised of freshwater specific impacts (eg. nitrogen and phosphorus leaching, acid deposition, etc.). Climate exposure indices can be quantified using climate models to describe the magnitude and rates of warming, and other climatic changes for different areas of the globe. Data for species-specific indices relating to the sensitivity and adaptive capacity components can be sourced from publicly accessible databases (e.g., FishBase.org), as well as via literature containing local-scale information on distribution, population status, and spatial occurrences.

Index selection was prioritized as in Boyce et al. (2022), selecting those that were grounded in ecological theory, robust, and validated, preferably through peer-review and publication. Within the selection method, indices were restricted to those able to be quantified and easily interpreted, and that were well-documented, while discarding correlated indices. While this study used the Boyce et al. (2022) framework as a base, each index within the sensitivity, exposure, and adaptive capacity components was adjusted to account for the full range of environmental and anthropogenic drivers that determine the health of freshwater fish populations. Indices specific to the marine environment included in Boyce et al. (2022), were removed in this study, such as vertical habitat use (Table 2). Where applicable, indices that were deemed not reflective of the freshwater context were transformed into parallel indicators, for instance geographic range extent (the marine area which a species occupies (km^2) and the latitude it spans) was transformed to geographic area (amount of wet area available to a species within a watershed). Indices were all standardized to a scale of 0-1, to ensure equal contribution of indices to overall vulnerability score.

Table 2 List of indices included in Boyce et al.'s marine CRIB, and adaptations to FW-CRIB. Black text indicates common indices; red text indicates indices included in the marine CRIB that were removed for the FW-CRIB; orange text indicates indices that were similar in ecological theory, but modified for the FW environment; blue text indicates the index was moved from its component; and green text indicates a new freshwater-specific index.

Sensitivity	**Exposure**	**Adaptive Capacity**
Thermal safety margin	~~Ecosystem disruption~~	Thermal habitat variability
~~Vertical habitat use~~	Time of climate emergence	~~Geographic range extent~~
Anthropogenic stressors -> Watershed Health Index	Thermal habitat loss	Maximum body length
Conservation statuses	Climate change velocity	Habitat fragmentation -> Barriers to connectivity
Ecosystem disruption	Rate of change in extreme precipitation days	Geographic Area

Species vulnerabilities were not calculated assuming a potentially global geographic range, as in Boyce et al. (2022). Rather, vulnerabilities were calculated with the assumption of watershed fidelity, where a species is geographically restricted to remain within their watershed of occurrence. Since freshwater habitats are constrained by land, fewer opportunities exist for aquatic species to expand their ranges. Some diadromous species exhibit site fidelity and homing behaviour, such as Atlantic salmon returning to their natal rivers to spawn, with little evidence of straying from these areas, let alone to other watersheds (Fontaine et al. 1997; Jonsson et al. 2003; Hendry et al. 2004; Dionne et al. 2008; COSEWIC 2011). From this information, we assume species vulnerability to be watershed-specific, due to the distinct populations that arise from watershed fidelity. This watershed-level approach indicates that the assessment framework is likely to overestimate vulnerability where natural or human-induced connectivity among watersheds or range expansion into new watersheds occurs (Dionne et al. 2008; Wirgin et al. 2020). All watershed vulnerabilities were calculated for all species, regardless of whether or not the species is currently present, to inform potential opportunities for introduction or relocation. In future iterations of the study, diadromous species' vulnerability scores should be considered in tandem with marine CRIB provided in Boyce et al. (2022) which have not yet been calculated and must be revisited.

2.3 Input data

The input data included in this study is open access, and therefore should be available to support application of the assessment to other regions. Input data to the Nature Conservancy of Canada's watershed health assessments are openly available for northeastern USA and for Canadian habitats east of Montreal. Due to strong autocorrelation between some variables included in the watershed health assessments, only non-correlated predictor variables were chosen to be included in the Watershed Health Index (WSHI) for this study: clear-cut land, percentage of land used by agriculture, percentage of impervious surface, presence of non-native species, and acid deposition (Millar et al. 2019).

To model future climate conditions, three RCP datasets from 1980-2100 were obtained from Climate Data Canada and used to calculate multiple indices in the exposure and sensitivity components of this study (Climate Data Canada 2023). These climate projection data were derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, however as the Coupled Model Intercomparison Project Phase 6 (CMIP6) is being released after this study's conclusion, these indices will need to be recalculated. In the marine CRIB, 15 climate models were used, and down weighted according to the number of models included, and the number of years over which they were projected (Boyce et al. 2022). In this study, 24 climate models were used, and downweighting was deemed unimportant with so many models included. All indices calculated using these data were calculated for each model; resulting index scores were then averaged across models.

Barrier passability data was collected from the Canadian Aquatic Barrier Database (CABD), for both barrier occurrence and barrier passability scores (CABD 2023). In speaking with representatives from CABD about the calculation of various passability scores, it became known that an updated database will be available in 2024, and as such, these calculations must be revisited, and results must be updated (CABD, pers. comm., July 2023).

As noted in the previous section, species selection was contingent on temperature tolerance data availability. There were few instances where a species was considered for inclusion and temperature tolerance was not listed in various databases or literature (i.e., blacknose shiner, chain pickerel, round whitefish, splake, tiger trout). To collect upper and lower sublethal and maximum lethal temperature tolerance data, FishBase.org was consulted, as were published aquatic animal physiology papers (data was often derived from in-situ experiments, and as such, in-vivo tolerances may differ) (Miller and Hart 1953; Otto et al. 1976; Faber and

McAllister 1979; Spotila et al. 1979; Guderley and Blier 1988; Hofmann and Fischer 2002; Kneeland and Rhymer 2008; Wilkes 2008; Righton et al. 2010; Kieffer et al. 2011; Pandolfo et al. 2012; Zhang and Kieffer 2014; Jacquin et al. 2019; Zanuzzo et al. 2019; Bayse et al. 2020; Gilbert et al. 2020; Markin and Secor 2020; Katzenberger et al. 2021; Sargent et al. 2021; Penny et al. 2023). For the indices using species temperature tolerances, the sublethal and maximum lethal temperature points were averaged. Sublethal temperature tolerances indicated behavioural change, including seeking thermal refugia within the watershed; hence, exposure to sub-lethal temperatures may not result in extirpation. However, using the maximum lethal temperature tolerances produced results where an unrealistic majority of species across watersheds and RCPs were not at risk of extirpation.

Other species physiology data were collected, including maximum body length, which acts as a proxy for several life history traits (Boyce et al. 2022). These data were largely taken from literature review, and in some cases were taken from the COSEWIC reports (Campbell et al. 2005; Holm and Dextrase 2007; Johnson 2009; Bradbury 2010; Brown et al. 2013; Brown et al. 2014).

To collect population statuses for the species included in this study, the most recent COSEWIC reports, DFO management plans, and the Wild Species database were consulted (Canadian Endangered Species Conservation Council 2022; Government of Canada 2023a). COSEWIC is an advisory body to the government of Canada, and conducts population-level health assessments for both marine and terrestrial species in Canada. The Canadian government uses these assessments to guide when a species should be listed under SARA. The Wild Species database is an inter-provincial government initiative that includes species not assessed by

COSEWIC and provides statuses to flag potential at-risk species (Canadian Endangered Species Conservation Council 2022).

Many index calculations used global scaling to generate vulnerability scores between 0 and 1 (e.g., WSHI). However, some indices were scaled by the study area maxima (e.g., for the geographic area index, each watershed's network length was scaled by the largest watershed's network length (Saint John River Basin)), rendering them not immediately reproducible using this code. This was done to reflect the area specific worst or best case scenario, where scaling by the global maxima would be ecologically illogical.

2.4 Sensitivity component calculations

Due to the nature of the freshwater environment relative to marine, freshwater species often exhibit heightened sensitivity to environmental changes. This phenomenon is due to stronger habitat specificity, more direct exposure to human stressors, reliance on thermal refugia, dependence on environmental cues, and lower connectivity, largely due to human development (Pörtner and Peck 2010; Comte and Olden 2017; Sunday et al. 2019). The sensitivity component characterizes the imminence of climate driven threat, existing species traits which put them at higher risk of extirpation, and the severity of other contributing anthropogenic stressors. Indices within this component include thermal safety margin, projected ecosystem disruption, population status, and WSHI. These indices are non-redundant, reproducible, based in robust ecological theory, and where possible, calculation methods have been taken or adapted from Boyce et al.'s marine CRIB (2022).

2.4.1 S1-Thermal safety margin

The thermal safety margin (TSM) is an index of a species' sensitivity to further warming in its habitat (Sunday et al. 2014; Comte and Olden 2017; Pinsky et al. 2019). A narrow TSM indicates that a species is inhabiting environments with temperatures already close to its upper thermal tolerance, which translates to a high sensitivity to climate warming (Comte and Olden 2017; Pinsky et al. 2019). TSM was calculated as a species-specific index, producing a score from 0-1 for each watershed to species pair, following Boyce et al.'s methods (2022). This was done by calculating the difference between the species' upper thermal tolerance and the maximum average monthly temperature (projected near surface air temperatures -3°C, to translate to water temperature, and averaged over watersheds) that species had experienced from 2010-2020. The differences calculated (i.e., TSMs) were then standardized using equation 1 to ensure uniform scores, as per Boyce et al. (2022):

$$S\,TSMs,w = e^{-\lambda TSM\ s,w} ,$$

Equation 1

, where S $TSM_{s,w}$ represents the species, s, and watershed, w, specific TSM, and λ is the rate parameter (0.33). For each watershed to species pair (64 watersheds with 14 species in each), a TSM score between 0-1 was calculated, for each of three RCP scenarios.

2.4.2 S2-Ecosystem disruption

Ecosystem disruption represents the proportion of species at risk of extirpation in each watershed by 2100 under three RCP scenarios. A high ecosystem disruption score indicates that a watershed is at risk of losing a large proportion of its species. High levels of ecosystem disruption can give rise to cumulative, long-term, large-scale biological and cultural consequences, restricting future management initiatives and reducing potential efficacy (Frissell and Bayles 1996). To ensure that the 14 species were representative of the thermal tolerance limits of the broader ecological community (ensuring the ecosystem disruption index based on only these 14 species would be representative of broader community-level disruptions), a list of 44 freshwater species and the average of their upper sublethal and max lethal thermal tolerances within the maritime provinces were compared against those included in this study. The subset of the 14 species in this study were indeed representative of the thermal tolerances within the broader community (Figure 2), implying that the ecosystem disruption index was also representative.

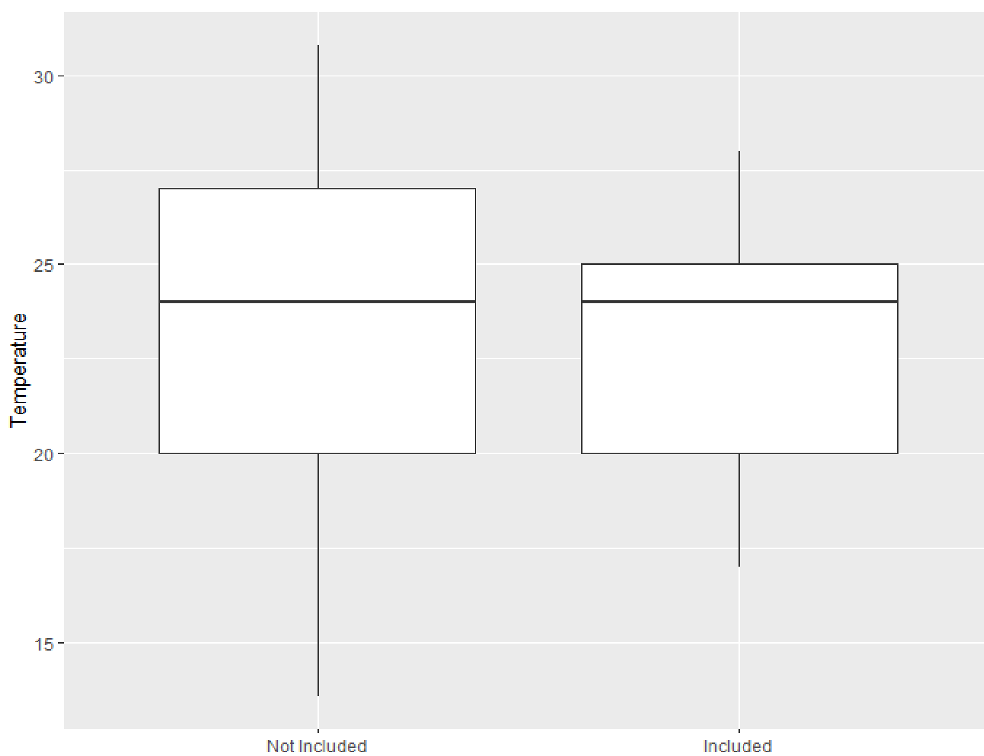


Figure 2 Species temperature tolerances (average of sub-lethal and maximum lethal) of those included (n = 14) and not included (n = 44) within this study.

Using the projected loss of habitat calculation, ecosystem disruption was calculated from 0-1 according to Boyce et al. (2022):

$$S\ EDw = \frac{THLw}{TSPw}\ ,$$

Equation 2

, where $S\ ED_w$ is the proportion of ecosystem disruption within a watershed, THL_w is the sum of species at risk of extirpation by 2100 in a watershed (according to the habitat loss index in the exposure component), and TSP_w is the total species present (of which there are 14 included in this study) in each watershed.

2.4.3 S3-Conservation status

Whether a population is already under threat of extinction due to severe depletion and/or other threats, will determine the species' sensitivity to further disturbance via environmental change. Boyce et al. (2022) used the International Union for Conservation of Nature (IUCN) global species rankings for this index. For the freshwater environment, many species are not assessed by IUCN, and therefore this study employed the population-level statuses as provided by the COSEWIC and Wild Species Canada (Canadian Endangered Species Conservation Council 2022). Species' statuses were transformed to numeric values as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment (as listed by Wild Species) = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.

2.4.4 S4-Watershed health index

Oftentimes in CCVAs, the focus is solely on climatic changes, and the influence of other anthropogenic stressors is ignored (Gregory et al. 2009; Mantyka-Pringle et al. 2011; Moyle et al. 2013; Watson and Segan 2013; Pacifici et al. 2015). To combat this oversight, the marine CRIB quantified water quality change through anthropogenic stressors by employing the Halpern index as one of the 12 indices included in the assessment (Halpern et al. 2008; Halpern et al. 2015; Halpern et al. 2019; Boyce et al. 2022). The Halpern index is a comprehensive, quantitative assessment that combines 19 anthropogenic stressors in the marine environment: benthic structures, commercial shipping, ocean-based pollution, species invasion, ocean acidification, UV levels, sea temperature, fishing of differing methods, pollution of differing sources and types, nutrient input, and more (Halpern et al. 2015). As the Halpern index has not yet been applied to freshwater ecosystems, the FW-CRIB obtained raw spatial data for stressors found in the Nature Conservancy of Canada's (NCC) WSHI (Millar et al. 2019). The NCC's pre-calculated WSHI was not used in the FW-CRIB directly as many stressors were duplicates of existing indices. Acid deposition, non-native fish presence, percentage of clear cut land usage, percentage of agriculture land usage, and percentage of impervious surface land usage data were compiled across the study area. To select these five predictor variables and ensure minimal redundancy in the calculation, a correlation matrix was carried out for all NCC predictor variables, and the five included in this study were selected (Figure 3). Variables that were excluded include pesticide leaching, nitrogen, and phosphorus leaching, since they exhibited a strong correlation to agriculture land usage. Values were then standardized to a scale of 0-1 by dividing by the global worst case scenarios, as found in the literature (Tao and Feng 2000; Leprieur et al. 2008; Lang et al. 2019; Hinz et al. 2020; Global Forest Watch 2023). The final WSHI was calculated as per equation 3:

$$S\,WSHIw = \frac{\sum_{n}^{1} log(n)}{\sum_{n}^{1} log(global\ max\ n)},$$

Equation 3

, where $WSHI_w$ represents the watershed specific WSHI score, and n represents the five predictor variables as provided by NCC.

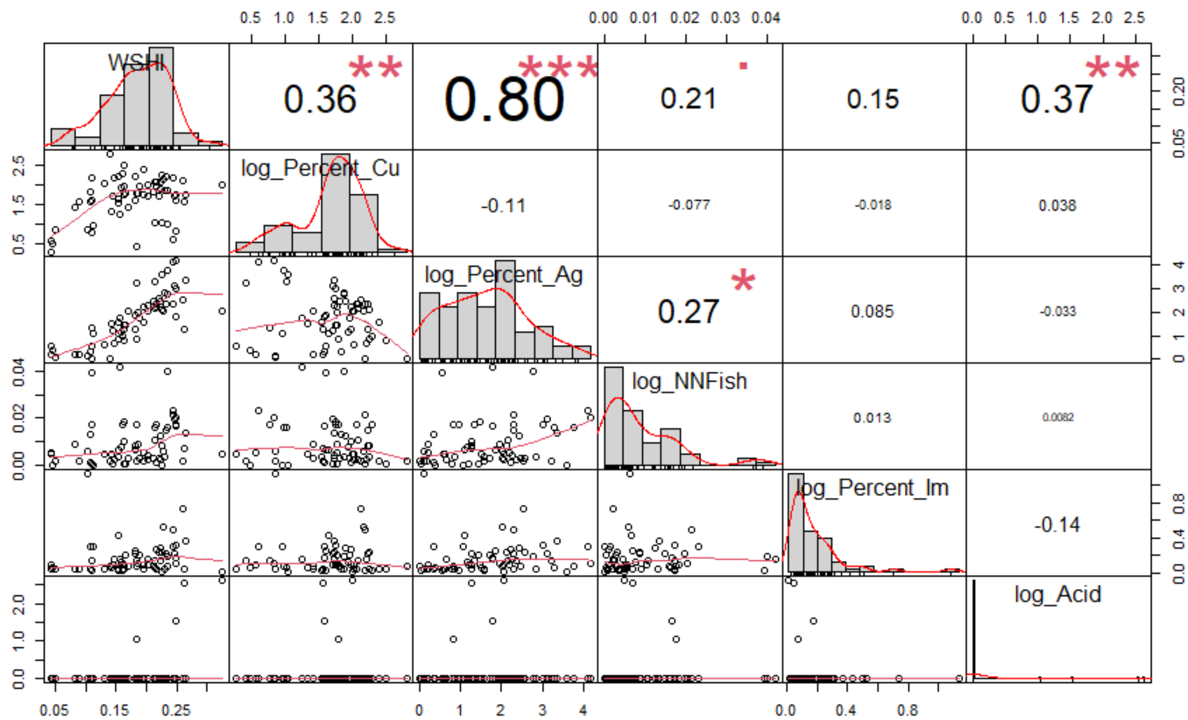


Figure 3 Correlation matrix of cumulative impact parameters on overall watershed health index (WSHI).

2.5 Exposure component calculations

Meteorological records indicate that surface temperatures over land are warming more rapidly than over the ocean, and as such freshwater ecosystems are disproportionately at risk (IPCC 2021). Furthermore, the increase in surface temperatures are leading to more extreme weather phenomena, such as extreme warming events, intense storms, and extreme fluctuations in precipitation, which are impacting freshwater ecosystems with greater detriment than to those in the marine environment (IPCC 2021). These assessments used two climate change indices, temperature and precipitation (as a proxy for water flow), both of which are commonly found in other freshwater specific CCVAs (Moyle et al. 2013; Olusanya and Van Zyll De Jong 2018; Nyboer et al. 2019). Climate data used in the exposure component indices were obtained from the Canadian Centre for Climate Services (CCCS) (Climate Data Canada 2023) of Environment and Climate Change Canada (ECCC). Twenty-four statistically downscaled climate scenario datasets (simulations) were derived from global climate model projections from the CMIP5 for Nova Scotia, New Brunswick, and Prince Edward Island. The datasets included projected daily, monthly, and annual near surface (~1.5m) air temperatures (°C), and daily precipitation (cm), for the period of 1980-2100, under three different RCP scenarios (2.6, 4.5, and 8.5). As freshwater temperatures are not widely documented or publicly available and therefore were not available in the climate models, near surface air temperatures were used as a proxy for surface water temperatures; an adjustment of -3°C was used to translate projected measurements to better approximate water temperatures, according to average differences found in the literature (Harvey et al. 2011; Brodeur 2015).

2.5.1 E1-Climate change velocity

Velocity of climate change (VoCC) represents the rate at which environmental conditions are changing, and consequently putting species that use the area at risk (Loarie et al. 2009; Burrows et al. 2011; Field et al. 2014). Where Boyce et al.'s (2022) marine CRIB calculates velocities of change (km yr^{-1}) within 1°x1° cells, which equates to ~111km^2, the FW-CRIB instead calculates VoCC at the watershed scale. The function gVoCC in the VoCC R package was used (García Molinos et al. 2019) to calculate the velocity of change (km yr^{-1}) in average annual air temperature (-3°C to estimate water temperature), as in Boyce et al. (2022). This method employs rasters of temporal trends (°C yr^{-1}) and spatial gradients (°C km^{-1}) for the period of 2015-2100. This calculation was run for all 24 statistically downscaled climate simulations from CMIP5 and averaged for each watershed, for each RCP (2.6, 4.5, 8.5). The resulting average velocities were standardized to a scale of 0-1 as follows (Boyce et al. 2022):

$$E\ TVoCCw = 1 - e^{-\lambda VoCC\ w} ,$$

Equation 4

, where TVoCCw is the warming velocity in watershed w, until 2100, and λ is the rate parameter, set at 0.02, relative to rates of warming seen globally (Boyce et al. 2022).

2.5.2 E2-Magnitude of precipitation change

While, in eastern Canada, total annual precipitation is expected to increase slightly, the variability of precipitation (extreme precipitation events followed by periods of drought) is expected to increase more drastically (Pendergrass et al. 2017). Magnitude of precipitation change was calculated by converting total daily precipitation projections from 2015-2100 to units of absolute standard deviation relative to the average daily totals for the 1980-2021 period. These calculations were run for each RCP scenario (2.6, 4.5, 8,5). The occurrence of days greater than one absolute standard deviation from the historical mean were then summed, and divided by 365 days in the year. This resulted in the projected proportion of days per year from 2015-2100 that would exceed one standard deviation from the historical mean, and therefore be considered a precipitation or drought extreme. The index value was the average of the extreme day proportions from 2015-2100. Precipitation extreme events could result in flooding, causing increased runoff levels and habitat modification (Stuefer et al. 2017). Periods of drought can decrease riparian habitat, leading to habitat destruction and species displacement (Stuefer et al. 2017).

2.5.3 E3-Projected time of thermal niche emergence

The projected time of thermal niche emergence (ToE) index calculates when a species in each watershed will face exposure to temperatures above their upper thermal tolerance limit for an extended period (Trisos et al. 2020; Xu et al. 2020). ToEs were estimated as the year in which the projected monthly mean air temperature (-3°C to estimate water temperature) will exceed the species upper thermal tolerance (average of sub-lethal and maximum lethal tolerance limits) for at least two consecutive years. The time scale of two consecutive years was chosen based on Atlantic salmon life cycle relevance after consultation with managers and experts, and potential for disruption based on sexual maturation and generation length. If a species was not projected to reach their thermal maxima by 2100, the ToE was set to 2101, a year after the maximum time frame in this assessment. These calculations were run for each RCP scenario (2.6, 4.5, 8.5). The ToE estimated years were then represented as the number of years after 2020, and standardized to a scale of 0-1 as follows (Boyce et al. 2022):

$$E\ ToEs,w \ = \ e^{-\lambda ToEs,w} \ ,$$

Equation 5

, where ToE s,w is the projected time of emergence for species, s, in watershed, w, and λ, is set as the rate parameter (0.033) (Boyce et al. 2022).

2.5.4 E4-Projected habitat loss

The projected habitat loss index is directly correlated with the ToE index. Habitat loss was calculated as a binary value, where 0 indicates that a species will be at risk of extirpation by 2100, and 1 represents that a species will not be at risk of extirpation by 2100. This index offers an accessible visualization of climatic risk for each species, in each watershed, across each RCP scenario (2.6, 4.5, 8.5). No standardization calculations were needed for this index.

2.6 Adaptive capacity component calculations

The adaptive capacity component quantifies the ability of a species to physiologically adapt or behaviourally respond to changing environmental stressors (Field et al. 2014). Many of the indices included in the marine CRIB adaptive capacity component were not applicable to the freshwater ecosystem due to reduced interconnectivity of habitat and differences in water column usage (Boyce et al. 2022). For example, the marine CRIB used geographic range extent as an index, referring to the total area and latitude spanned by a species. Highly distributed species are likely to have a suitable habitat within their geographic range, and therefore are more able to adapt to changing conditions (Boyce et al. 2022). As this study assumes watershed fidelity, geographic range extent was adapted to geographic area, which instead used the amount of wet area available to a species in a watershed as an index of adaptive capacity. Additionally, the marine CRIB used geographic habitat fragmentation as an index to refer to the number of distinct isolated habitat patches that a species occupies, where more fragmentation indicates lower adaptivity (Boyce et al. 2022). Habitat fragmentation is not an applicable index in the FW-CRIB, as we assume watershed fidelity where the entire watershed is assumed to be appropriate habitat. This index was adapted in the FW-CRIB to “barriers to connectivity”, which quantifies the density of dams, road crossings, and other aquatic barriers, weighted by passability, in each watershed. For the purpose of these methods, an adaptive capacity component score of one indicates poor adaptivity, and can be defined as maladaptivity.

2.6.1 AC1-Geographic area availability

The available wet area to a species determines the ability of a watershed to support larger populations, indicating stronger resilience to climate change and giving populations the ability to shift in distribution. The geographic area index used the NCC network length layer (km), and scaled watershed-specific lengths to a value of 0-1 by dividing the values by the total network length across the study area (sum of network lengths in km across all three provinces, totalling 64 watersheds). From this standardization method, a geographic area score of one indicates abundant wet area, and therefore a higher adaptivity capacity score, to ensure that index values of one were indicative of lower adaptive capacity. Values were then subtracted from one to make a geographic area score of zero indicate a watershed with abundant wet area.

2.6.2 AC2-Thermal habitat variability

The thermal habitat variability index was calculated following the methods found in Boyce et al. (2022). Species which inhabit a variable thermal habitat are thought to have a greater capacity to tolerate temperature changes, decreasing their sensitivity to climate change, and in turn, affording them a higher adaptive capacity. This index was composed of two parts - the range of average temperatures (°C) experienced in the watershed (1983-2023), and the proportion of average daily temperatures in which a species occupied that range over the same period. The two sub-indices were standardized to a scale of 0-1 using the following equations (Boyce et al. 2022):

$$AC\ TRanges, w\ =\ \frac{max(T) - min(T)}{90},$$

Equation 6

, where $Trange_{s,w}$ is the historic (1983-2023) temperature range in which a species inhabits in each watershed, and T represents the raw historic temperature data -3°C (Boyce et al. 2022).

$$AC\ SProps, w = e^{\frac{4Prop}{e^4}},$$

Equation 7

, where $SProp_{s,w}$ is the proportion of time a species spent in their temperature niche in each watershed historically, and Prop is the number of days in a watershed within each year that fell within the species' thermal niche (defined by upper and lower tolerance limits, averaged between sub-lethal and maximum lethal) over the same time period (Boyce et al. 2022). These two values were then averaged to derive the historical thermal habitat variability index for each species-watershed pair.

2.6.3 AC3-Barriers to connectivity

A well-connected watershed supports shifting distributions of species and populations, therefore increasing the ability of a species to adapt to climate change. To characterize this connectivity within a watershed, the FW-CRIB adapted the habitat fragmentation index from the marine CRIB (Boyce et al. 2022) into an index relevant to the freshwater environment. We considered multiple layers of spatial data constructed by NCC (Noseworthy and Nussey 2020), including road crossings (roads intersecting with rivers, with no bridge present), dams, dykes, and other aquatic barriers. These barriers were then weighted by passability, based on scores from the CABD, where a score of one represents an impassable barrier (e.g. dam with no fishway), two is a partially passable barrier (e.g. dam with a fishway), and three is a passable barrier (e.g. abandoned or removed dam).

These scores were then translated to upweight impassable barriers, and downweight passable ones. This was done by keeping impassable barriers as a score of one, changing partially passable from a score of two to a score of 0.75, and changing passable from a score of three to a score of 0.1. These modified passability scores were then overlaid with coordinates of occurrence of aquatic barriers. The outcome was a value of one for occurrence of a barrier at a given coordinate, multiplied by its corresponding passability score.

Passability weighted occurrences were then compiled for each watershed and scaled by dividing by the total network length of wet area (km) within the watershed. This resulted in a value representing the density of barriers per km, weighted by passability for each watershed. The barriers to connectivity score was then calculated as follows:

$$AC\ BCw = \frac{1}{1 + e^{-\left(\frac{10}{x-0.15}\right)(x-0.15)}},$$

Equation 8

, where AC BC_w is the barriers to connectivity score for watershed w, and x is the passability weighted density for watershed w.

2.6.4 AC4-Maximum body length

Maximum body length is commonly used as a proxy for life history traits, such as generation time, time to maturity, population growth rate, and fecundity. These life history traits determine a species' ability and speed at which they can adapt and evolve to changing conditions (Romanuk et al. 2011; Chessman 2013; Foden et al. 2019). In general, species with smaller body lengths have shorter generation times and exhibit r-selected reproductive patterns, allowing them quicker adaptation and evolution times. A standardized index of maximum body length, adapted from Boyce et al. (2022) was calculated as follows:

$$AC\ MLs\ =\ 1\ -\ \frac{log(MLs + 1)}{log(274 + 1)}\ ,$$

Equation 9

, where ML_s is the maximum body length for species s, and 274 (cm) is a scaling factor corresponding to the approximate maximum length of the largest freshwater species in Canada (lake sturgeon (*Acipenser fulvescens*)) (Page and Burr 1991).

2.7 Overall vulnerability calculations

To calculate exposure, sensitivity, and adaptive capacity component scores, index scores were averaged. The standard deviations of component level scores were also calculated and used in further calculations. To find the overall vulnerability of each watershed to species pair, the variance-weighted mean of component scores was calculated, as in Boyce et al. (2022):

$$Vw,s\ =\ \frac{(Ew,s \cdot wEw,s) + (Sw,s \cdot wSw,s) + ((1 - ACw,s) \cdot wACw,s)}{wEw,s + wSw,s + wACw,s}\ ,$$

Equation 10

, where Ew,s, Sw,s, and ACw,s are the final vulnerability scores of the exposure, sensitivity, and adaptive capacity components, respectively, calculated as the mean of their constituent indices, and wEw,s, wSw,s, and wAC,w,s, are the reliability weights of component scores, calculated as follows (Boyce et al. 2022):

$$wCw,s\ =(\frac{\sigma Cw,s}{Cw,s})^{-1}\ ,$$

Equation 11

, where $wC_{w,s}$ is the reliability weight of the exposure, sensitivity, and adaptive capacity component scores, $\sigma C_{w,s}$ is the standard deviation of the component's index scores, and $C_{w,s}$ is the mean of the component's constituent index scores. This weighted approach ensures that components with highly variable index scores had less influence when contributing to the final vulnerability score. Finally, for each freshwater species, an overall vulnerability score across all watersheds was calculated as the mean of all watershed-specific vulnerability scores for that species.

2.8 Transformations to risk

To transform vulnerability scores of 0-1 to risk levels of low, medium, high, or critical, the CCRA was conducted. The CCRA transformations for indices in common with Boyce et al.'s (2022) thresholds were maintained, based on rationales as described in their paper. For adapted or added indices, literature reviews were performed to find low (little to no ecosystem degradation occurs with extinction and extirpation unlikely), medium (reversible ecosystem degradation occurs with extinction and extirpation likely), and high (irreversible ecosystem degradation occurs with extinction and extirpation imminent) thresholds (Table 3).

Table 3 Thresholds for each index included in this study and rationale for selection.

Dimension	Index	Included Parameters	T_{low}	T_{med}	T_{high}	Rationale	Global Maximum	Units
Sensitivity	Thermal Safety Margin	NA	5	2	1	Boyce et al. 2022	NA	°C
Sensitivity	Conservation Status	NA	Secure	Secure	V, T, En	COSEWIC	NA	NA
Sensitivity	Cumulative Impacts	% Clearcut	10	30	50	de Graaf 2009; Hinz et al. 2020; Peacock et al. 2023 (threshold); Global Forest Watch 2023 (global max)	41	%
		% Agriculture	10	30	50	de Graaf 2009; Peacock et al. 2023 (threshold); Hinz et al. 2020(global max)	100	%
		Non-Native Species	0	0.3	0.6	Leprieur et al. 2008	2	Species / km^2
		% Impervious Surfaces	1	10	25	Elvidge et al. 2007 (threshold); Lang et al. 2019 (global max)	20	%
		Acid	200	400	1200	Forsius et al. 2021 (Critical Load Exceedance); Tao and Feng 2000)(global max)	3250	eq/ha/yr
Sensitivity	Ecosystem Disruption	NA	5	10	20	Boyce et al. 2022	NA	%
Adaptive Capacity	Geographic Area	NA	0.04	1	4	Boyce et al. 2022	NA	%
Adaptive Capacity	Thermal Variability	NA	5	10	15	Boyce et al. 2022	NA	°C
Adaptive Capacity	Barriers to connectivity	NA	80	90	99	Inverse of Boyce et al. 2022 fragmentation	NA	%
Adaptive Capacity	Maximum Body Length	NA	100	30	10	Boyce et al. 2022	NA	cm
Exposure	Climate Change Velocity	NA	6	15	30	Boyce et al. 2022	NA	Km / yr^{-1}
Exposure	Magnitude of Precipitation Change	NA	0.25	0.50	0.75	NA	NA	Proportion of days / Year
Exposure	Thermal Niche Emergence	NA	75	50	25	Boyce et al. 2022	NA	Years
Exposure	Projected Loss of Habitat	NA	5	10	20	Boyce et al. 2022	NA	%

To define risk within the sensitivity component, the following methods were used. The thermal safety margin index, low, medium, and high thresholds were taken from Boyce et al. (2022), defined as 1°C, 2°C, and 5°C, respectively, guided by observed and projected rates of global surface warming. Ecosystem disruption thresholds were set at 5, 10, and 20% for low, medium, and high, as defined in Boyce et al. (2022). Conservation status thresholds were defined as 0 (secure), 0.25 (candidate species for assessment), and 0.5 (special concern), for low, medium, and high levels, respectively. The watershed health index differed from the cumulative impacts index in Boyce et al. (2022), and therefore risk thresholds were defined in this study. Percentage land usage of impervious surfaces and agriculture were then linearly modeled against WSHI scores to produce a regression equation. The thresholds found in the literature (Table 3) were then included in these equations, and the output WSHI scores were averaged to find low, medium, and high WSHI thresholds (0.187, 0.278, 0.307, respectively) (Figure 4).

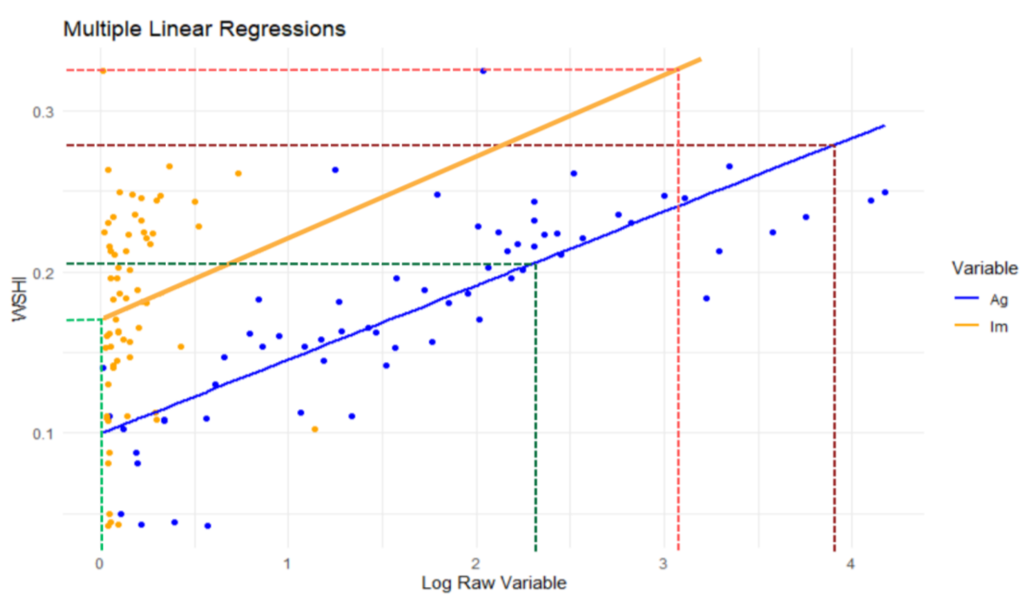


Figure 4 Linear regression lines for percentage of agriculture and impervious surfaces in relation to WSHI scores. Green lines indicate low risk thresholds as found in the literature, red lines indicate high risk thresholds as found in the literature.

Exposure component risk thresholds were defined as follows. The climate change velocity index low, medium, and high risk thresholds were set at 6, 15, and 30 km/yr^{-1} respectively, following Boyce et al.'s (2022) methods (Table 3). Magnitude of precipitation change's risk thresholds were set as 25, 50, and 75% for low, medium, and high risk, respectively, and are represented as a proportion of extreme days within a year (Table 3). Time of thermal emergence threshold definitions followed those set in Boyce et al. (2022), at 75, 50, and 25 years, for low, medium, and high risk, respectively (Table 3). The habitat loss risk thresholds were set at 5, 10, and 20% for low, medium, and high risk, respectively, according to Boyce et al.'s (2022) methods (Table 3).

The adaptive capacity component risk thresholds were largely unique to the FW-CRIB, and were calculated as follows. The geographic area index low, medium, and high thresholds were set at 0.99, 0.89, and 0.017, respectively. These were calculated by dividing the smallest watershed's total network length (km) (Missaguash, ~79 km) by the largest watershed's total network length (km) (Saint John River Basin, ~63,960 km) to determine the high risk threshold, taking the median network length (km) and dividing by the largest watershed's total network length (km) for the medium risk threshold, and setting the low risk threshold to one. The thermal habitat variability risk thresholds were defined through two metrics. The percentage of time a species occupies an area was set to 8, 95, and 99% for low, medium, and high risk levels, respectively, according to Boyce et al. (2022), which were guided by the quantiles of statistical distribution. The second metric was the thermal habitat variability, set at 5, 10, and 15°C, for low, medium, and high risk levels, according to Boyce et al. (2022). The barriers to connectivity index risk thresholds were set by defining a logistic regression curve with an upper asymptote of 1/5 (one impassable barrier per 5 km) and a lower asymptote of 0.5/5 (one partially passable barrier per 5 km). Low, medium, and high thresholds were then set at 0.019, 0.5, and 0.981, respectively, based on the weighted density of barriers per km of river score's inflection points from the logistic regression output (Figure 5). The maximum body length index thresholds were set at 100, 30, and 10 cm, according to Boyce et al. (2022), guided by the intrinsic rate of population increase.

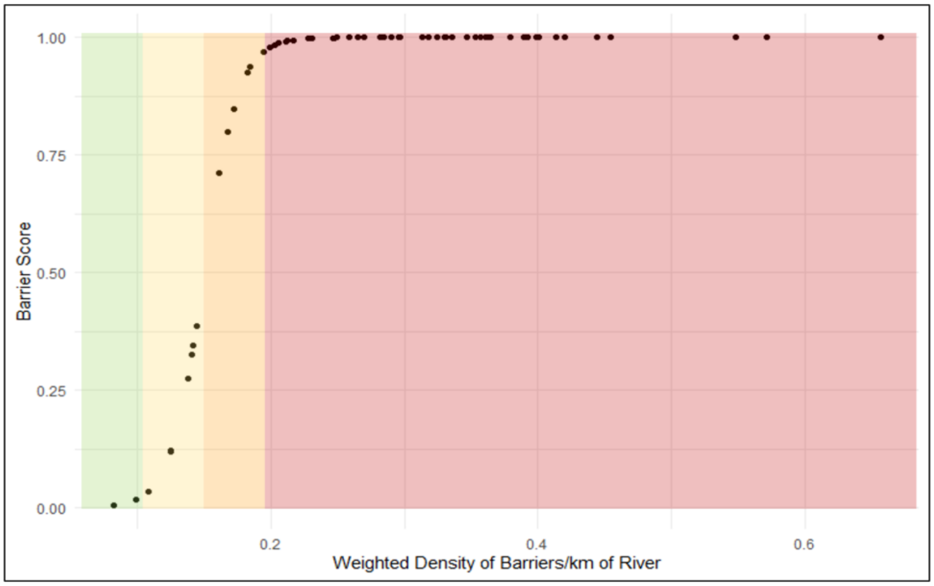


Figure 5 Barriers to connectivity index score plotted against the weighted density of barriers per km of river logistic regression outputs. Green indicates low risk, yellow is medium, orange is high, and red is critical.

Once defined, threshold values were calculated using their respective equations to determine vulnerability scores. The risk thresholds formatted as vulnerability scores were then compared against their respective index vulnerability scores, and each watershed-species pair was then given a value of low (0 to low risk threshold), medium (low risk threshold to medium risk threshold), high (medium risk threshold to high risk threshold), or critical (high risk threshold to 1) levels.

All analyses were conducted using R statistical software, version 3.4.1, using the following packages: sf, dplyr, plyr, VoCC, devtools, raster, mcdf4, tidyverse, ggplot2, scales, rnaturalearth, ggpsatial, viridis, ggsflabel, cowplot, RColorBrewer, and patchwork. All code will be available on GitHub. Minor edits to code will need to be implemented for further iterations on other study areas.

Chapter 3. Results

In the following subsections, each species' index, component, and vulnerability scores (and associated risk categories) are provided in map format (e.g., see Figure 1 map of watersheds) for each of three representative concentration pathways: RCP2.6, RCP4.5, and RCP8.5, representing low, medium, and high emissions scenarios/ climate futures, respectively. Provision of the results in this format will allow managers to identify not only the most and least vulnerable (and highest and lowest risk) watersheds, but also the indices and components responsible for that vulnerability/risk. Additionally, evaluation of vulnerability and risk under the different emission scenarios provides a broader view of potential futures (dependent on government- and industry-driven mitigation strategies) for the species and areas assessed.

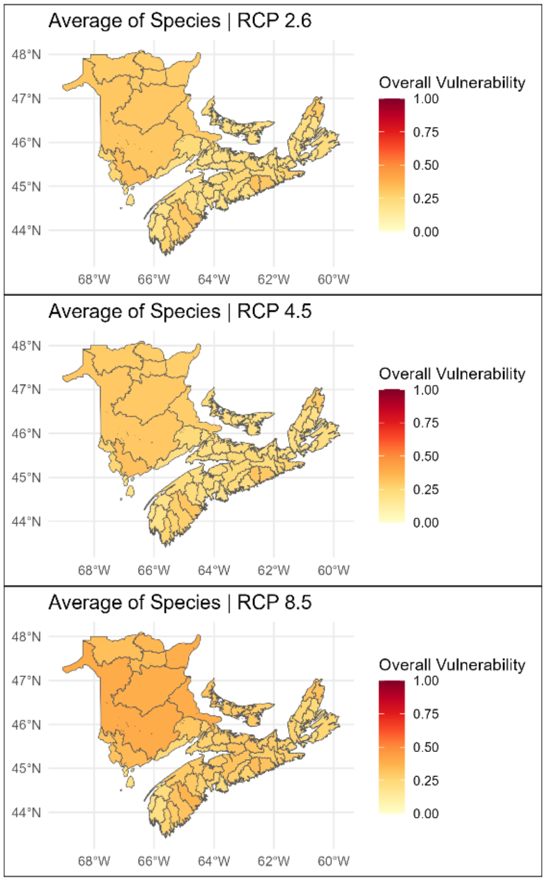
These results provide a broad estimation of species climate vulnerabilities and species/watershed-specific indices of sensitivity, exposure, and adaptive capacity given the climate projections available (for near-surface air temperature). Due to the nature of freshwater data availability, water temperatures were unable to be acquired and used in this study, and instead, near-surface air temperatures were adapted (as discussed in section 2.4.1). An index not included in this study with proven ecological importance to the adaptive capacity of a population is groundwater inclusion.

3.1 Summary of results

3.1.1 Ecosystem-level

3.1.1.1 Overall vulnerability and risk levels

Final overall vulnerability scores are presented in map format in Figure 6. Maps are shaded from 0-1 according to vulnerability scores, calculated by combining sensitivity, exposure, and adaptive capacity component scores (described in Section 2.7). The highest ecosystem level vulnerability is found within the Saint John River Basin, under RCP 8.5, with a score of 0.399 (Figure 6). Lowest overall vulnerability scores were found in the Isle Madame watershed under RCP 4.5, with a score of 0.183 (Figure 6). Scores were then translated to risk levels as described in Section 2.8 and presented in Figure 5. Select New Brunswick watersheds presented high risk levels under RCP 8.5, whereas the remaining watersheds in the study area presented medium risk levels (Figure 7). When we remove the spatial component of the vulnerability and risk analyses, all species are within the medium risk level across all RCPs (Figure 8). This result demonstrates the importance of being spatially explicit in these assessments.



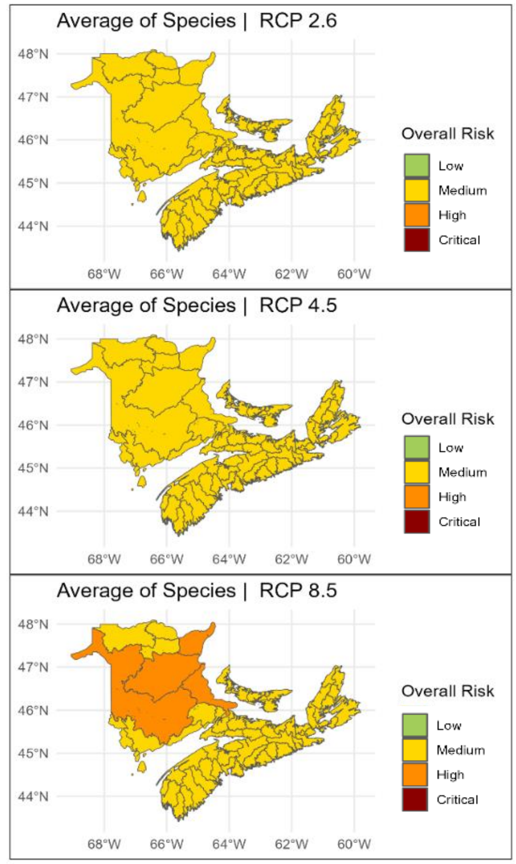


Figure 6 Map of study area coloured by overall vulnerability scores from 0-1, averaged across species for each watershed under three different RCP models (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

Figure 7 Map of study area coloured by ecosystem-level risk scores, averaged across species, for each watershed, under three RCPs (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

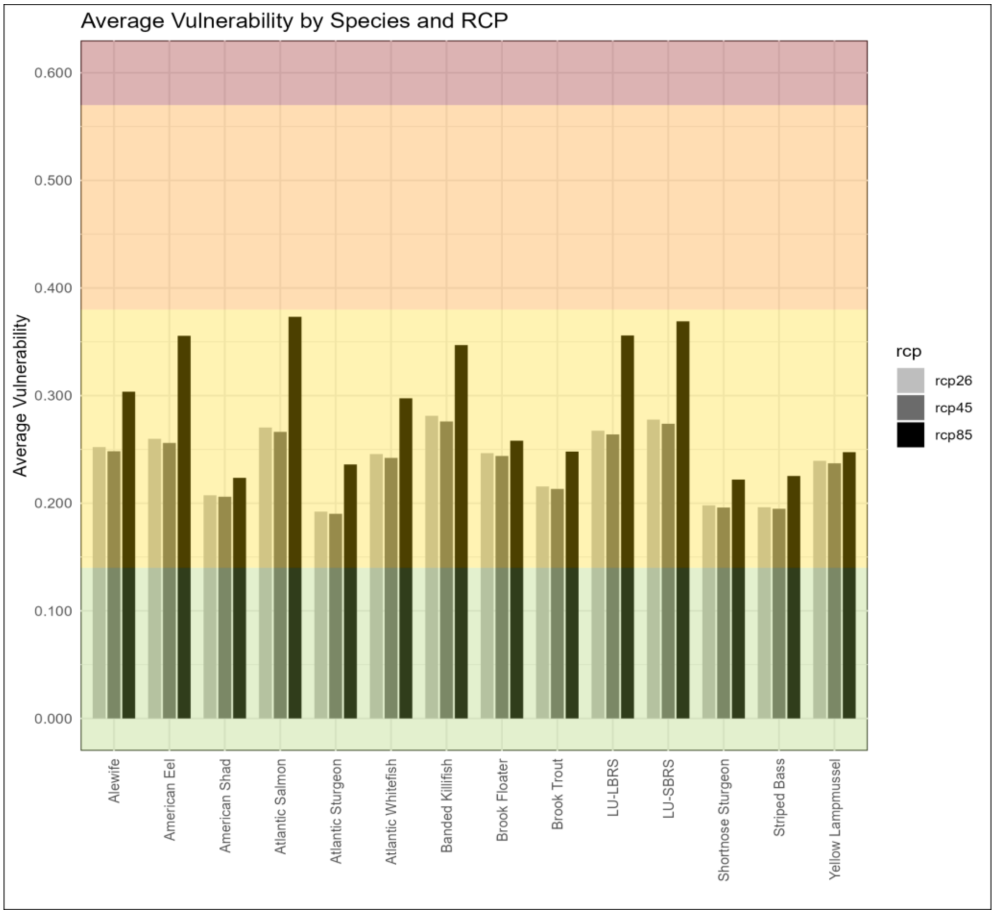


Figure 8 Vulnerability scores for species and RCPs, averaged across watersheds. Background colouring indicates associated risk levels (green = low, yellow = medium, orange = high, red = critical).

3.1.1.2 Sensitivity component

Sensitivity component scores (the average across four indices) are presented in map format in Figure 9. Indices included in the sensitivity component calculation include thermal safety margin, ecosystem disruption, population status, and WSHI. The sensitivity component describes the environmental stressors that populations are currently exposed to. The highest sensitivity component score is seen in the Acadian Peninsula Composite watershed, under RCP 8.5, with a score of 0.465, when compared to an average of 0.260 across all watersheds and

RCPs (Figure 9). The lowest sensitivity component score was found in the Barrington/Clyde watershed, under RCP 2.6, with a score of 0.108 (Figure 9).

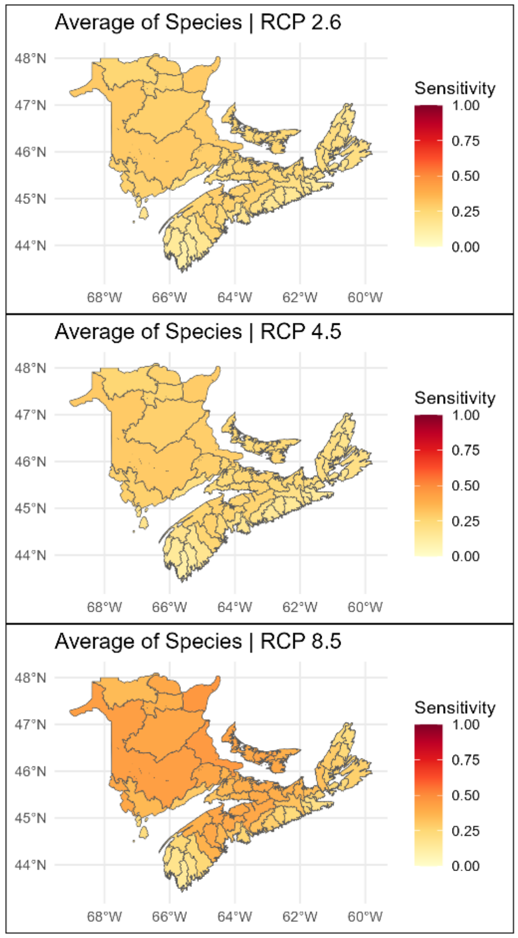


Figure 9 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by sensitivity component scores from 0-1 for each RCP (2.6, 4.5, and 8.5).

3.1.1.2.1 S2-Ecosystem disruption index

The watershed specific ecosystem disruption index saw a rapid increase in vulnerability under RCP 8.5 relative to 2.6 or 4.5 (Figure 10). The highest vulnerability watershed was the Acadian Peninsula Composite under RCP 8.5, with a score of 0.643, which aligns with the overall sensitivity component's highest vulnerability score (Figure 9). The lowest ecosystem disruption score was found in the Acadian Peninsula Composite as well, under RCP 2.6, with a score of 0 (Figure 10), however many watersheds shared a score of 0 under RCPs 2.6 and 4.5. With the risk transformations, the difference in vulnerability under RCP 8.5 becomes abundantly clear, as almost all watersheds are at critical risk, meaning within these watersheds, more than 20% of the 14 species included within this study are at risk of extirpation by 2100 (Figure 11).

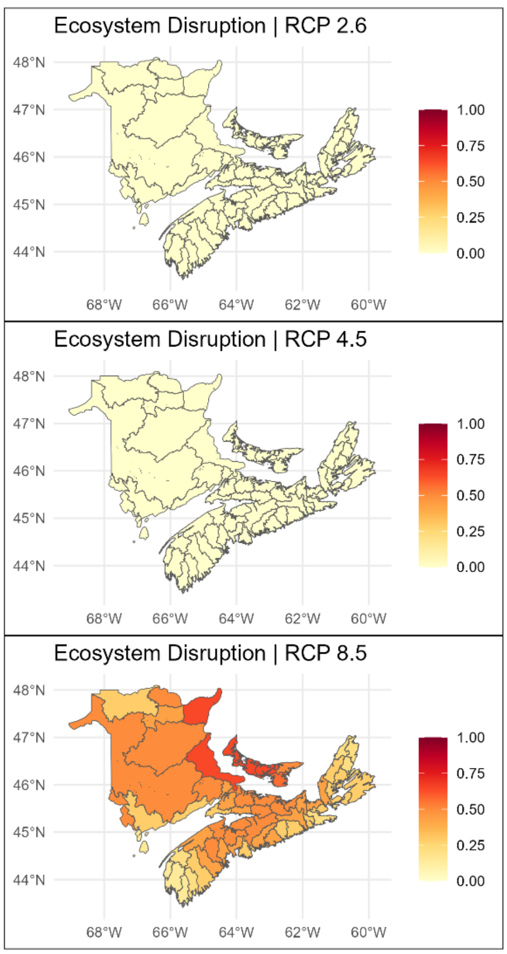


Figure 10 Map of study area coloured by watershed specific, ecosystem disruption index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

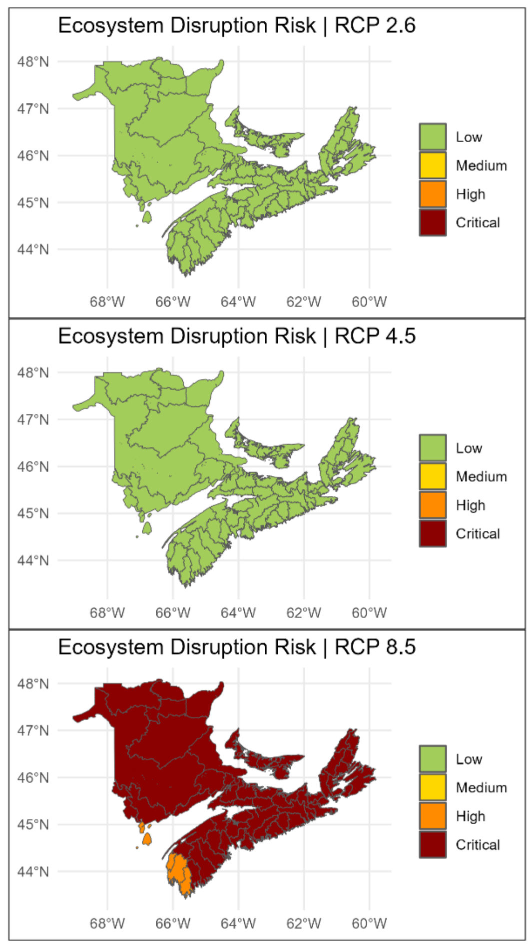


Figure 11 Map of study area coloured by ecosystem disruption index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.2.2 S4-Watershed health index

The watershed health index, comprising percentage of land usage by agriculture, impervious surfaces, and clearcut area, acid deposition, and non-native species data are displayed in Figure 12. These predictor variables were scaled by global maxima, as documented in the literature (Tao and Feng 2000; Leprieur et al. 2008; Lang et al. 2019; Hinz et al. 2020; Global Forest Watch 2023), and resulted in relatively low vulnerability scores for Eastern Canada. These methods were maintained for applicability to global scenarios, and colouring to increase visibility in Figure 13 was changed from 0-1, to 0-0.3 (local maximum). Currently, the only watershed above the medium risk level is the Lahave watershed (Figure 14).

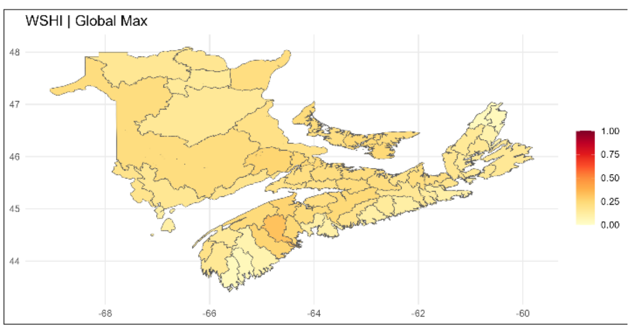


Figure 12 Map of study area coloured by WSHI scores from 0-1, as scaled by global maxima; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

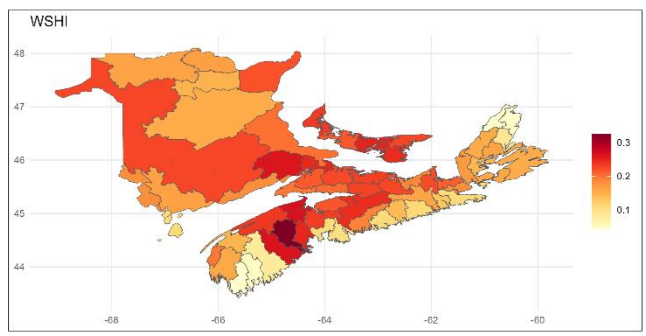


Figure 13 Map of study area coloured by WSHI scores from 0-0.3, as scaled by local maxima, to increase visibility; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

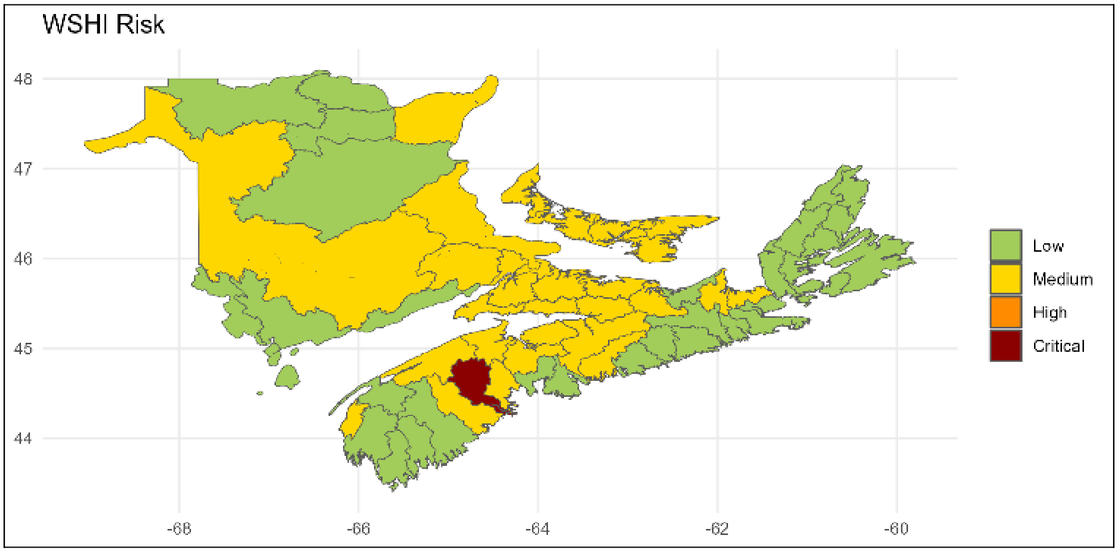


Figure 14 Map of study area coloured by WSHI risk levels; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.3 Exposure component

Exposure component results (the average across four indices) are presented in map format in Figure 15. Indices included in the exposure component calculation include climate change velocity, magnitude of precipitation variance, projected time of emergence, and habitat loss by 2100. The exposure component describes the environmental stressors that populations are projected to be exposed to. The exposure component largely comprises indices in which climate models were used. The highest exposure component score is seen in the Western Prince Edward Island watershed, under RCP 8.5, with a score of 0.296, when compared to an average of 0.126 for other watershed's exposure component scores (Figure 15). The lowest exposure component score was found in the East/Indian watershed under RCP 2.6, with a score of 0.08 (Figure 15).

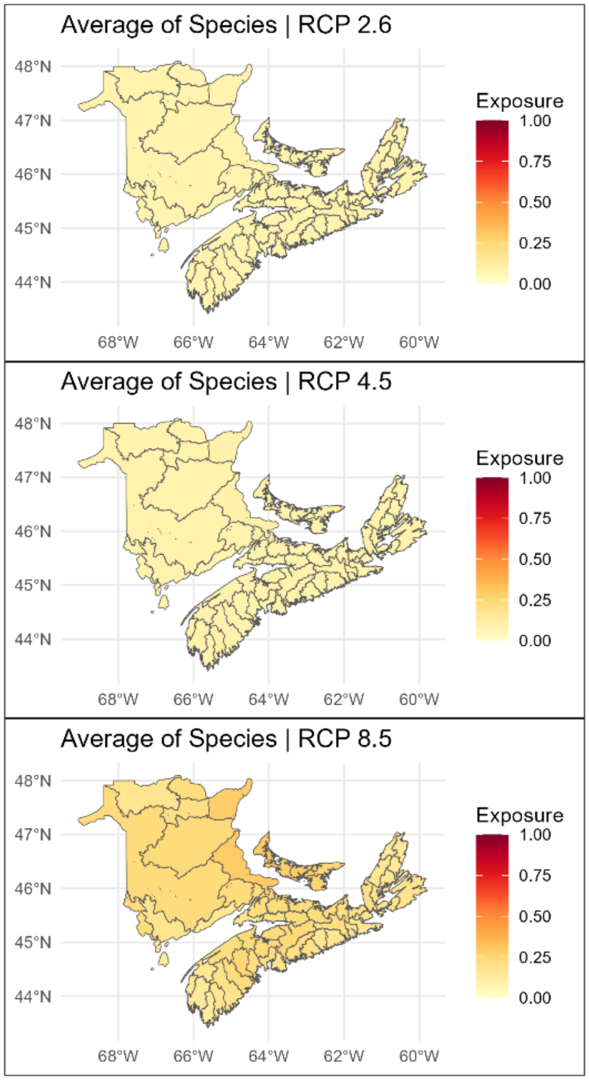


Figure 15 Map of study area coloured by exposure component scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.3.1 E1-Climate change velocity

The climate change velocity index was found to be consistently low risk across watersheds and RCPs. Figure 16 displays the index score results on a scale of 0-1, showing little variation in scores. The maximum climate change velocity score was found in the Isle Madame watershed under RCP 8.5, with a score of 0.245 when compared to an average of 0.039 across all watersheds and RCPs (Figure 16). The lowest climate change velocity score was found in the

Economy watershed under RCP 2.6, with a score of 0 (Figure 16). To allow for easier visualization of differing scores across watersheds, Figure 17 shades by local maxima under each RCP. All watersheds were translated to low risk under RCPs 2.6 and 4.5, and 11 out of 64 were found to be medium risk under RCP 8.5 (Figure 18).

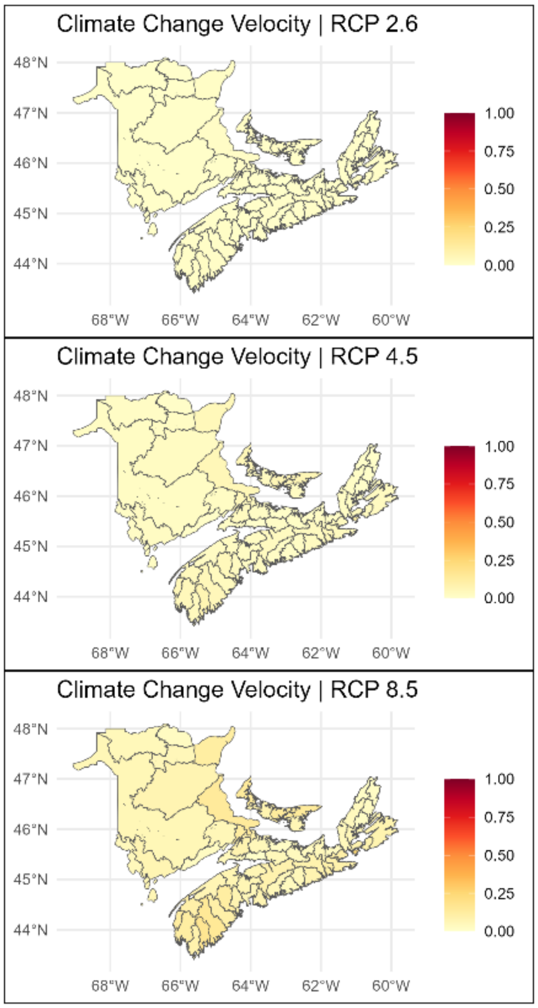


Figure 16 Map of study area coloured by climate change velocity scores from 0-1 for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

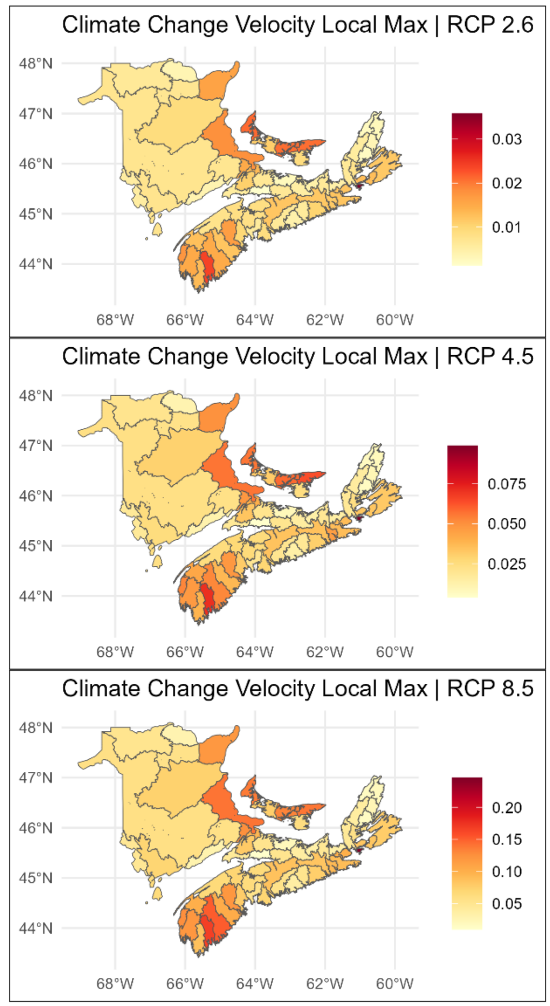


Figure 17 Map of study area coloured by climate change velocity scores from 0-0.3 for each RCP (2.6, 4.5, 8.5), as scaled by local maxima, to increase visibility; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

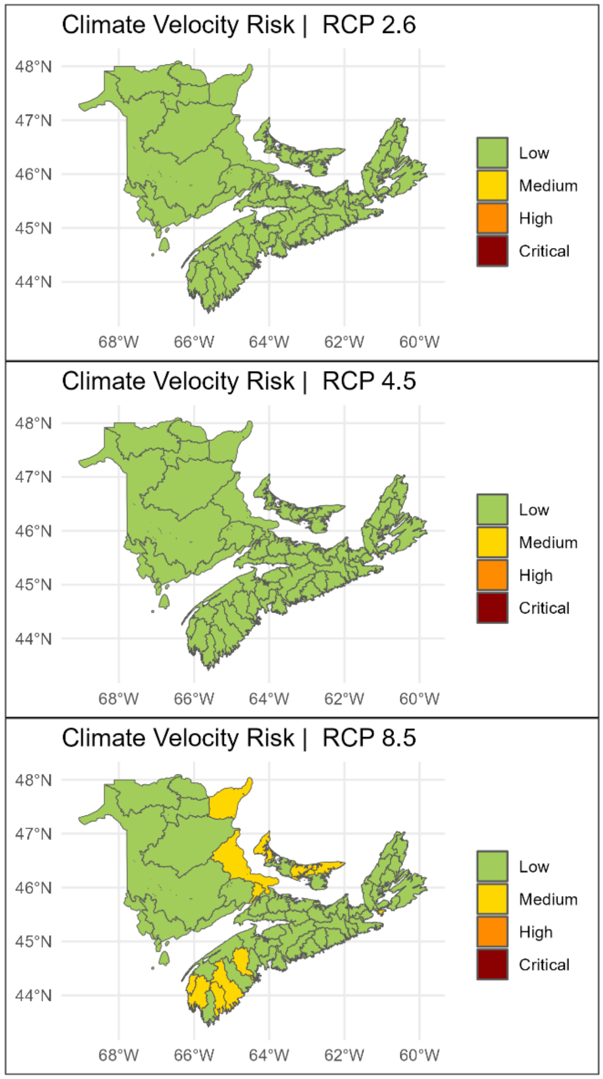


Figure 18 Map of study area coloured by climate change velocity risk levels for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.3.2 E2-Magnitude of precipitation variance

The magnitude of precipitation variance index measured the proportion of days within a year which deviated from one standard deviation of the historical mean, representing precipitation or drought extremes. All watersheds under all RCPs were largely uniform in precipitation patterns, with the highest score being in the Restigouche watershed under RCP 8.5, with a score of 0.132 when compared to an average of 0.114 across all watersheds and RCPs

(Figure 19). The lowest magnitude of precipitation variance score was found in the Sackville watershed under RCP 8.5, with a score of 0.102 (Figure 19). The local maximum is used to shade Figure 20 for ease of visualizing variance between watersheds. This index produced low risk levels for all watersheds across all RCPs (Figure 21).

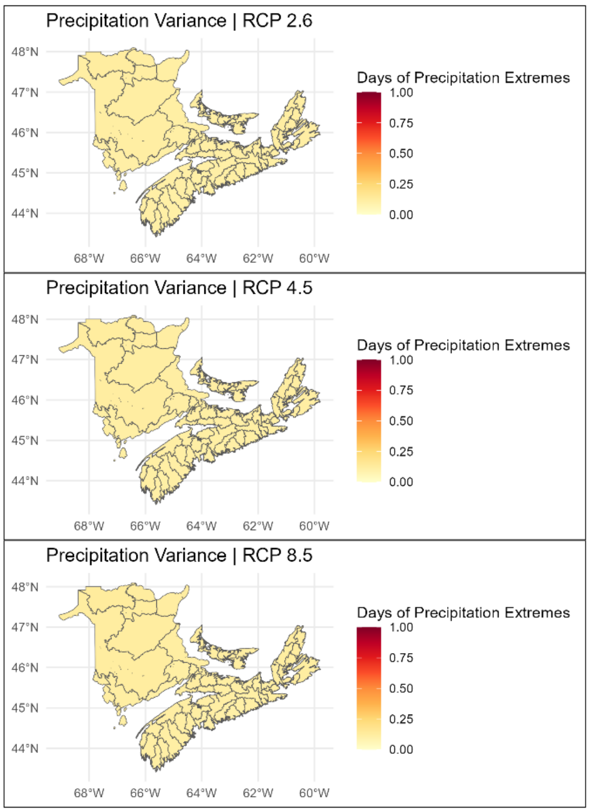


Figure 19 Map of study area coloured by magnitude of variance in precipitation scores from 0-1 for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

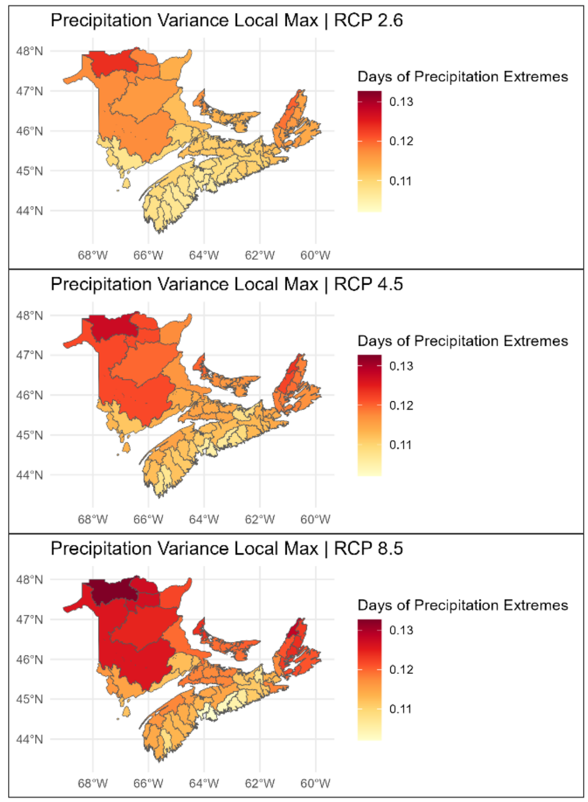


Figure 20 Map of study area coloured by magnitude of variance in precipitation from 0-0.13 for each RCP (2.6, 4.5, 8.5), as scaled by local maxima, to increase visibility; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

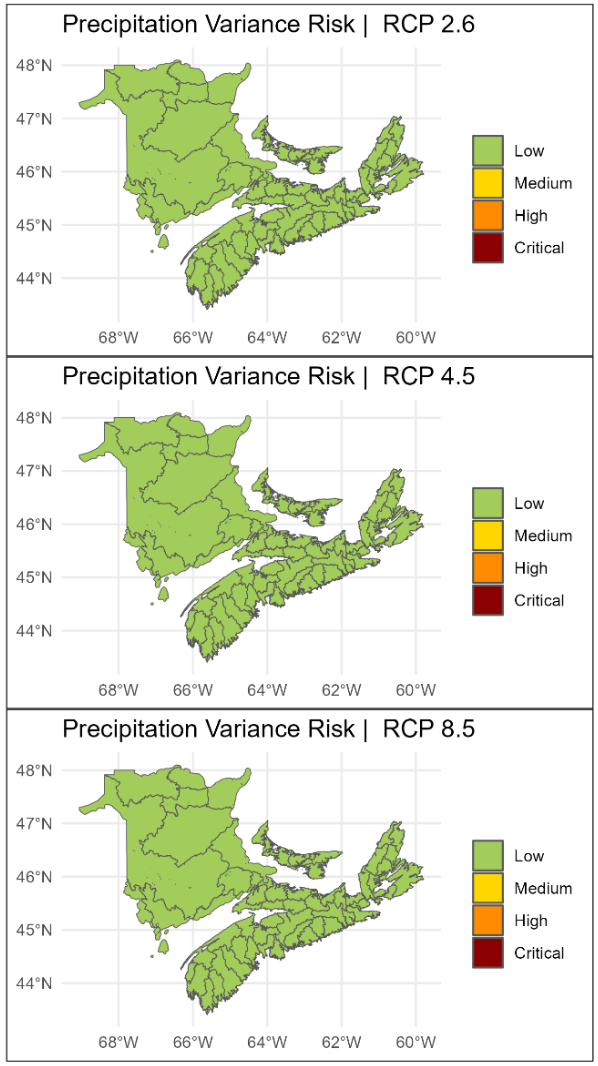


Figure 21 Map of study area coloured by magnitude of precipitation variance risk levels for each RCP (2.6, 4.5, 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.4 Adaptive capacity component

Adaptive capacity component results (the average across four indices), are presented in map format in Figure 22. Indices included in the adaptive capacity component calculation included geographic area, thermal habitat variability, barriers to connectivity, and maximum body length. The adaptive capacity component describes the ability of a species or population in a given area to respond or adapt to current and emerging environmental stressors. The highest adaptive capacity component score was seen in the Missaguash watershed, under RCP 2.6, with a score of 0.772, when compared to an average of 0.691 for other watershed's adaptive capacity component scores across all RCPs (Figure 22). A high adaptive capacity score indicates a lack of adaptive ability and can be referred to as "maladaptivity". The lowest adaptive capacity (indicating a high potential for adaptivity) was found in the Mersey watershed under RCP 4.5, with a score of 0.492 (Figure 22).

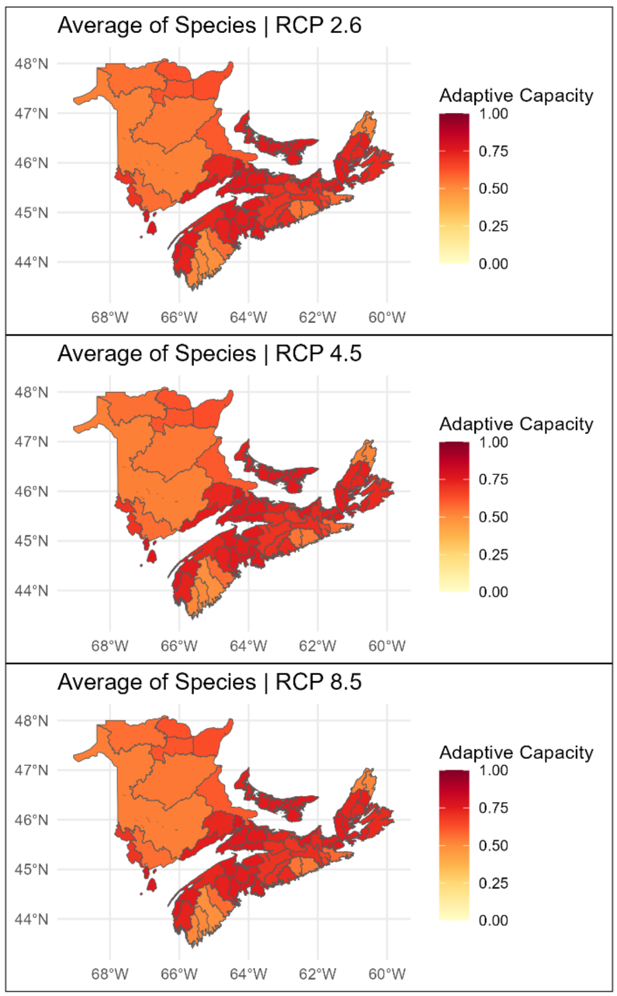


Figure 22 Map of study area coloured by adaptive capacity component scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.4.1 AC1-Geographic area

The geographic area index represents the amount of wet area in a watershed that is available to a species, and vulnerability scores are displayed in Figure 23. This index was scaled by the study area maximum, the Saint John River Basin. These methods were maintained for applicability to local species, but must be modified when being applied to an area outside Eastern Canada. Results from 0-1 for the geographic area index can be seen in Figure 23, where a score of 0 indicates abundant available wet area, and scales directly with watershed size. When translated to risk, the low risk threshold was defined as the largest watershed, the Saint John River Basin, with a score of 0.016 (Figure 23, Figure 24), and the high risk threshold was defined as the smallest watershed in the study area, Missaguash with a score of 0.995 (Figure 23, Figure 24). Due to the scaling of this index, variability within watershed vulnerability scores are high, and as such, are not weighted as significantly in the overall vulnerability calculations.

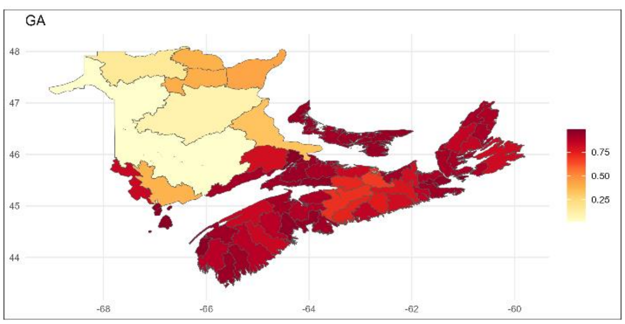


Figure 23 Map of study area coloured by geographic area scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

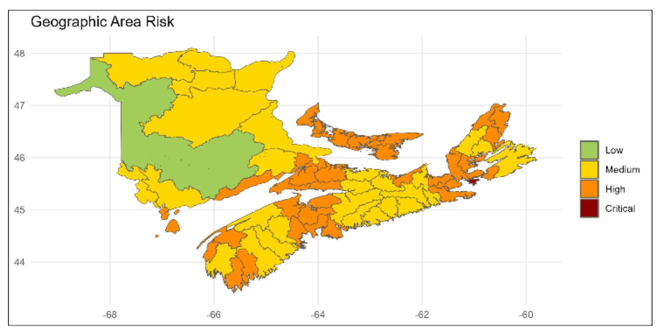


Figure 24 Map of study area coloured by geographic area risk levels; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.1.4.2 AC3-Barriers to connectivity

The barriers to connectivity index displays the density of barriers (km), weighted by passability scores. The calculation of this index does not factor in the swimming ability, resident of still bodies of water status, or river network usage of species, and should incorporate these factors in further iterations of this study. Within the current framework, this index is watershed specific, and the highest index score was found in the Gaspereau watershed, with a score of 1 (Figure 25). The lowest barriers to connectivity score was found in the Mersey watershed, with a value of 0.005 (Figure 25). Figure 26 displays the translation to risk levels, with many watersheds across New Brunswick and Prince Edward Island displaying high risk levels. Two watersheds in Nova Scotia show low risk; the Mersey watershed, and Roseway/Sable/Jordan Figure 26).

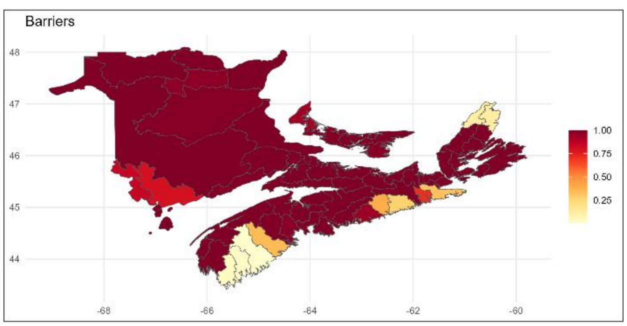


Figure 25 Map of study area coloured by barriers to connectivity index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

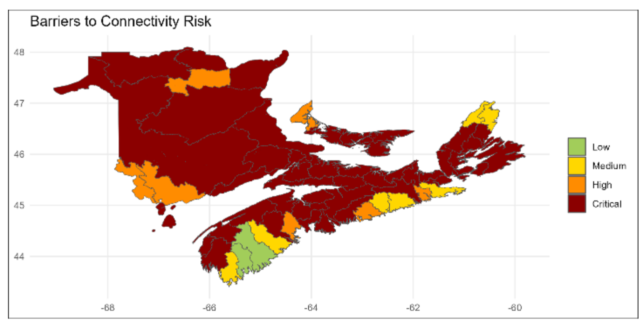


Figure 26 Map of study area coloured by barriers to connectivity index risk levels; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.2 Species-specific results

3.1.2.1 Overall species vulnerability and risk

To present species-specific vulnerability scores and associated risk levels, Atlantic salmon and striped bass will be presented throughout the results section. All 14 species results are included in the Appendices. These two species were chosen to represent the breadth of vulnerability scores, as Atlantic salmon was high risk, and striped bass was generally low risk (Figure 8). Figure 27 shows Atlantic salmon's vulnerability highest in the Saint John River Basin under RCP 8.5, with a score of 0.527. The lowest vulnerability scores for Atlantic salmon were found in the Isle Madame watershed under RCP 2.6 for Atlantic salmon, with a score of 0.125 (Figure 27). These results were then translated to risk levels, with most watersheds in the study area presenting high risk levels for Atlantic salmon under RCP 8.5 (Figure 28). Figure 28 illustrates the increase in risk severity under RCP 2.6 and 4.5 versus under RCP 8.5, as seen in most results across species, indices, and overall results.

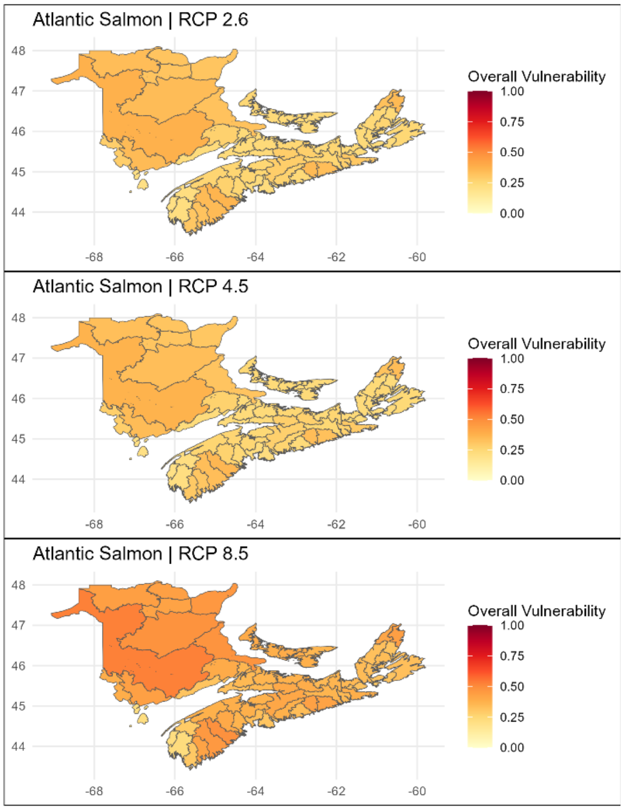


Figure 27 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic salmon (Salmo salar) overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).

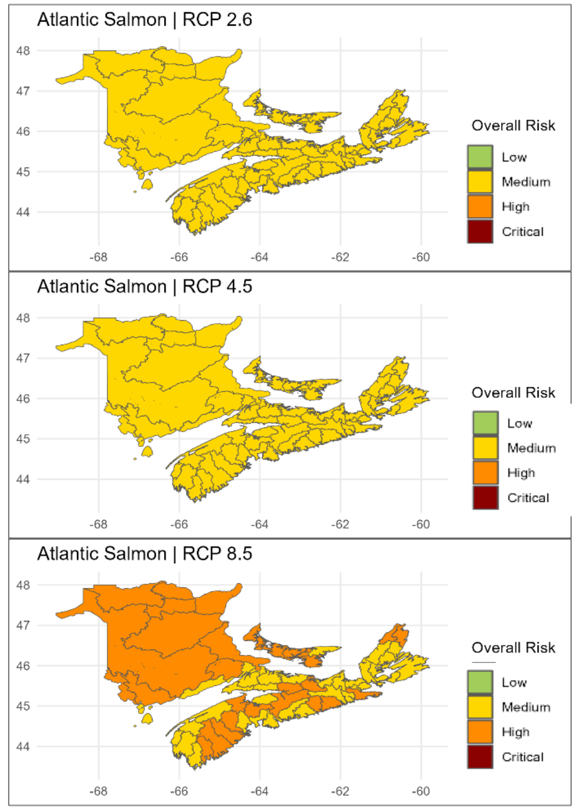


Figure 28 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic salmon (Salmo salar) overall risk levels for each of three RCPs (2.6, 4.5, 8.5).

Striped bass vulnerability results are presented in Figure 29, as an example of a species that is generally low risk to climate change in the study area. The lowest vulnerability scores for striped bass were found in the Isle Madame watershed, under RCP 2.6, with a score of 0.132 (Figure 29). The highest vulnerability scores were found in the Saint John River Basin under RCP 8.5, with a score of 0.350 (Figure 29). Results from risk translation for striped bass presented in Figure 30, with RCP 2.6 and RCP 4.5 maintaining two watersheds with low risk; East/Indian River and Meteghan.

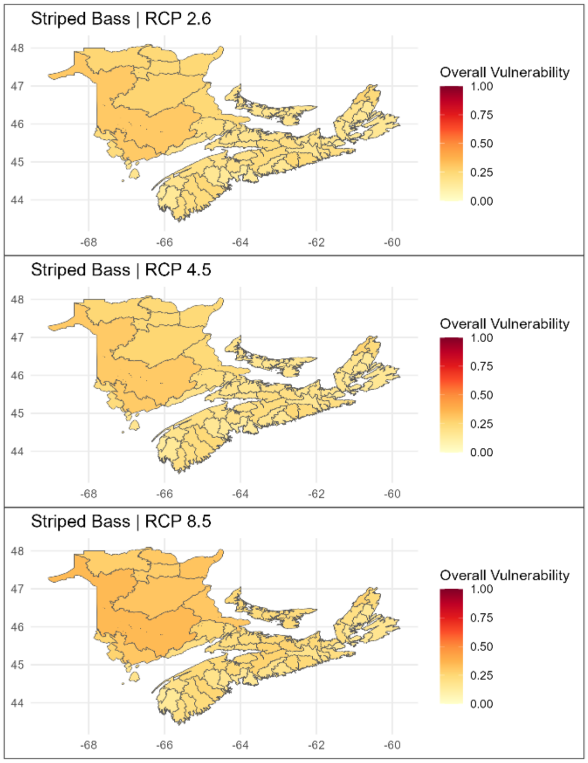


Figure 29 *Map of study area coloured by striped bass (Morone saxatilis) overall vulnerability scores for each watershed across three RCPs (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.*

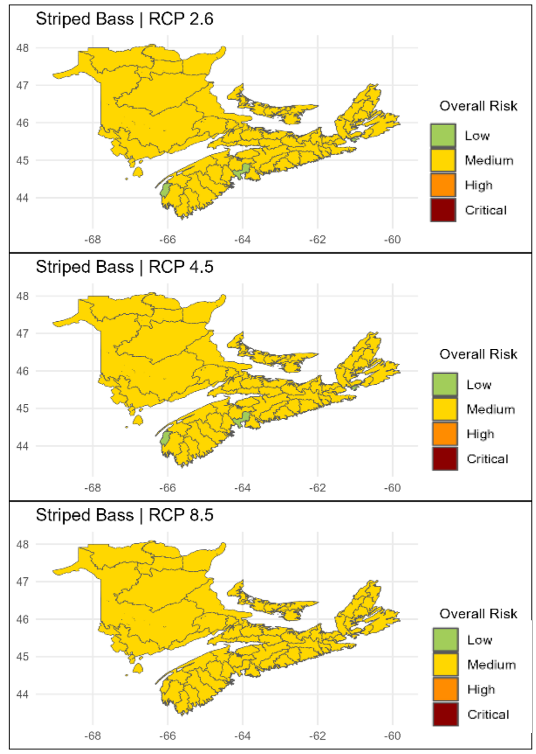


Figure 30 Map of study area coloured by striped bass (Morone saxatilis) overall risk levels for each watershed across three RCPs (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.3.1 S1-Thermal safety margin

Thermal safety margin index results for Atlantic salmon, with scores of 0-1 are presented in Figure 31. Highest salmon scores for the thermal safety margin index were found in the Acadian Peninsula Composite under RCP 2.6, with a score of 1 (Figure 31). The lowest vulnerability score was found in the Barrington/Clyde watershed under RCP 2.6, with a score of 0.322 (Figure 31). This index's vulnerability scores aligned with overall sensitivity component scores, indicating a direct correlation between the two. Thermal safety margin risk levels are presented in Figure 32, with southwest Nova Scotia and Cape Breton watersheds maintaining relatively low risk levels.

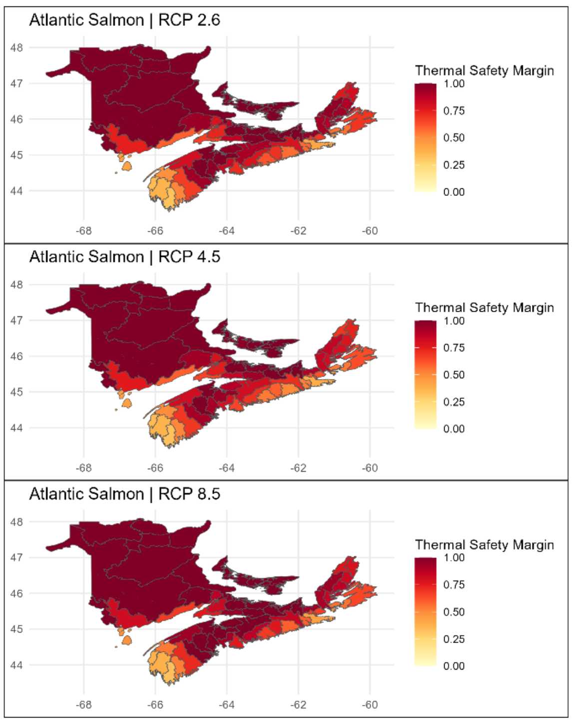


Figure 31 Map of study area coloured by Atlantic salmon (Salmo salar) thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

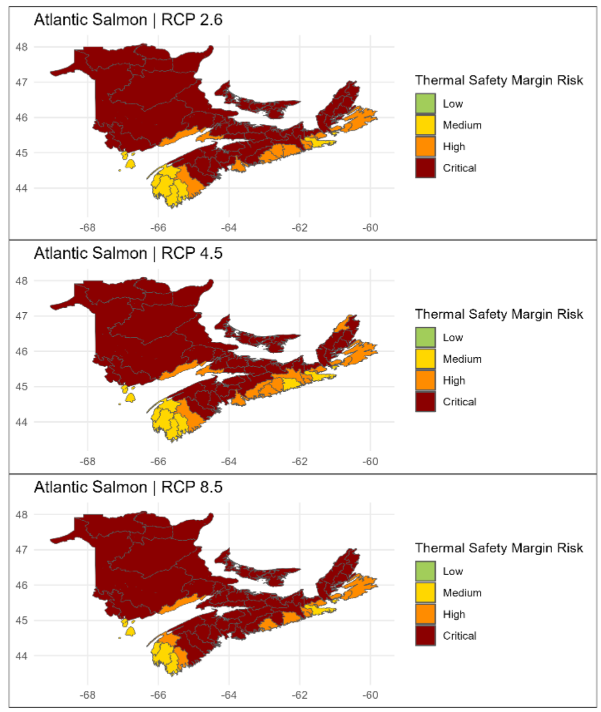


Figure 32 Map of study area coloured by Atlantic salmon (Salmo salar) thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

Striped bass thermal safety margin index scores are presented in Figure 33. All watersheds under all RCPs present relatively low vulnerability scores when compared to those of Atlantic salmon (Figure 33; Figure 31). The lowest thermal safety margin scores for striped bass are found in the Barrington/Clyde watershed under RCP 2.6 with a score of 0.062 (Figure 33). Conversely, the highest scores are found in the Acadian Peninsula Composite under RCP 8.5, with a score of 0.385, which is relatively low when compared to the average across all species (0.476) (Figure 33). Striped bass's low scores are seen when translated to risk levels in Figure 34. New Brunswick watersheds present higher risk levels than other provinces, but do not exceed the high threshold, and therefore remain as medium risk (Figure 34).

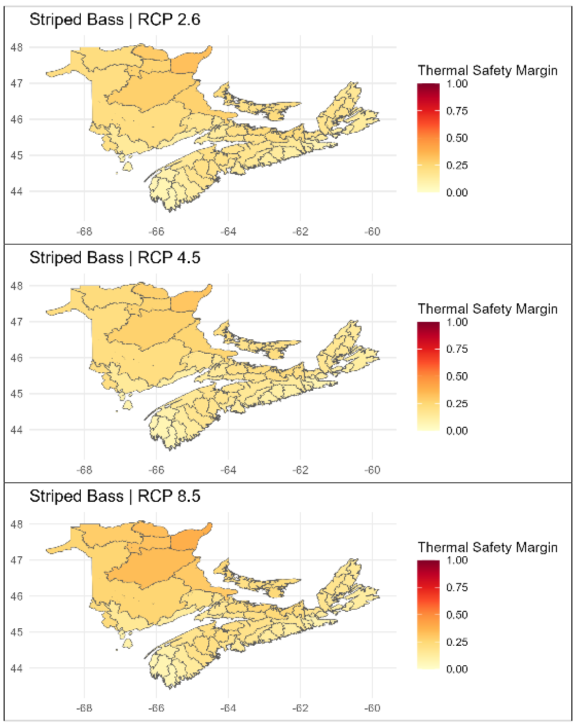


Figure 33 Map of study area coloured by striped bass (Morone saxatilis) thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

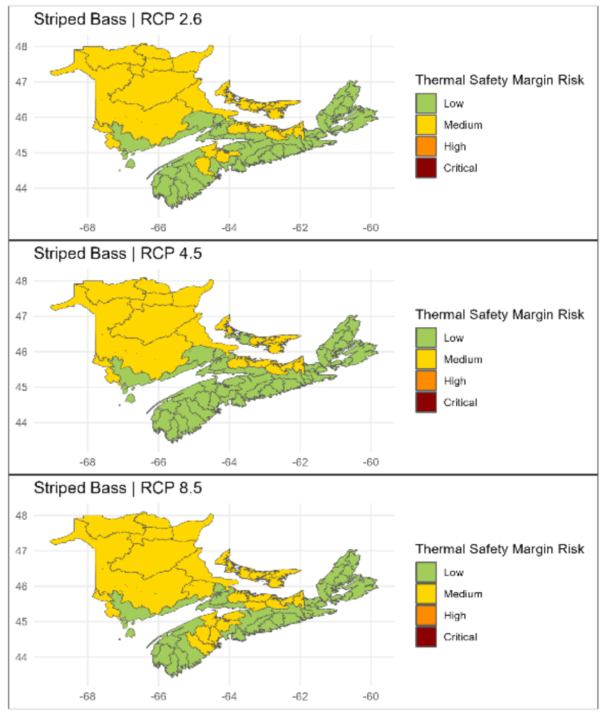


Figure 34 Map of study area coloured by striped bass (Morone saxatilis) thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.3.3 S3-Population status

The population status index qualitatively describes the published health of a population, and its occurrence in an area. Figure 35 displays the Atlantic salmon population statuses, which include five separate populations, each with different assessments (Southern Gulf of St Lawrence, Southern Uplands, Inner Bay of Fundy, Outer Bay of Fundy, and Eastern Cape Breton). Population statuses for striped bass are also differentiated, with two distinct populations that have been assessed separately (Southern Gulf of St Lawrence and Bay of Fundy), however watersheds in which striped bass have not been documented or assessed are shaded grey (Figure 36).

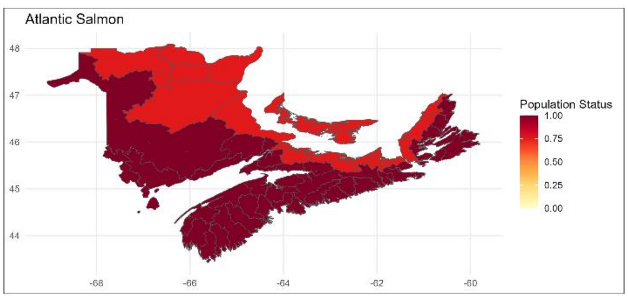


Figure 35 Map of study area coloured by Atlantic salmon (Salmo salar) population status index scores from 0-1. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.

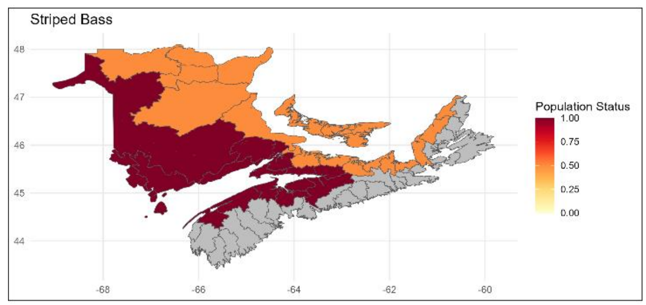


Figure 36 Map of study area coloured by striped bass (Morone saxatilis) population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.

3.1.4.3 E3-Time of thermal niche emergence results

The projected time of thermal emergence, calculated and presented in years is displayed in Figure 37 for Atlantic salmon. The earliest year found in our projections for salmon extirpation is in the Central Prince Edward Island - Hillsborough watershed under RCP 8.5, where they will be at risk in 2064 (Figure 37). Years are translated into risk levels in Figure 38, where the Southern Gulf of St Lawrence is of greater concern under RCP 8.5 than the rest of the study area. Striped bass are not projected to reach their upper thermal tolerance limits for two consecutive years within the time frame of the study (present until 2100), under any carbon emission scenarios (Figure 39), and are therefore low risk throughout Eastern Canada for this index (Figure 40).

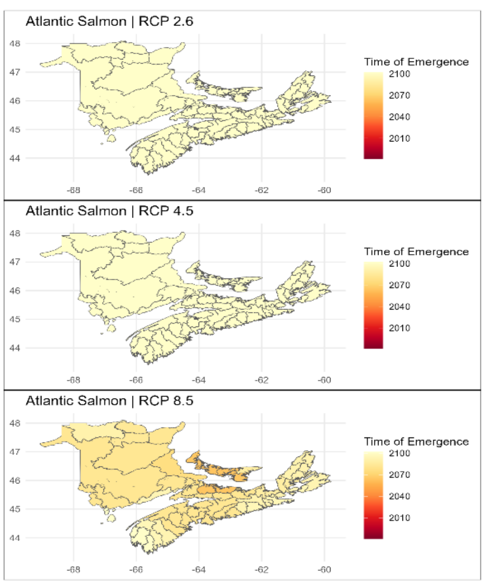


Figure 37 Map of study area coloured by Atlantic salmon (Salmo salar) time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

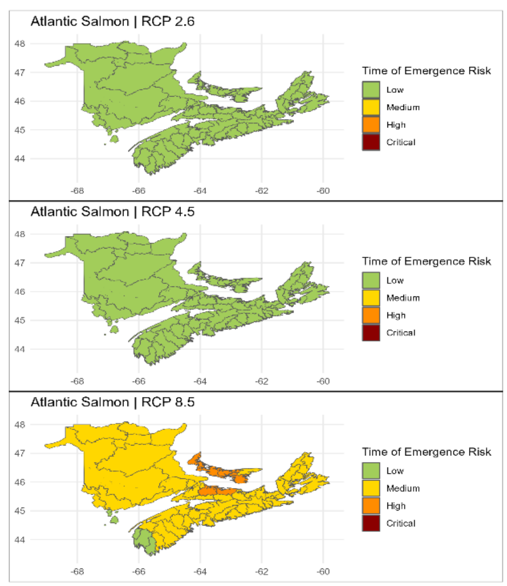


Figure 38 Map of study area coloured by Atlantic salmon (Salmo salar) time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

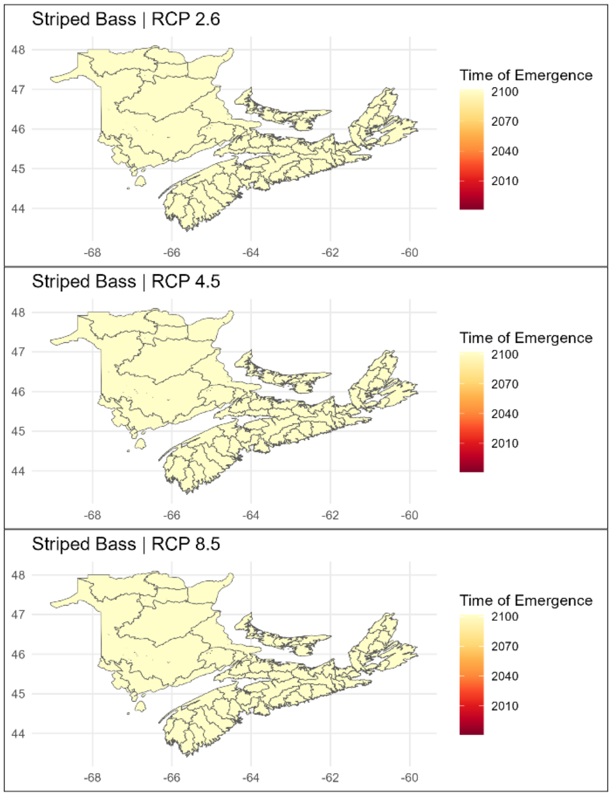


Figure 39 Map of study area coloured by striped bass (Morone saxatilis) time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

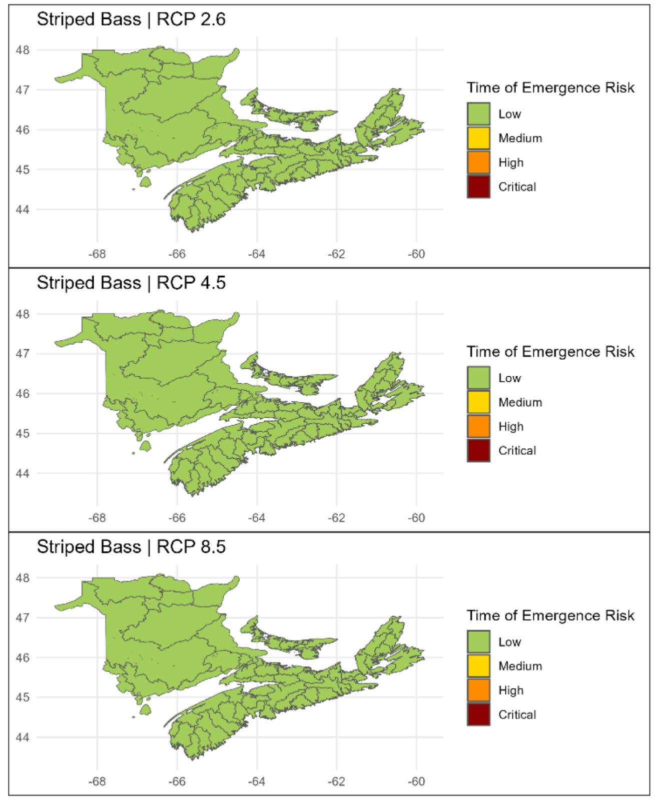


Figure 40 Map of study area coloured by striped bass (Morone saxatilis) time of emergence risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.4.4 E4-Projected habitat loss results

The projected habitat loss by 2100 index presents a binary result of emerged or not emerged for each watershed to species pair, based on the projected time of emergence index. Atlantic salmon only see widespread emergence from their thermal niche by 2100 under RCP 8.5 (Figure 41), whereas striped bass are not predicted to emerge from their thermal niche in any watershed under any RCP (Figure 42).

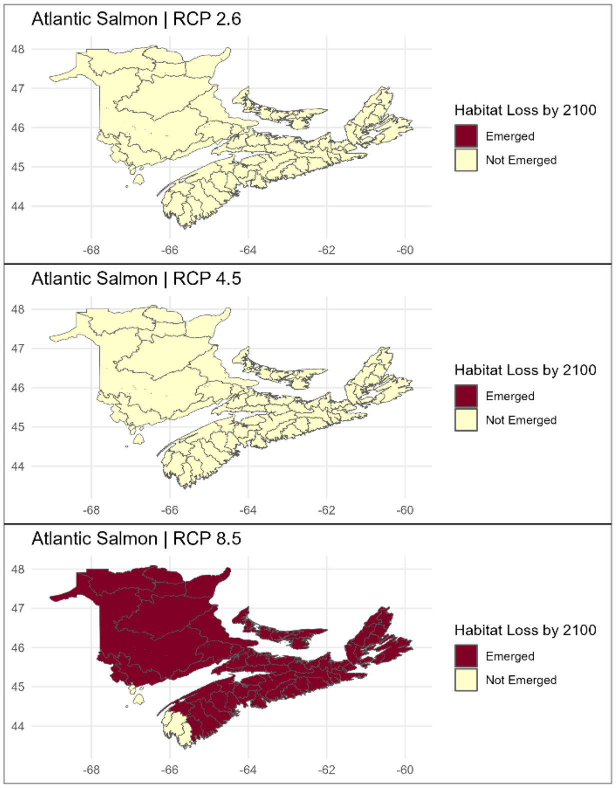


Figure 41 Map of study area coloured by Atlantic salmon (Salmo salar) habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

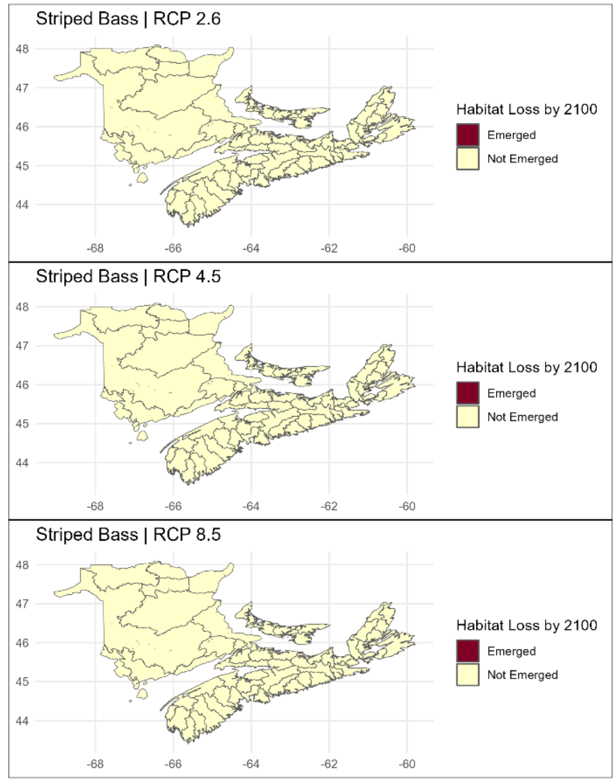


Figure 42 Map of study area coloured by striped bass (Morone saxatilis) habitat loss by 2100 index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

3.1.5.2 AC2-Thermal habitat variability results

The thermal habitat variability index scores from 0-1 for Atlantic salmon are displayed in Figure 43. Little variation exists amongst results across watersheds and RCP models. According to thresholds defined in Table 3, all watersheds across all RCPs result in medium risk levels, with the highest score being 0.409 in the St. Croix River Basin watershed under RCP 8.5, when compared to an average of 0.374 across all watersheds and RCPs, further highlighting the uniformity in this index's results (Figure 44). The lowest thermal habitat variability score for

Atlantic salmon was found in the Cheticamp River watershed under RCP 4.5, with a value of 0.354 (Figure 43). When looking at results of this index for striped bass, Figure 45 again shows little variation amongst score results, with the highest being the River John watershed under RCP 2.6 with a score of 0.413. The lowest thermal habitat variability score for striped bass was found in the Cheticamp River watershed under RCP 4.5, with a value of 0.357 (Figure 43). This slightly higher thermal habitat variability score for striped bass could indicate a more narrow thermal tolerance margin for the species, resulting in a lowered plasticity to thermal variance, but still translates to uniform medium risk levels across watersheds and RCPs (Figure 46).

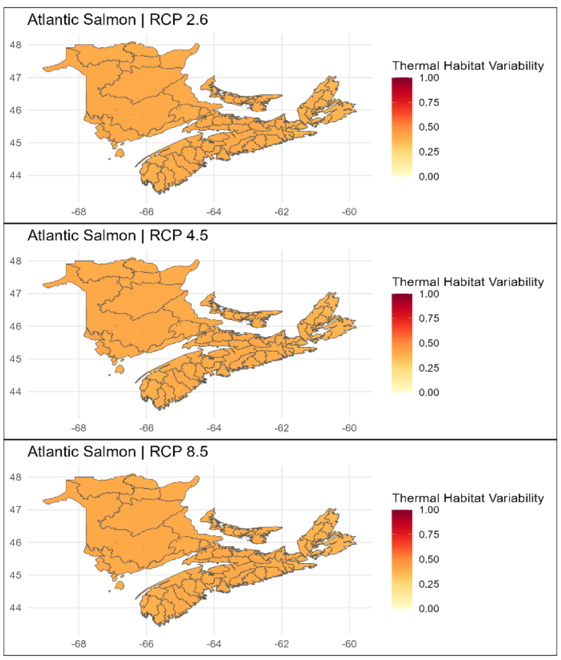


Figure 43 Map of study area coloured by Atlantic salmon (Salmo salar) thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

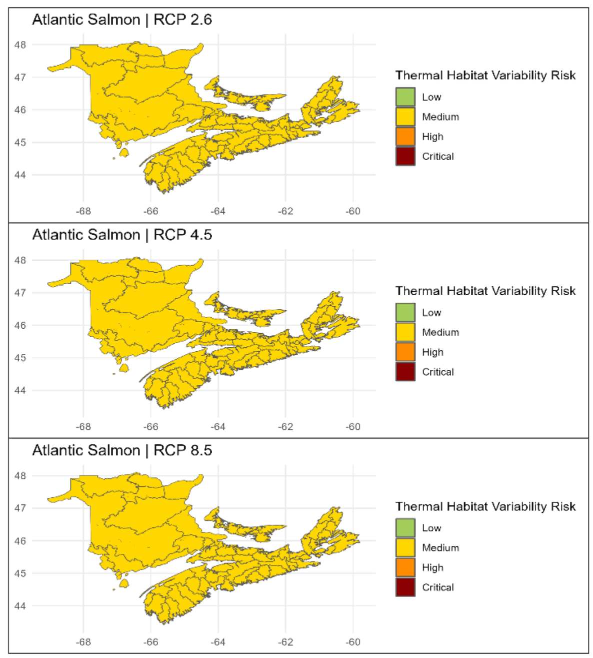


Figure 44 Map of study area coloured by Atlantic salmon (Salmo salar) thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

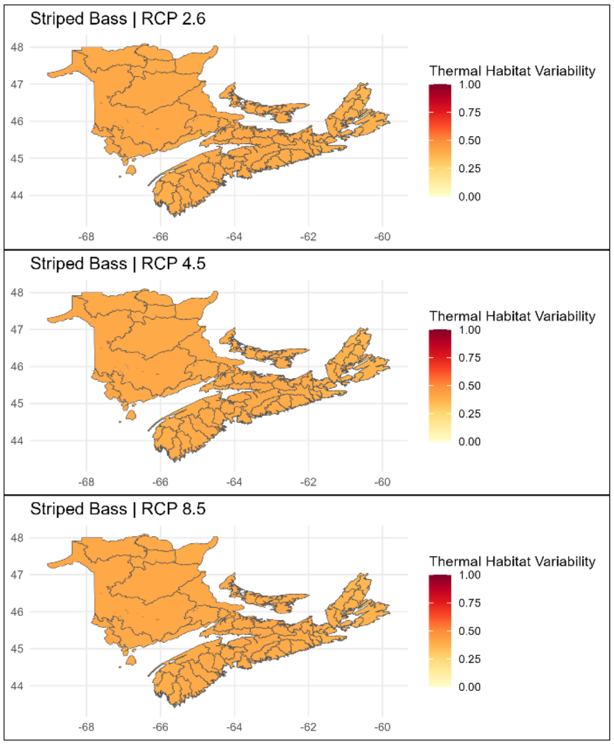


Figure 45 Map of study area coloured by striped bass (Morone saxatilis) thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

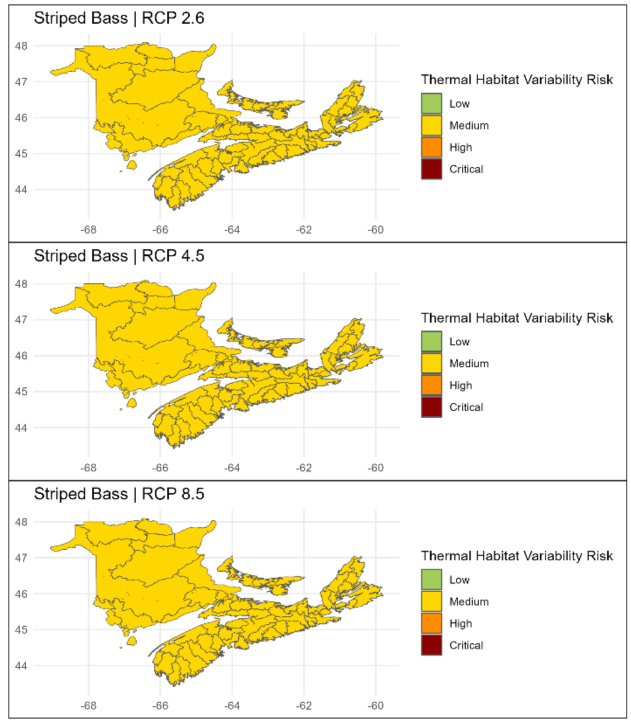


Figure 46 Map of study area coloured by striped bass (Morone saxatilis) thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.

Chapter 4. Discussion

With climate change emerging at the forefront of global issues, the need for effective and lasting conservation methods is growing (Du Pontavice et al. 2020). The FW-CRIB framework provides results on where, when, and why watersheds and the species that inhabit them, are vulnerable, giving managers the ability to enact meaningful and effective policy and conservation measures. With Canada's recent commitments to aquatic conservation, as outlined in the 2021 mandate letter to the Minister of Fisheries, Oceans and the Canadian Coast Guard, the expansion of climate vulnerability-based research will become more prevalent, in an effort to better inform aquatic conservation management and planning (Prime Minister of Canada 2021). The results from this framework contribute to these goals with the ability to expand and be reproduced, while considering the caveats listed in section 4.2. Within this section, potential ways to expand and fortify these methods will be discussed, as well as several potential management applications, and recommendations given the results of this study.

4.1 Further improvement of the framework

To broaden the applicability of this study, the inclusion of more indices can be explored. An important factor to consider is the equal weighting of component level scores. To keep components unbiased on overall vulnerability calculations, an equal number of indices must be maintained across sensitivity, exposure, and adaptive capacity. Noting this, indices that were of interest to include were groundwater influence, seawater intrusion, and bolstering the clearcutting contribution to the watershed health index, potentially separating it fully.

In future iterations of this study and applications of this framework, the inclusion of more species could be considered. Although constrained by thermal tolerance data availability (as described in Section 2.3), new studies providing thermal tolerance data for a broader list of species are continuously being produced and published. The inclusion of a wider breadth of species would make the framework more ecologically robust, and encourage the use of results for a wider stakeholder audience. This inclusion could also promote the analysis of species interactions through finer scale analyses (Foden et al. 2019).

Groundwater input to surface freshwater water bodies is known to provide thermal regulation and localized thermal refuges (KarisAllen et al. 2022). If included in the FW-CRIB framework, vulnerability may decrease in areas where groundwater input is high, since the probability of a species employing thermal refugia is likely. This index could provide insight to a watershed's ability to adapt to warming temperatures and downscale near-surface air temperatures and climate change velocity. While no model projections of future water temperatures have been developed to include the influence of groundwater on the rivers of Nova Scotia, an index of resistance to air temperature warming given the influence of groundwater relative to surface water should be included in the sensitivity component of this CCVA. Currently, data for groundwater inclusion has been collected through modeling for the province of New Brunswick only and should be applied to other provinces (O'Sullivan et al. 2021). This index was therefore not included in this iteration of the FW-CRIB, since data was not available for all provinces.

Seawater intrusion to freshwater watersheds not only threatens the un-acclimated species present, but poses threats to human activities and uses of the area (Xiao et al. 2021). This threat is an expected consequence, by way of superficial seawater overtopping from increases in storm surge severity and sea level rise, and seawater groundwater intrusion (Venâncio et al. 2020). Models to predict seawater intrusion to freshwater habitats are currently non-exhaustive and exist mostly for small island settings, where the issue is imminent (Venâncio et al. 2020). The inclusion of this index could produce higher sensitivity and future exposure levels to coastal watersheds and draw attention and highlight the need for an imminent response to preserve biodiversity in affected areas. Venâncio et al. (2020) observed avoidance of freshwater species, as well as habitat degradation, and ultimate emigration and extirpation from affected areas. In terms of human activities, the introduction of seawater to an area hinders the ability of communities to rely on freshwater for drinking water, agricultural uses, and more. Although data for this index is not well collected, Tang et al. (2020) created a series of mathematical equations to estimate the cumulative volume of freshwater channels under different tidal levels, to estimate seawater intrusion. This index has potential to provide important context in coastal watersheds with sea level rise, increasing severity in storm surges, and estuary interactions with watersheds.

Another potential index to include is the expansion of clearcutting land usage as its own index, separate from the WSHI. Historical records and plans for future forestry in New Brunswick are available, however, future plans for forestry are not available for Nova Scotia and Prince Edward Island; therefore inclusion of a future-looking index related to this stressor was not possible within the scope of this project (Government of New Brunswick 2023). The sub-index of present-day forestry clearcutting activity was considered for removal from the WSHI (to be a stand-alone index), to highlight impacts of deforestation on riparian zones. Evidence suggests that deforestation decreases the biodiversity and habitat health of streams, as well as significantly increases littoral temperatures (Steedman et al. 1998; Jones et al. 1999). This degradation contributes to lack of shelter from the sun in riparian zones, leading to a potential decrease of thermal refugia, and increased velocity of warming (which is not characterized by the near surface air temperature projections available and included in this study). Clearcutting land usage has the potential to be included as a sensitivity or exposure component index. Under the sensitivity component, if proper biodiversity and temperature data in riparian littoral zones is compared to baseline data, current threats to species can be quantified and added to pre-existing risks. As an index of exposure, data would be needed on the long-term future plans for the study area, which are typically unavailable. In January 2023, the province of Nova Scotia released a "High-Production Forestry Phase" (clearcutting) development plan, outlining Crown land area eligible for this type of forestry (Government of Nova Scotia 2023). The variable and not globally applicable nature of future forestry planning may deem this index too unpredictable to include, and further discussion is needed.

Finally, given the project's geographic scope, further collaboration with Indigenous Peoples, and public stakeholders in areas to discuss prioritization and inclusion of both species of interest and relevant indices should be explored. To increase applicability of future project's scope of the study area and biological inclusion, consideration should be given to the users of the area. Community collaboration should be done to ensure that the framework includes relevant species and indices for the study area. This collaboration and incorporation of local knowledge could produce results that are more inclusive of user needs, and support Canada's commitment to reconciliation.

4.2 Caveats within the study

In light of the study's focus on watershed-specific metrics, the inclusion of the barriers to connectivity index is a crucial aspect that warrants careful consideration. Despite its current measurement as the density of barriers (km) weighted by passability scores, sourced from NCC barrier occurrences and Canadian Aquatic Barriers dataset (as outlined in Section 2.3), a need for reassessment arises due to differences in life history and mobility among species leading to variation in sensitivities to different types of barriers. Upon discussions with subject matter experts (SMEs), the index has discernable and actionable improvements able to be made outside the scope of this study. The resident status of a species within lakes or other still bodies of water could downweight the index, as many smaller and bivalve species would theoretically not encounter a river dam or crossing. The downweighting severity needs further exploration, research, and discussion, since freshwater species movement and migration is never fully predictable (Venâncio et al. 2020). Swimming ability should also be included within index calculations, as the traits vary greatly between Atlantic salmon, American eel, and brook trout's swimming, climbing, and jumping abilities vary greatly and should not be given equal weight when assessing ability to use fish passages or culverts (Guderley and Blier 1988). Lastly, the magnitude of river and stream network usage should be included and down weighted as needed. If an impassable barrier occurs in an inland branch of a stream, and the historic usage of the area of Atlantic salmon does not reach that area of the network, the effect of that barrier may be down weighted, since the likelihood of exposure would be low. Although the index calculated with current methods is an insightful tool for area remediation through barrier removal, species specific vulnerability should be assessed for more thorough explanations and applications.

When evaluating climate model-dependent indices, the findings revealed that in few instances, higher vulnerabilities were identified in RCP 2.6 as opposed to RCP 4.5. Upon examining the Climate Data Canada dataset, it became apparent that the considerable temporal and spatial variability in CMIP5 RCP2.6 projected time series could lead to inaccurate climate estimates when evaluated relative to the less-variable RCP4.5 and RCP8.5 projections. While the average daily temperature for RCP 2.6 was lower than those for RCP 4.5 from 2013-2023, aligning with expectations, an in-depth examination of individual daily temperatures revealed that RCP 2.6 modeled temperatures that were both substantially higher and substantially lower than those in RCP 4.5. This variability was contingent on location. The study concluded that RCP 2.6 might better reflect current daily temperature fluctuations, resulting in exceptionally high temperatures in summer and extremely low temperatures in winter. In contrast, RCP 4.5 and RCP 8.5 may not adequately capture these weather phenomena, as they showcased a more gradual warming trend. Despite the averaging of climate data across 24 models in this study, CMIP5 exhibited unresolved spatial and temporal discrepancies. It is anticipated that these issues might find resolution in CMIP6, prompting a reassessment of the FW-CRIB when updated data becomes available.

4.3 Reproducible and open access methods

Aligning with the reproducible nature of the marine CRIB (Boyce et al. 2022), all FW-CRIB code will be available on GitHub at the time of publication. The framework uses R statistical software to conduct analyses and calculations, which is free and open-source. Further increasing these method's accessibility, all input data is open source and free to access upon request, as described in Section 2.3; the pre-processed input data layers used in this study will also be available via the project's GitHub repository. Most indices throughout this framework were calculated with global reproducibility in mind, however some were scaled through study area specific metrics; therefore, special attention should be given to these locally-scaled indices for those who wish to employ this framework in other regions (detailed in Chapter 2).

Chapter 5. Applications

5.1 Subject matter experts

Throughout the internship with the DFO from May to August 2023, a team of SMEs was created and were met with on a monthly basis. Members included my supervisors, Dr. Christine Stortini (DFO), Dr. Sarah Tuziak (DFO), and Aimee Gromack (DFO), as well as Dr. Daniel Boyce (DFO), Dr. Derek Hogan (DFO), Sarah Kingsbury (DFO), Christine Sabean (DFO), Dr. Nancy Shackell (DFO), Dr. Andrew Cooper (DFO), Dr. Michael van zyll de Jong (UNB), Ben Collison (DFO & Dalhousie University), Gavin Kennedy (Government of NS), Dr. Cindy Breau

(DFO), Ree Brennin Houston (DFO), Dr. Camille Macnaughton (DFO), Dr. Michael Coffin (DFO), Ian Luddington (DFO), Dr. Andrew Drake (DFO), and Scott MacFarlane (DFO). Meetings largely covered project progress, questions and advice periods on specific index questions, and inquiries about applicability of results. Part of a freshwater committee meeting that occurred early in the study period was the opening of a jam board, asking regional managers about applicability of results from the FW-CRIB to their respective regions. Some results from this exercise included a marine conservation target coordinator's interest in coastal watersheds and adjusting conservation priorities accordingly, monitoring changes in productivity, biodiversity, and habitat within estuaries, determining long term viability of ESAs, social and economic consequences of increased risk of freshwater species, aquatic invasive species targeted information, and more (Figure 47). This broad applicability of results across multiple disciplines and management areas highlights the importance for reproducibility and accessibility to CRIB frameworks to ensure sustainable and well-informed global ecosystem management.

Figure 47 Jam board brainstorm with the freshwater committee to identify potential management applicability for FW-CRIB results.

5.2 Management applications

Current issues freshwater managers face include where to effectively implement policy and regulatory tools to promote habitat preservation and biodiversity. In many cases globally, protection policies and regulatory tools are put in place based on partial data, public participation, and restrictions on usage within already managed areas (Du Toit and Pollard 2019; Fisheries New Zealand 2023; Government of Canada 2023b). Within Canada, human-linked freshwater environmental management falls under the *Canada Water Act*, which has recently used ecosystem-based approaches to manage water resources for social and human activity and usage (Government of Canada 2023c). Conservation focused measures are enforced under the *Fisheries Act* and SARA, and are often implemented through provincial authorities for recreational fisheries, making freshwater management multi-faceted and inherently complicated.

For biodiversity and ecologically-specific measures, usage restrictions are often placed on the public in areas of already managed water (Government of Canada 2023b). These often include recreational fishing restrictions in areas where ecologically significant species are threatened by aquatic invasives or habitat degradation. With recent initiatives to create new protected areas of ecological and biological significance, federal and provincial governments should apply and consider results from the FW-CRIB framework to inform decisions (see Chapter 6 for detailed description of potential applications of these results).

This strategy and use of the framework has the potential to employ the precautionary approach, predicting where and when certain strategies may work. The framework's adaptive nature lends itself to adjustment as needed, according to shifts in conservation priorities. This framework could also provide context on ESA usage, and when it may be an effective tool (Figure 47). The framework and results have the ability to provide quantitative justification where needed.

5.2 Socio-economic and cultural impact mitigation/response

Socio-economic impacts of climate change differ in each community. Results from these assessments can provide predictions to those who rely on ecosystems at risk. Through collaboration and consultation with the public, managers can identify what ecosystem services a community relies on, and what a critical risk area would look like for them. Through this understanding and communication, adaptation plans can be co-developed to support climate resilience in communities, aligning with UN SDG goal 13 (United Nations 2023). One option may be the community's exploration of emergent ecosystems, and switching to opportunistic fishing methods (Cline et al. 2022). Transparency of results and providing assessments openly can also guide fishers to where a certain species may be low risk and harvest or catch and release is permitted.

Chapter 6. Recommendations and conclusion

The FW-CRIB framework as applied in this study can be used to inform provincial and federal policy, and community-level decisions. For areas with low climate vulnerability, prioritization to establish watersheds as protected areas and refuges for at-risk species is recommended. Aquatic refuges for at-risk species see significant success, with management focusing on disturbance mitigation (Chester and Robson 2013). In this recommendation, special attention would need to be paid to monitoring species interactions and non-native species responses to changing management. Some aquatic invasive species (AIS) may become more prolific with climate change, and continuous monitoring and adaptation would need to be done.

Low vulnerability areas where a species of commercial, recreational, or ecological importance is not currently observed may provide opportunities for introduction. With this recommendation, special care must be taken in establishing a non-native species, with consideration for competition with ecologically similar native species, however evidence suggests not all non-native introductions are detrimental to ecosystems (Gozlan 2008; Catford et al. 2018). Gozlan (2008) highlights the lack of ecological impacts, and ample societal benefits in case studies from African lakes. The introduction of Nile perch (*Lates niloticus*) to Lake Victoria saw a significant increase in the fishery economy within the area, however with such growth and lack of enforcement on fishing regulations, the ensuing ecological decline was due to overfishing of the area through harmful methods, and development of the surrounding area for fishery-related activities (Gozlan 2008). With careful consideration for species interactions and emergent fisheries, introduction of species may be a viable option for species at risk of extirpation - especially those which are endemic to Eastern Canada, such as Atlantic salmon and Atlantic whitefish restocking initiatives.

Low climate vulnerability areas with high impacts from other stressors can be prioritized for remediation/restoration. As seen in the risk-level results for the barriers to connectivity index (Section 3.1.5.3), areas that exhibit relatively low risk for climate change related indices, but high risk for anthropogenic stressor-related indices, can be prioritized for remediation. Remediation of an area could include mitigation and removal of chemical and physical pollutants (Pico et al. 2019; Newton et al. 2023). Success through chemical pollutant remediation has been demonstrated in the Hudson River, New York, by removing polychlorinated biphenyls to promote freshwater mussel health and biodiversity (Newton et al. 2023). Larger scale remediation through aquatic barrier removal can also be successful and is being planned on the provincial scale in New Brunswick. Results from this framework could aid in the selection process of removal order (Freshwater Committee Meeting Attendees, personal communication, August 3, 2023).

For areas found to have high climate vulnerability, yet low impacts from other stressors, recommendations include establishing monitoring programs for change as the date of extirpation approaches. This results in the framework's ability to refute or confirm its own modeling accuracy, and based on accuracy of results, can be re-assessed to ensure maximum prediction accuracy throughout the temporal study range. Furthermore, these areas of high climate vulnerability present opportunities to monitor new ecosystems for emerging risks and ecosystem services, and can act as an in-vivo example of how climate change affects an area and its populations. If occurring in high anthropogenic impact areas, the areas at risk may be prioritized for restoration to protect emergent ecosystem services. Alternatively, these areas can be prepared for shifts in ecosystem service impacts. Not included in this study but relevant to human adaptive measures is seawater intrusion in Bangladesh (Baten et al. 2015). After the area experienced significant seawater intrusion on productive agricultural land, farmers shifted their crop varieties to be more saline-tolerant (Baten et al. 2015). This example saw success, however was employed as a reactionary approach. With accurate results from a CCVA, risks can be identified and prepared for, prior to their arrival.

In conclusion, with the global push for climate change adaptation and preparation, the FW-CRIB framework stands as a powerful decision-support tool based on modeling predictions, important to employ globally. The framework is reproducible, open-access, and has the ability to be continuously updated with emerging data availability. It delivers precise quantitative results, visualized in comprehensible maps for managers, communities, Rightsholders, and stakeholders. The FW-CRIB framework can promote precautionary measures and policy, for a sustainable and well-informed future for all.

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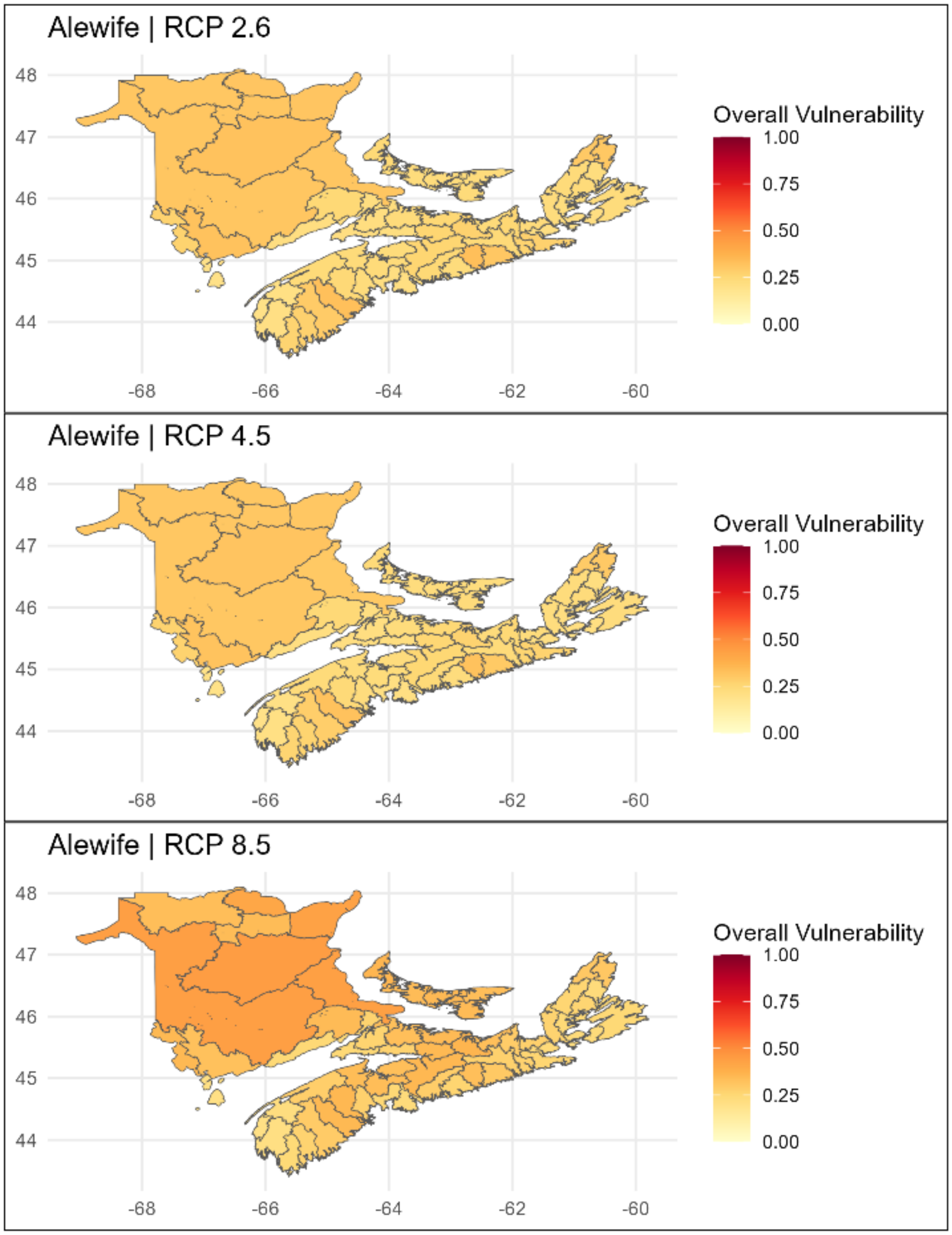
Appendices

Appendix 1 List of watershed names. Numbers correspond to Figure 1.

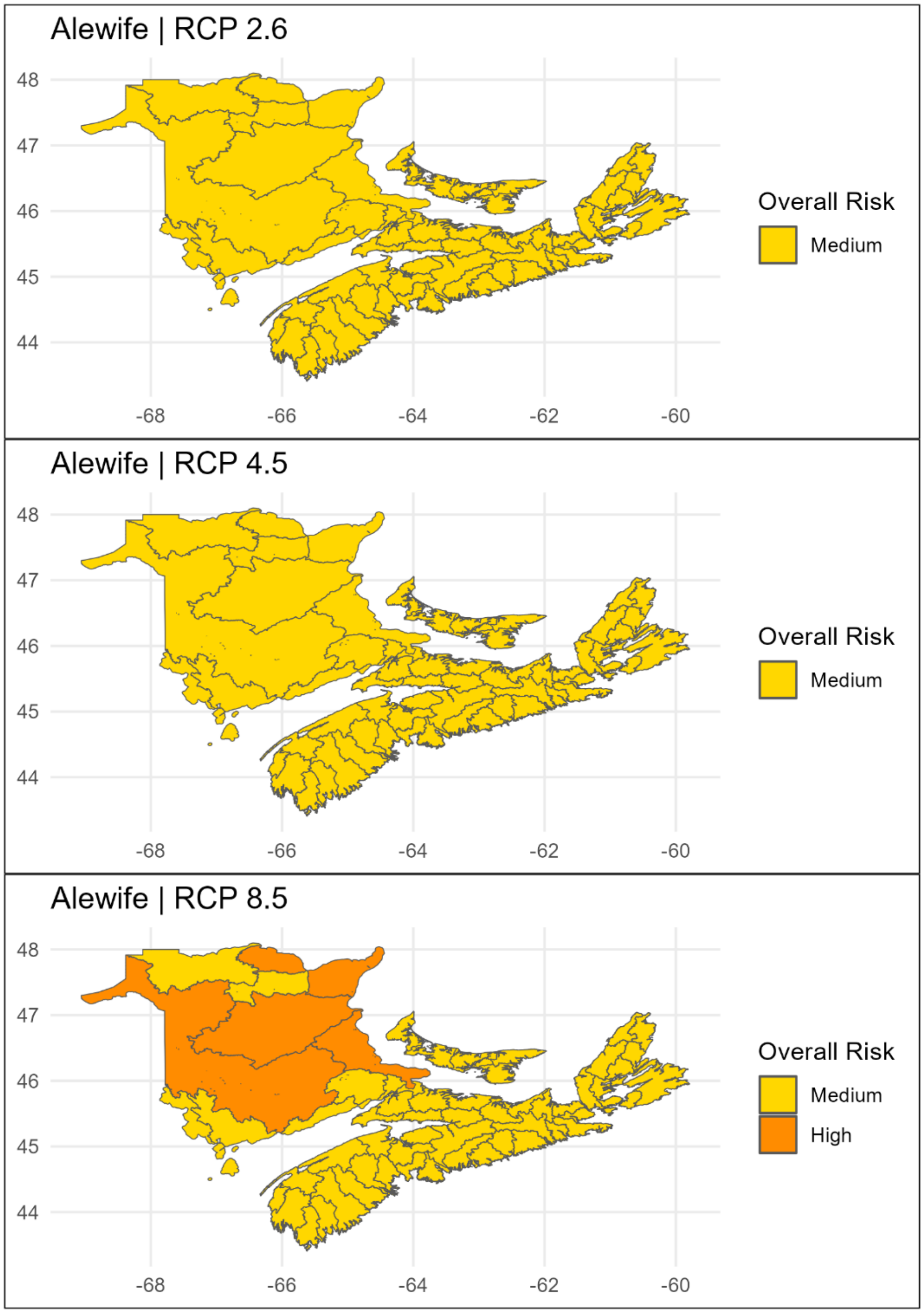
Watershed	Number	Province
Annapolis	1	Nova Scotia
Barrington/Clyde	2	Nova Scotia
Cheticamp River	3	Nova Scotia
Clam Hrb/St. Francis	4	Nova Scotia
Country Harbour	5	Nova Scotia
East/Indian River	6	Nova Scotia
East/Middle/West (Pictou)	7	Nova Scotia
East/West (Sheet Hbr)	8	Nova Scotia
Economy	9	Nova Scotia
French	10	Nova Scotia
Gaspereau	11	Nova Scotia
Gold	12	Nova Scotia
Grand	13	Nova Scotia
Herring Cove/Medway	14	Nova Scotia
Indian	15	Nova Scotia
Isle Madame	16	Nova Scotia
Kelly/Maccan/Hebert	17	Nova Scotia
Kennetcook	18	Nova Scotia
Lahave	19	Nova Scotia
Liscomb	20	Nova Scotia
Margaree	21	Nova Scotia

Mersey	22	Nova Scotia
Meteghan	23	Nova Scotia
Missaguash	24	Nova Scotia
Musquodoboit	25	Nova Scotia
New Hbr/Salmon	26	Nova Scotia
North/Baddeck/Middle	27	Nova Scotia
Parrsboro	28	Nova Scotia
Philip/Wallace	29	Nova Scotia
River Denys/Big	30	Nova Scotia
River Inhabitants	31	Nova Scotia
River John	32	Nova Scotia
Roseway/Sable/Jordan	33	Nova Scotia
Sackville	34	Nova Scotia
Salmon/Debert	35	Nova Scotia
Salmon/Mira	36	Nova Scotia
Shubenacadie/Stewiacke	37	Nova Scotia
Sissiboo/Bear	38	Nova Scotia
South/West	39	Nova Scotia
St. Croix	40	Nova Scotia
St. Marys	41	Nova Scotia
Tangier	42	Nova Scotia
Tidnish/Shinimicas	43	Nova Scotia
Tracadie	44	Nova Scotia
Tusket River	45	Nova Scotia
Wreck Cove	46	Nova Scotia

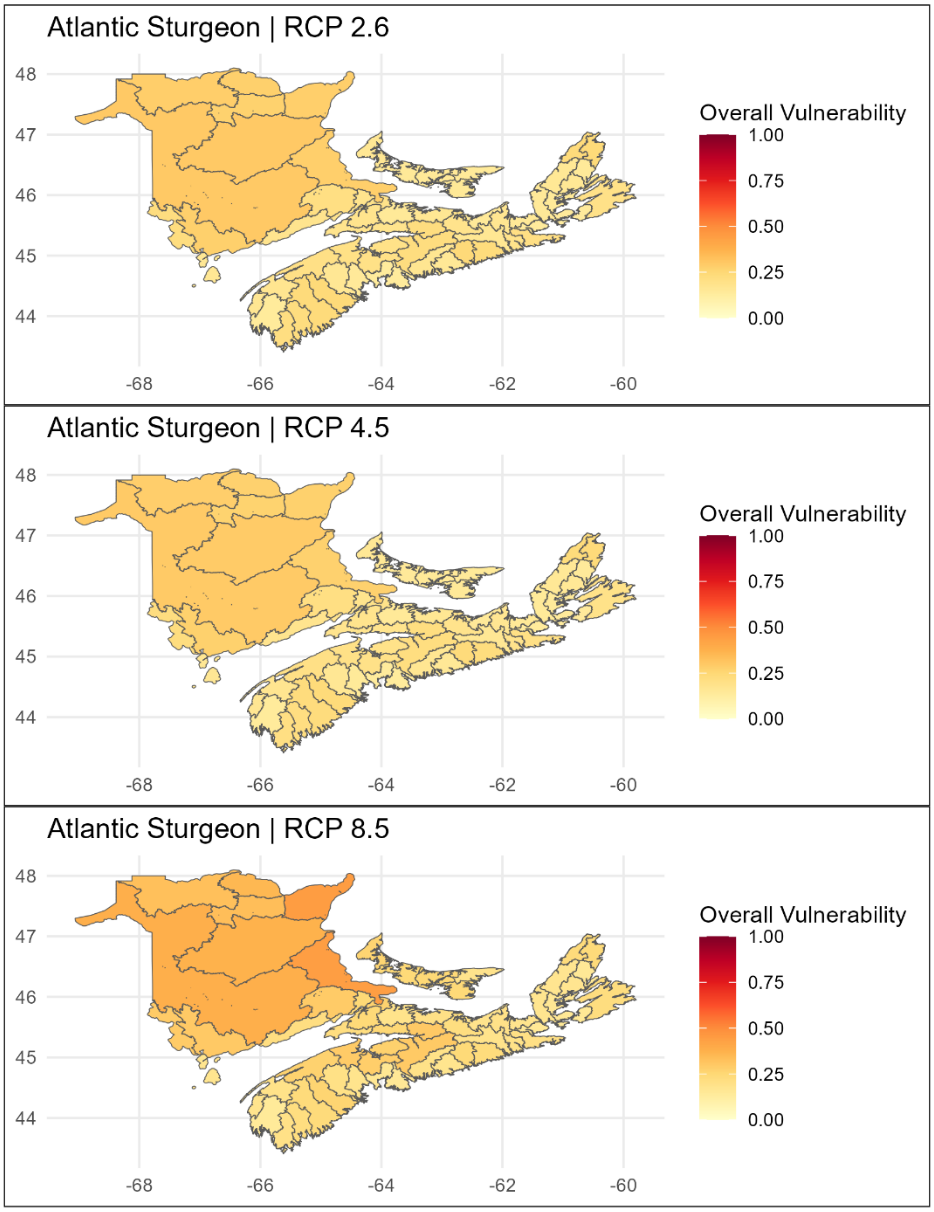
Central Prince Edward Island - Hillsborough	47	Prince Edward Island
Central Prince Edward Island - Wilmot	48	Prince Edward Island
Northeastern Prince Edward Island	49	Prince Edward Island
Southeastern Prince Edward Island	50	Prince Edward Island
Western Prince Edward Island	51	Prince Edward Island
Acadian Peninsula Composite	52	New Brunswick
Chaleur Bay Composite	53	New Brunswick
East Fundy Composite	54	New Brunswick
Fundy Isles Composite	55	New Brunswick
Inner Bay of Fundy Composite	56	New Brunswick
Miramichi River Composite	57	New Brunswick
Nepisiguit River Composite	58	New Brunswick
Northumberland Strait Composite	59	New Brunswick
Petitcodiac Composite	60	New Brunswick
Restigouche River Basin	61	New Brunswick
Saint John River Basin	62	New Brunswick
St. Croix River Basin	63	New Brunswick
West Fundy Composite	64	New Brunswick



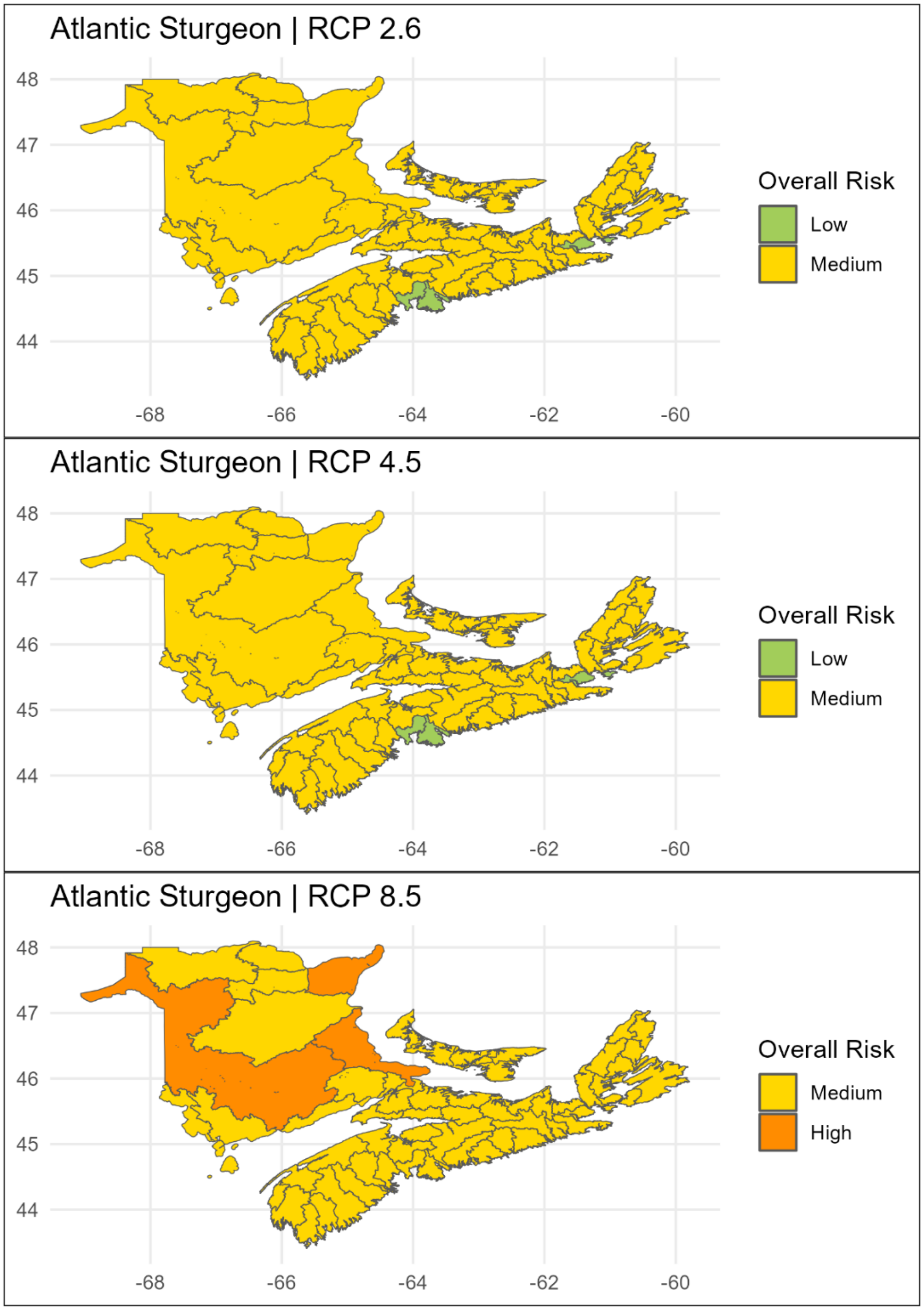
Appendix 2 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by alewife overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



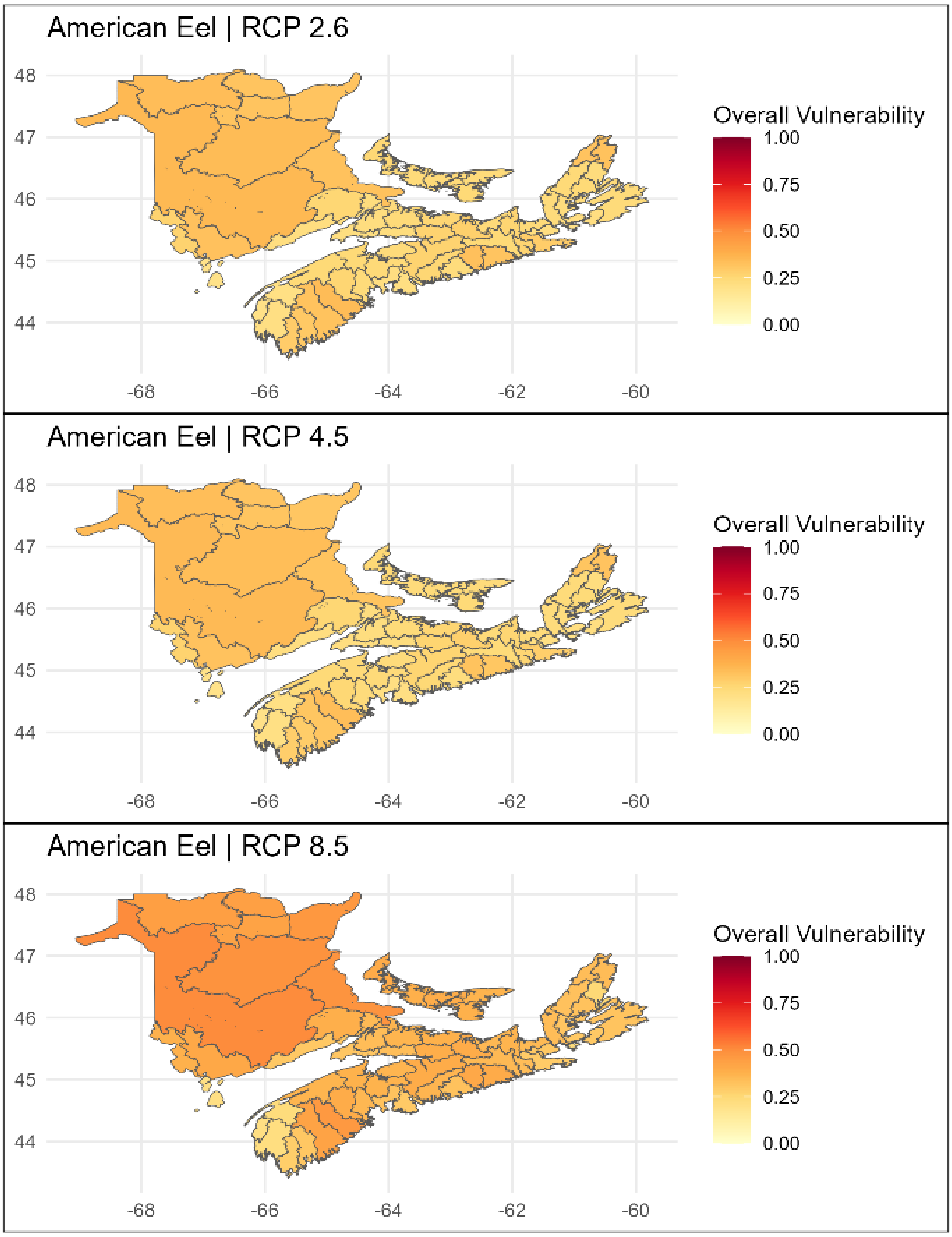
Appendix 3 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured alewife overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



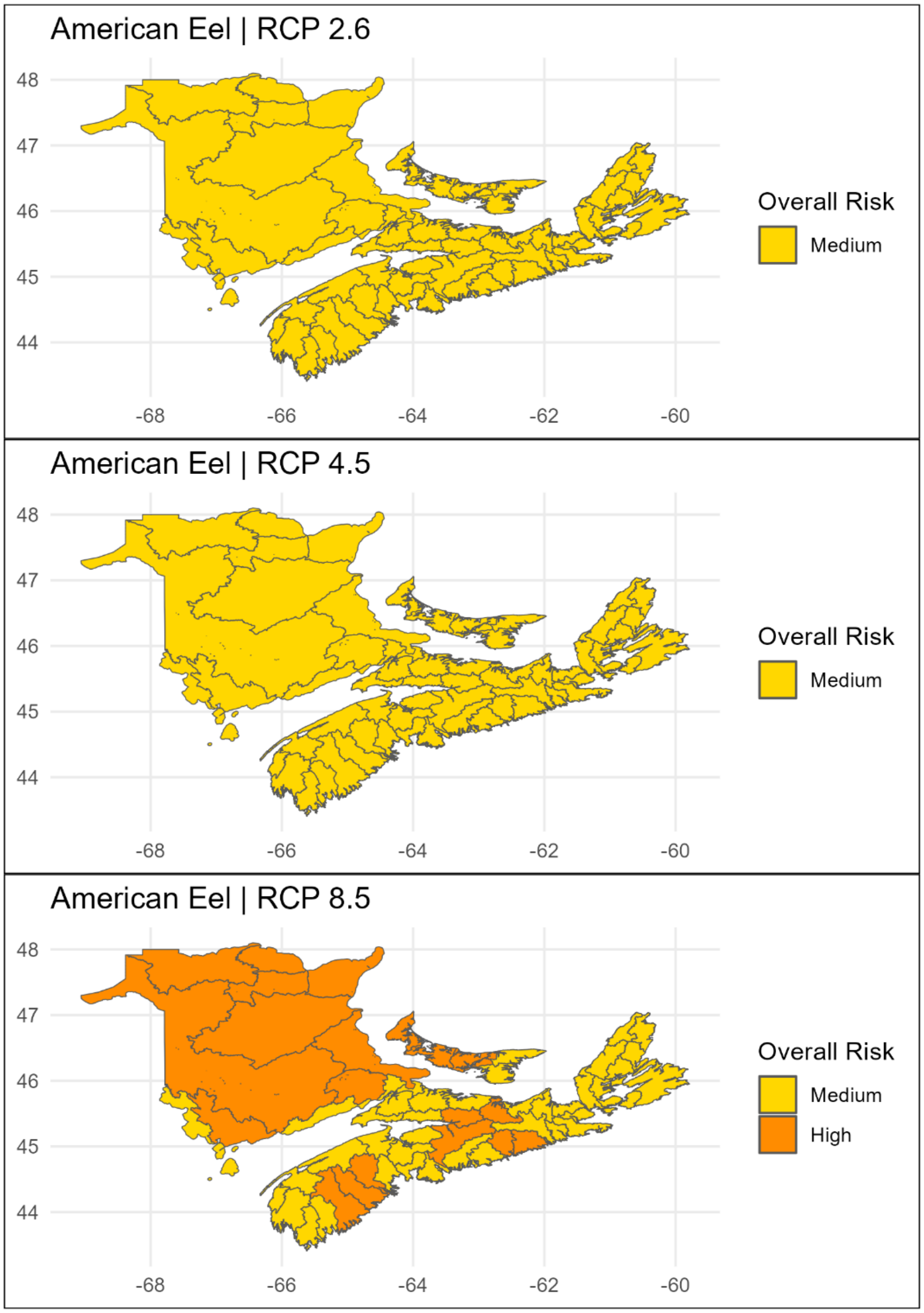
Appendix 4 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic sturgeon overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



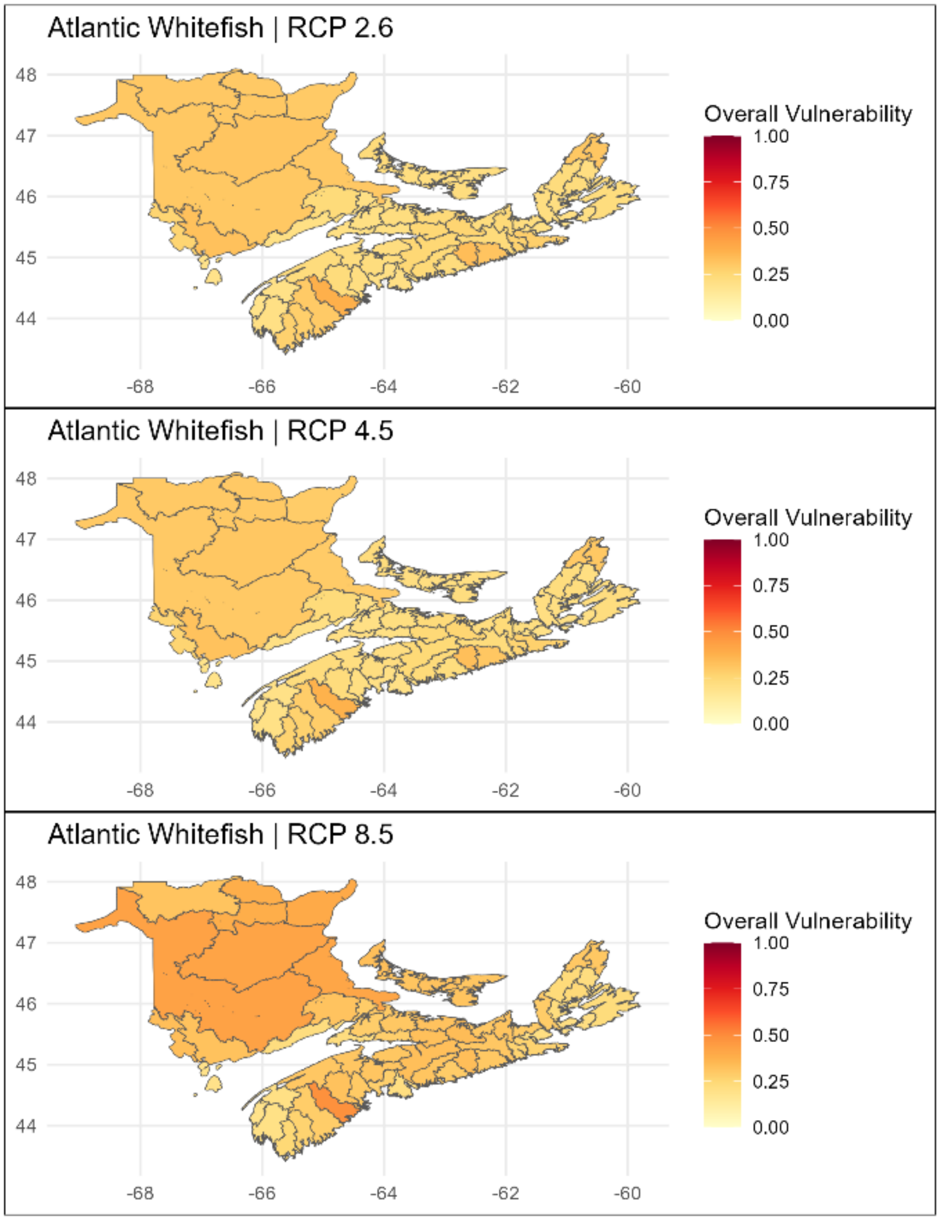
Appendix 5 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured Atlantic sturgeon overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



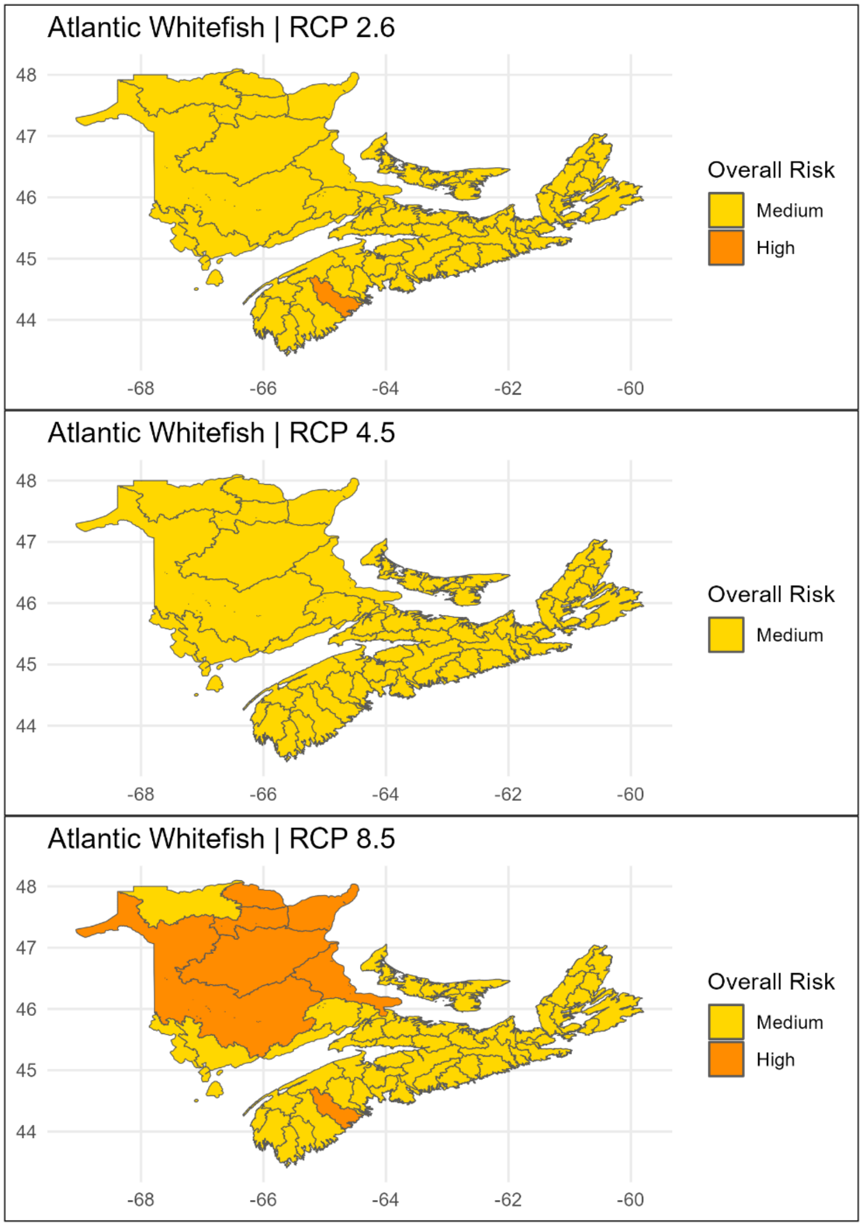
Appendix 6 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by American eel overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



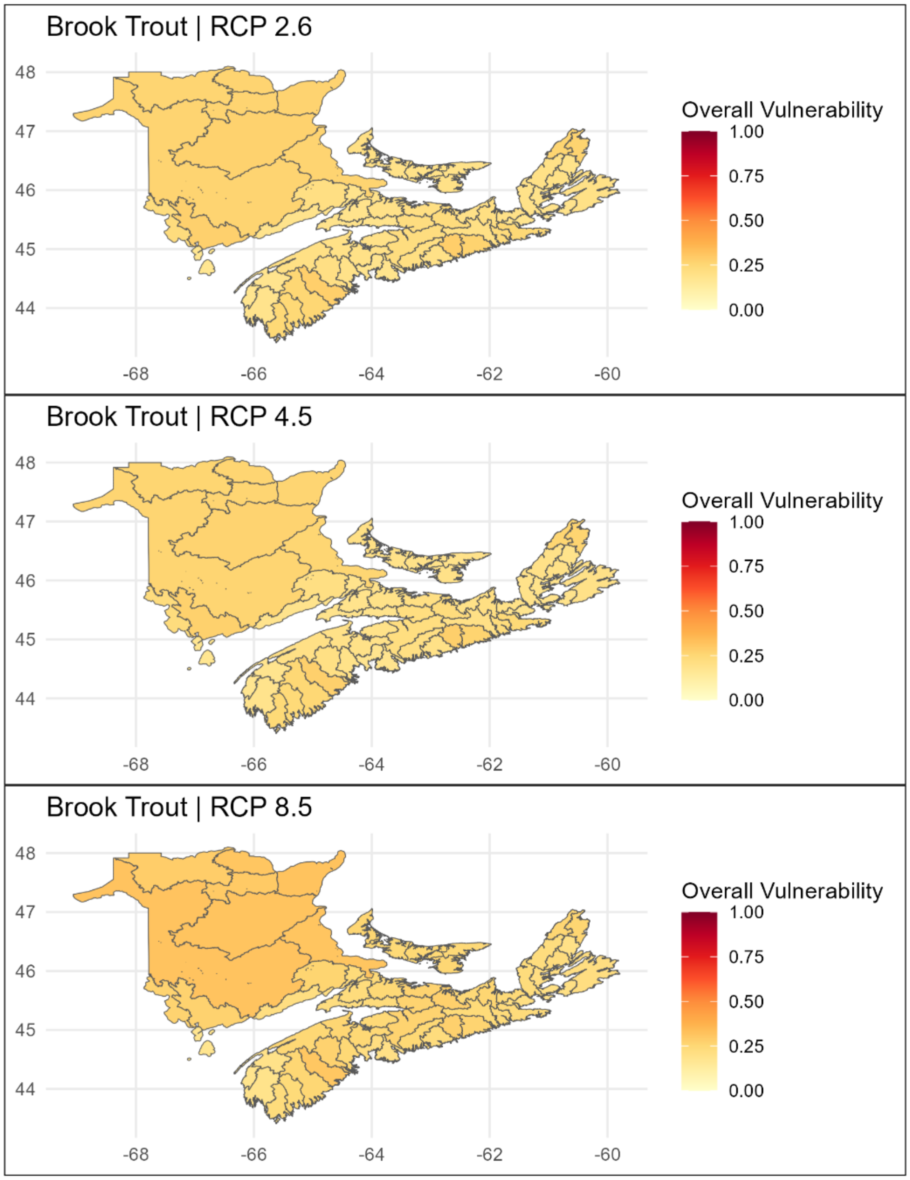
Appendix 7 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by American eel overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



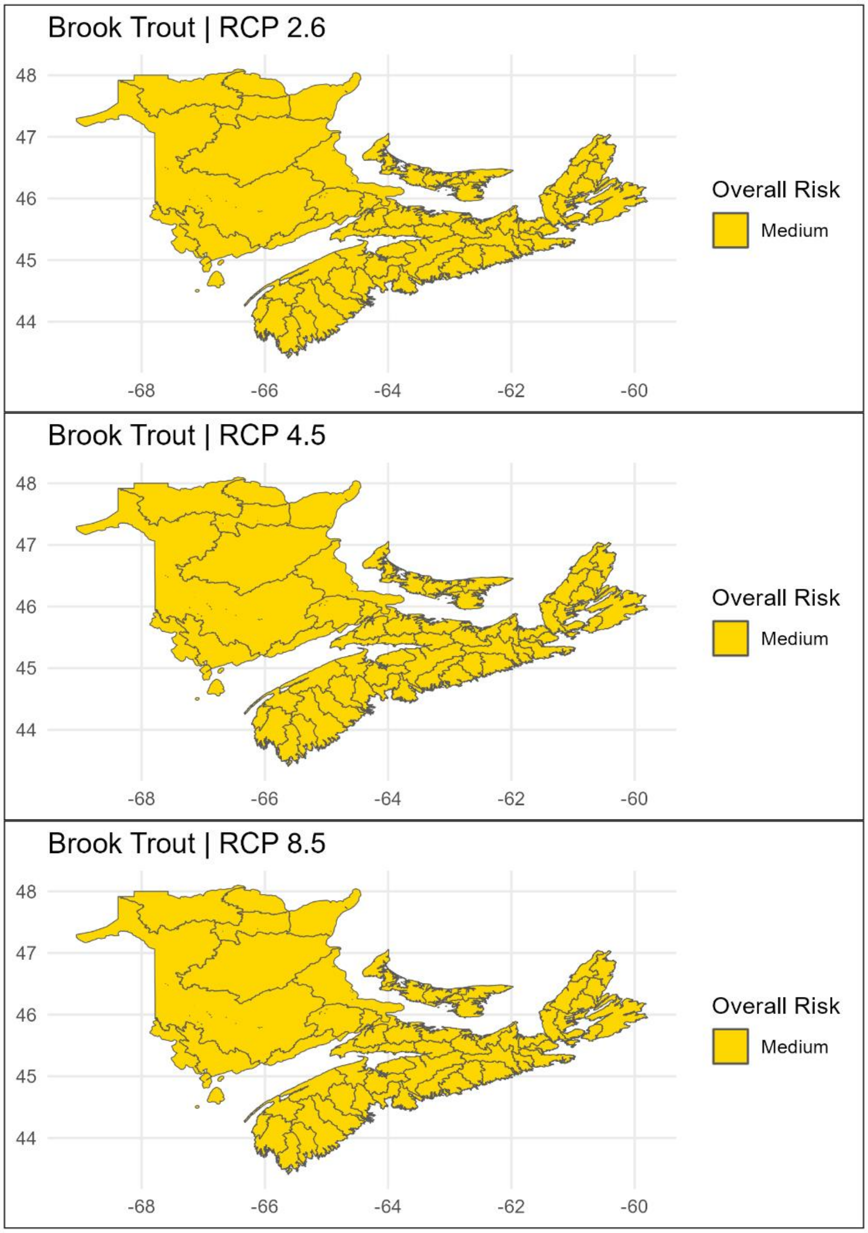
Appendix 8 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic whitefish overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



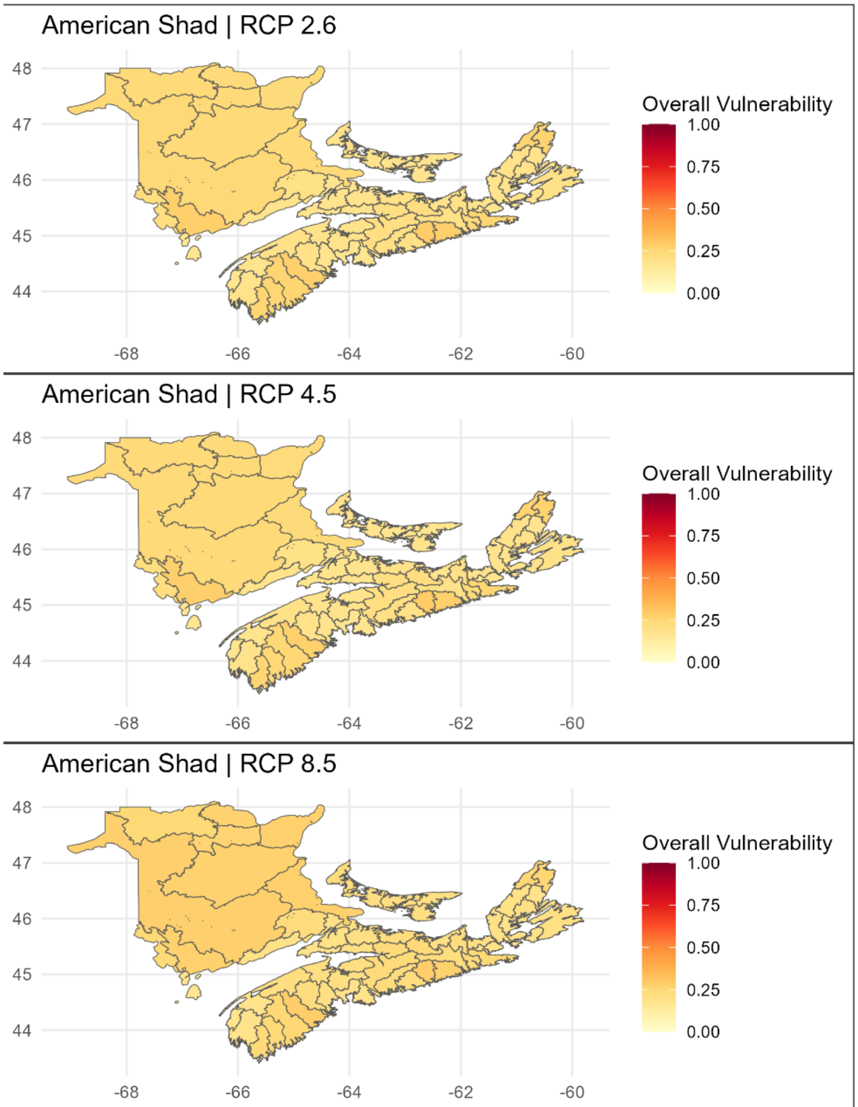
Appendix 9 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Atlantic whitefish overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



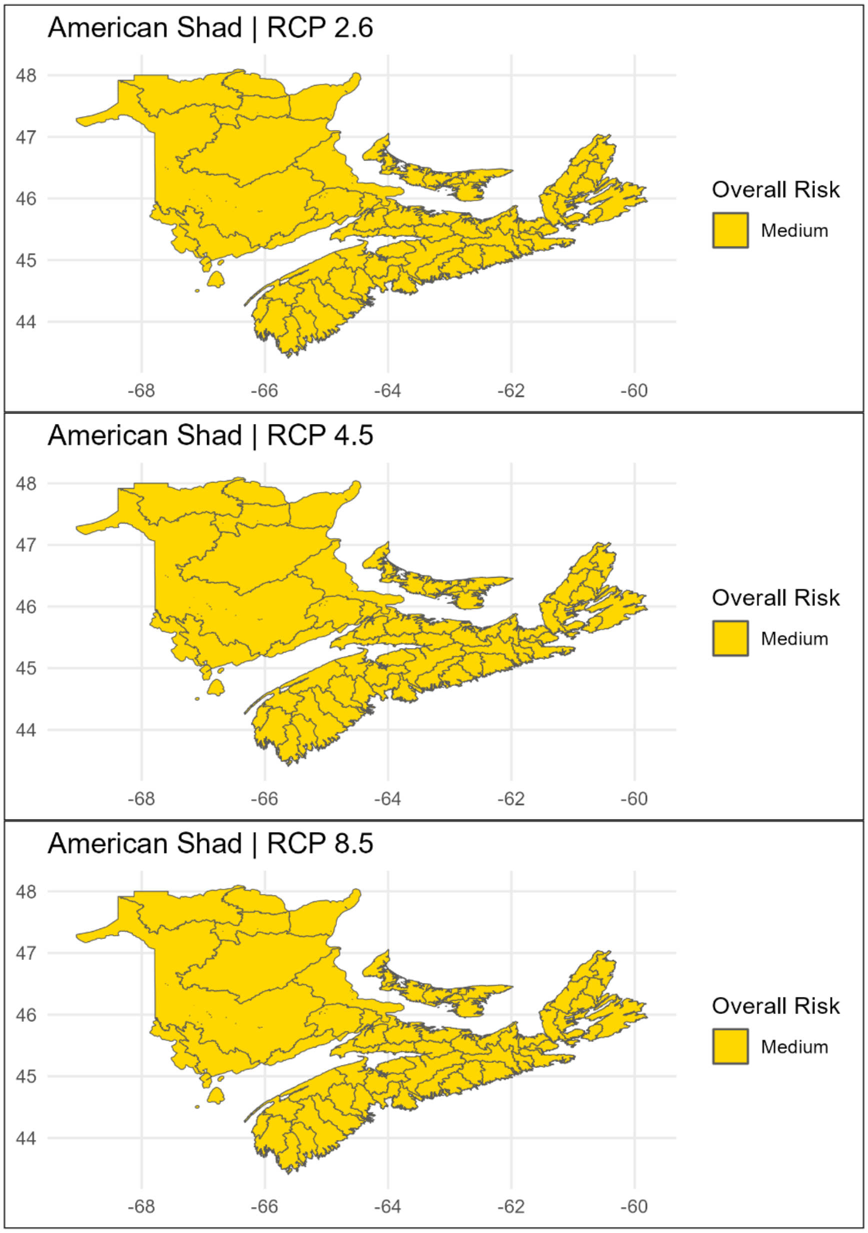
Appendix 10 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Brook trout overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



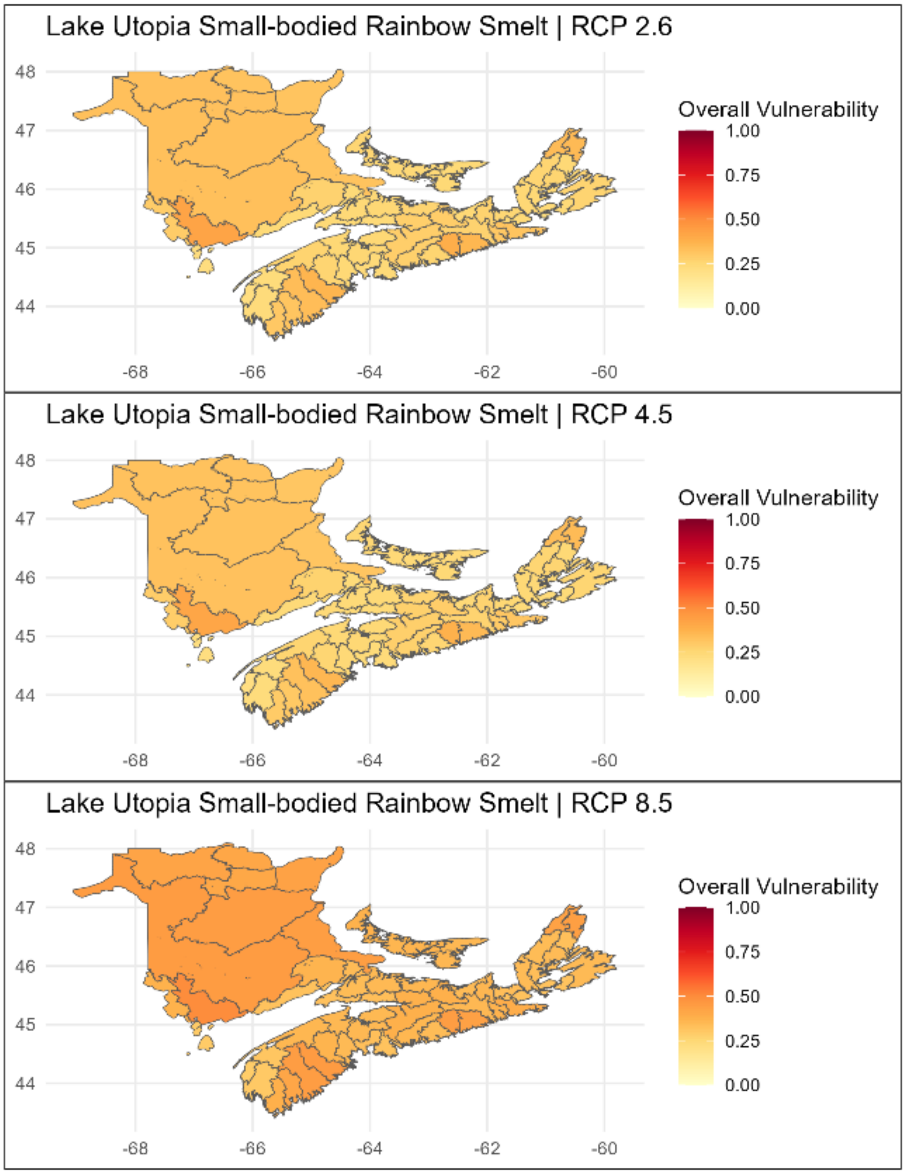
Appendix 11 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by brook trout overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



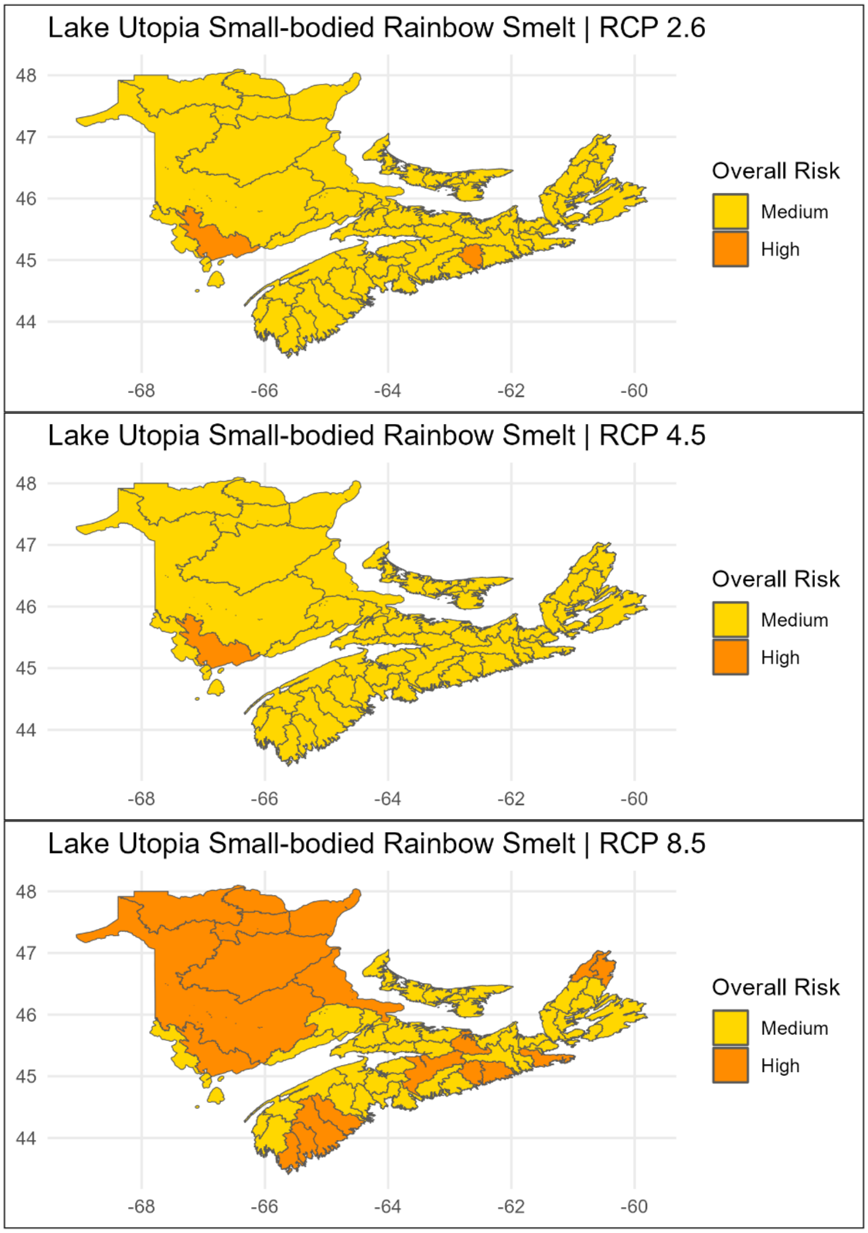
Appendix 12 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by American shad overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



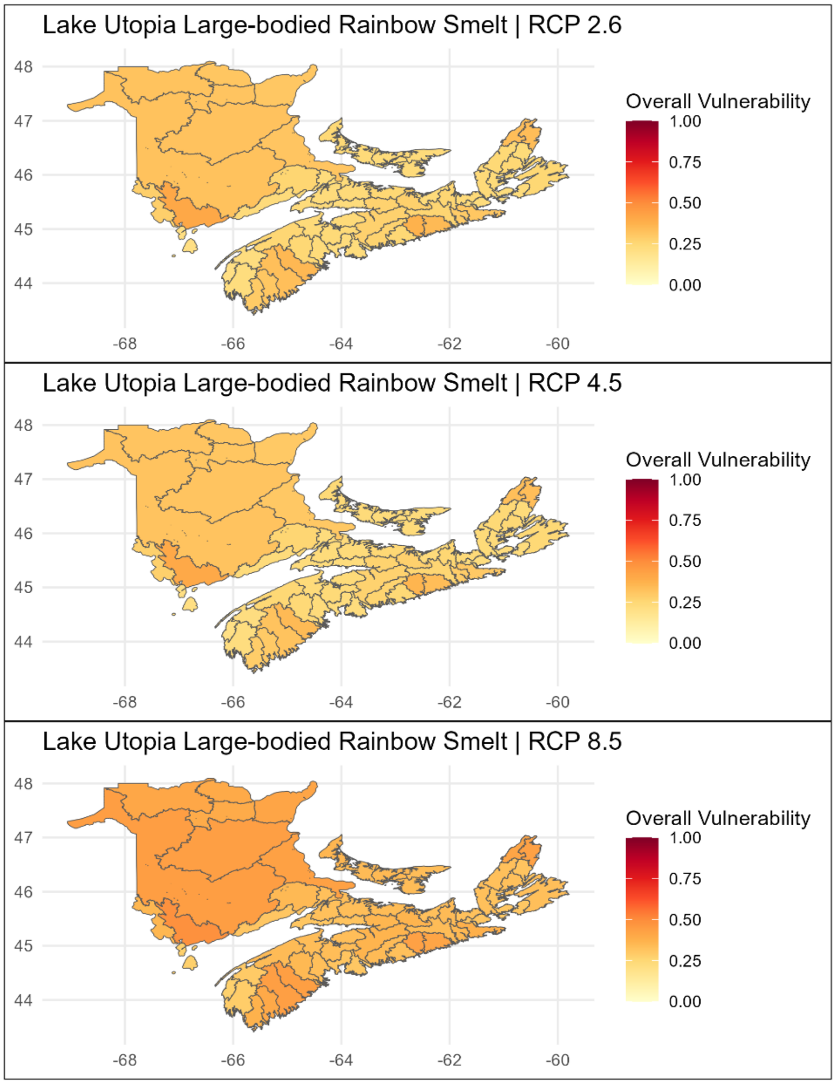
Appendix 13 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by American shad overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



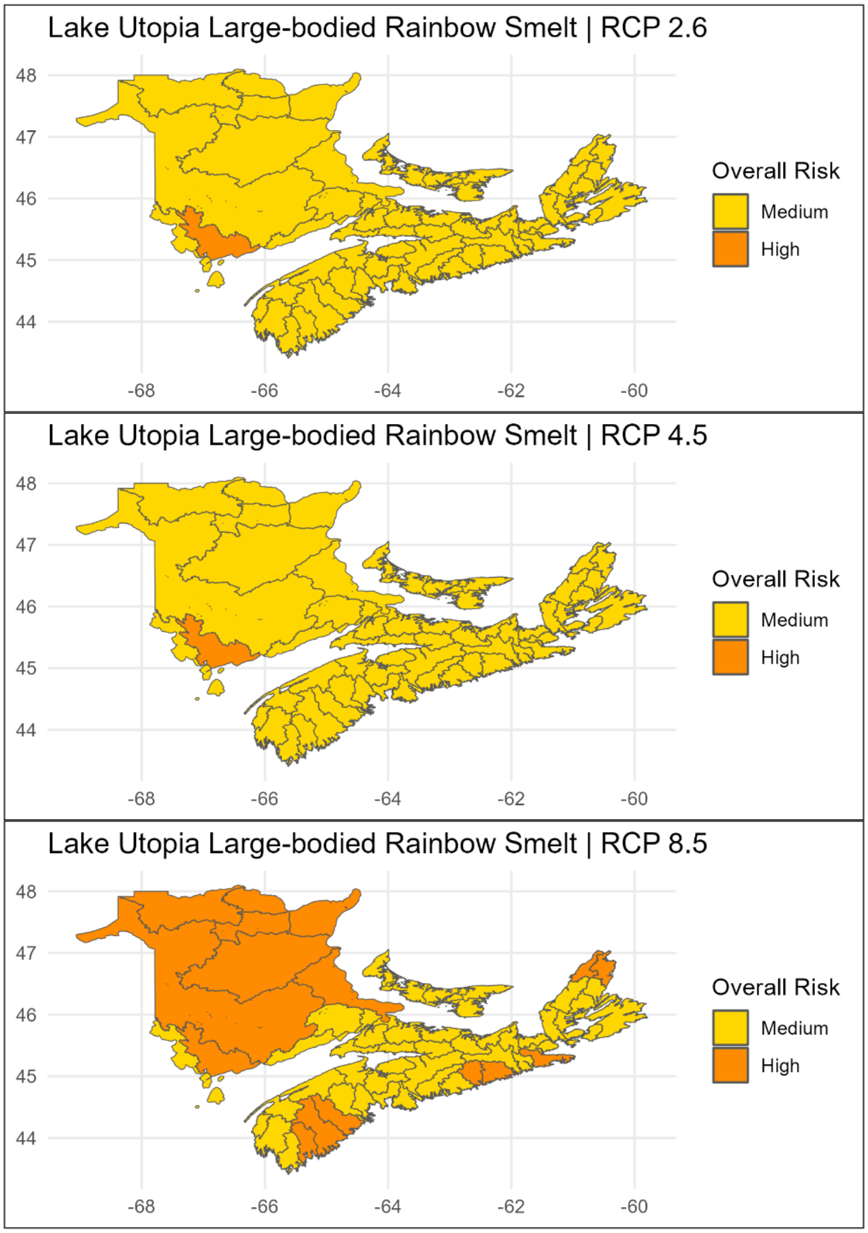
Appendix 14 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Lake Utopia small-bodied rainbow smelt overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



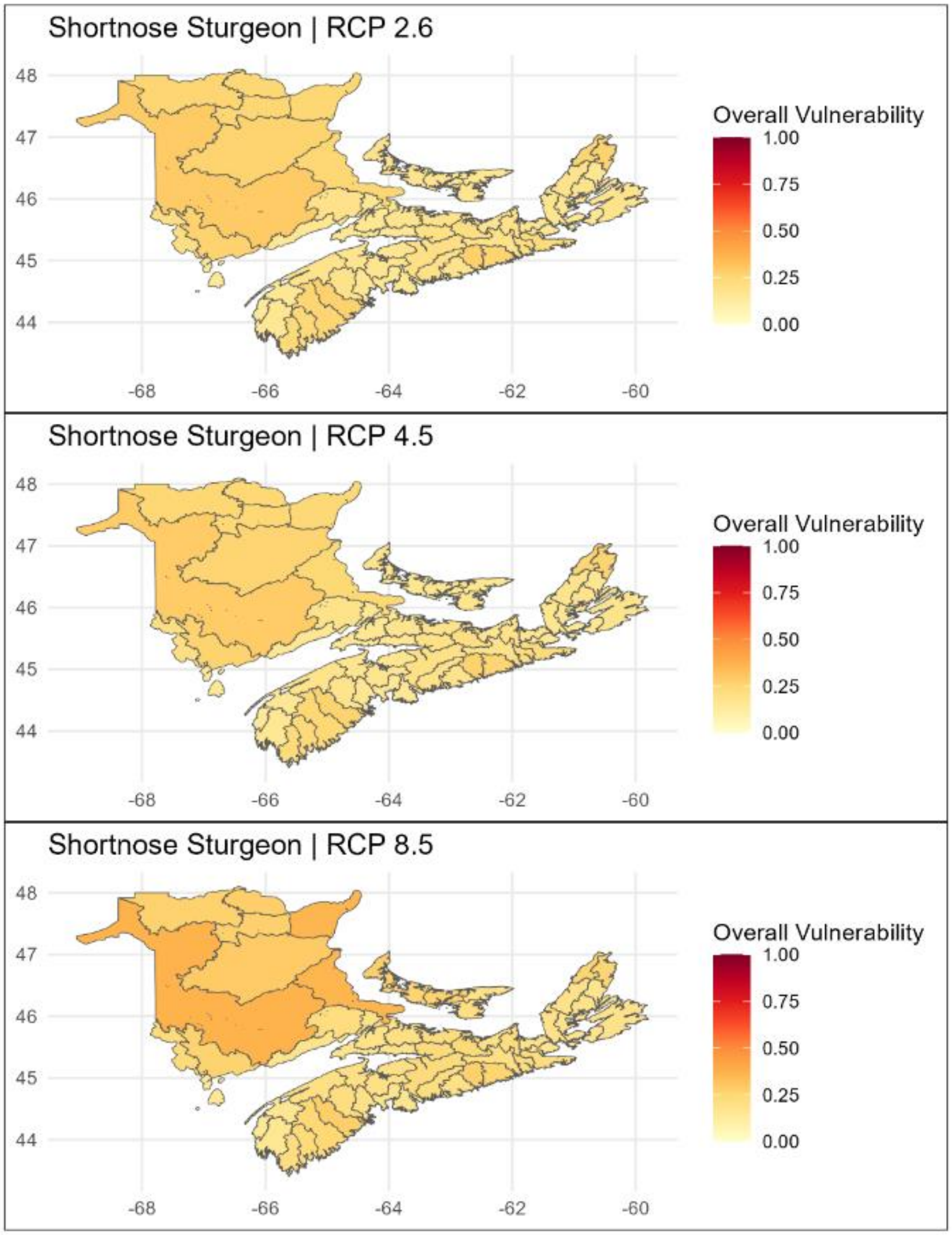
Appendix 15 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Lake Utopia small-bodied rainbow smelt overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



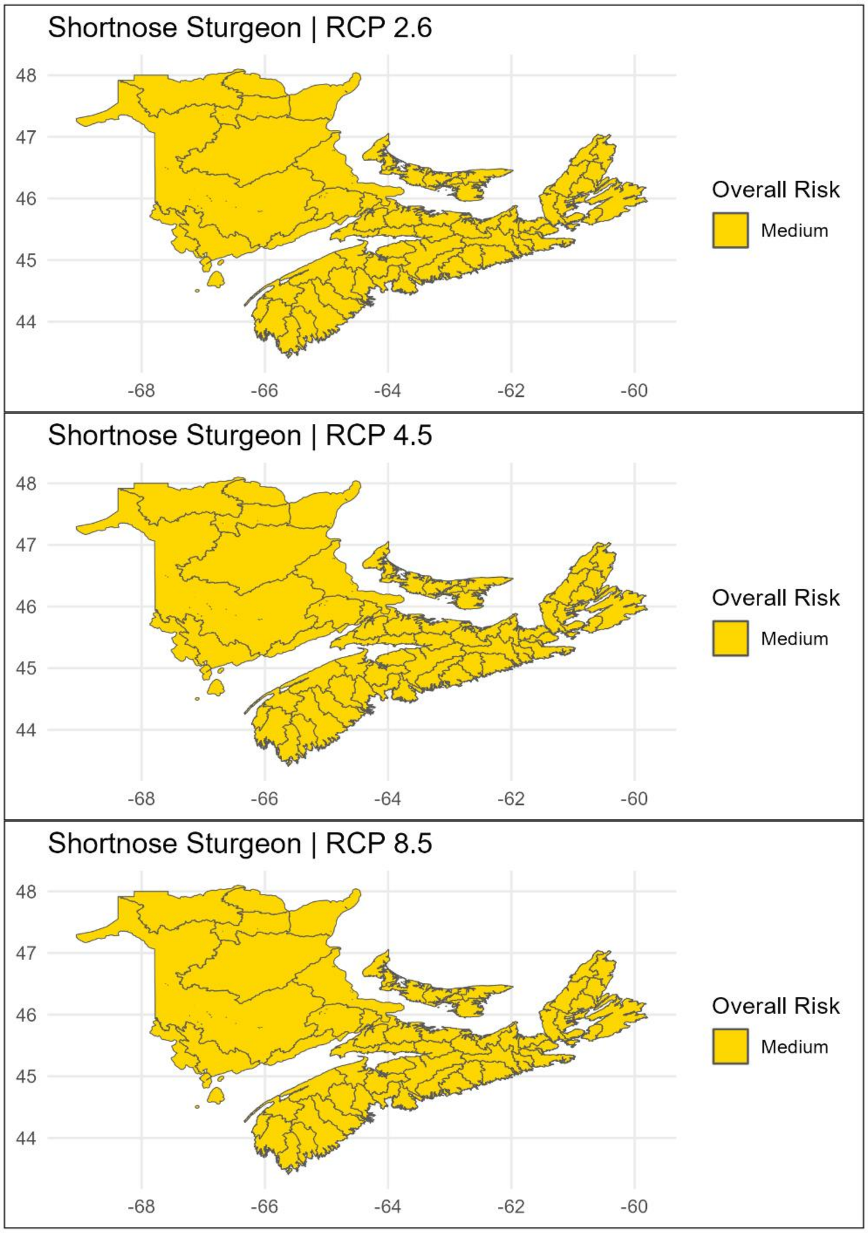
Appendix 16 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Lake Utopia large-bodied rainbow smelt overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



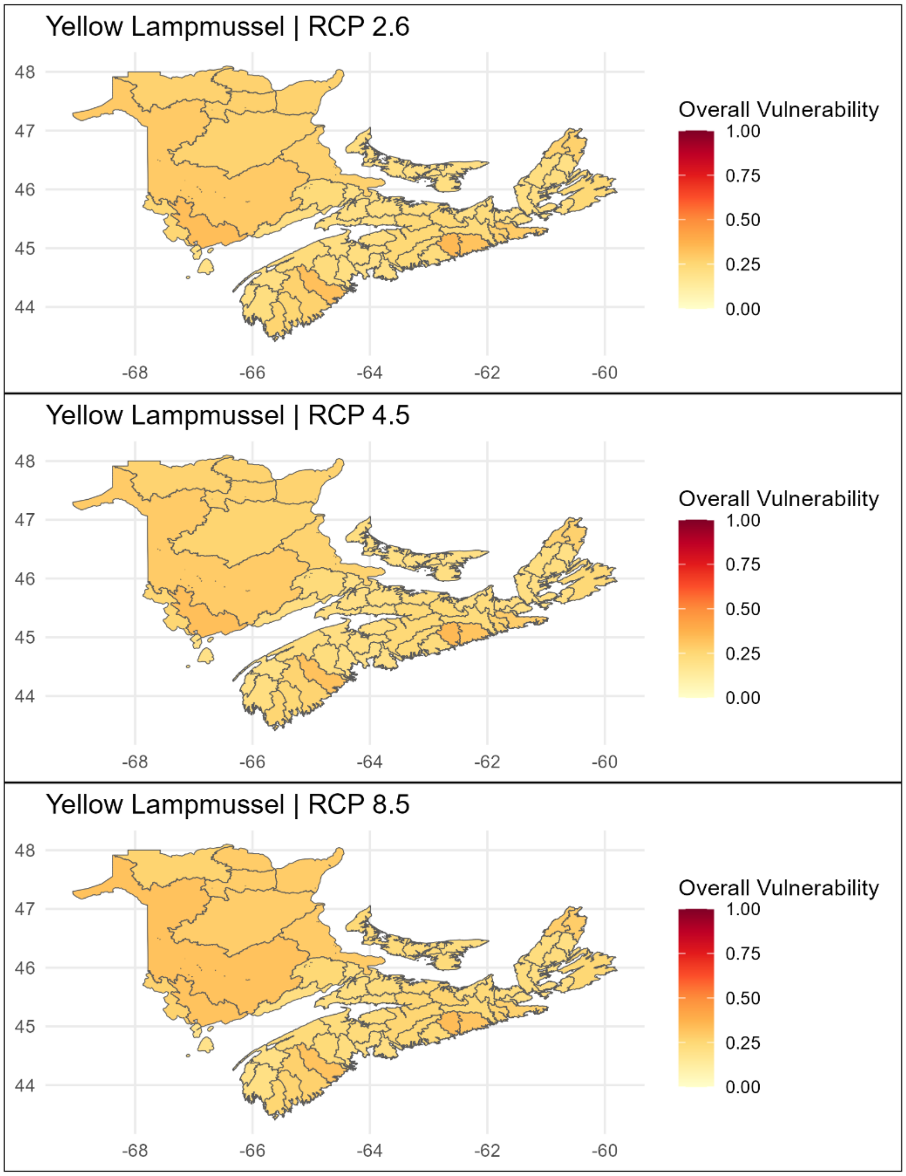
Appendix 17 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by Lake Utopia large-bodied rainbow smelt overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



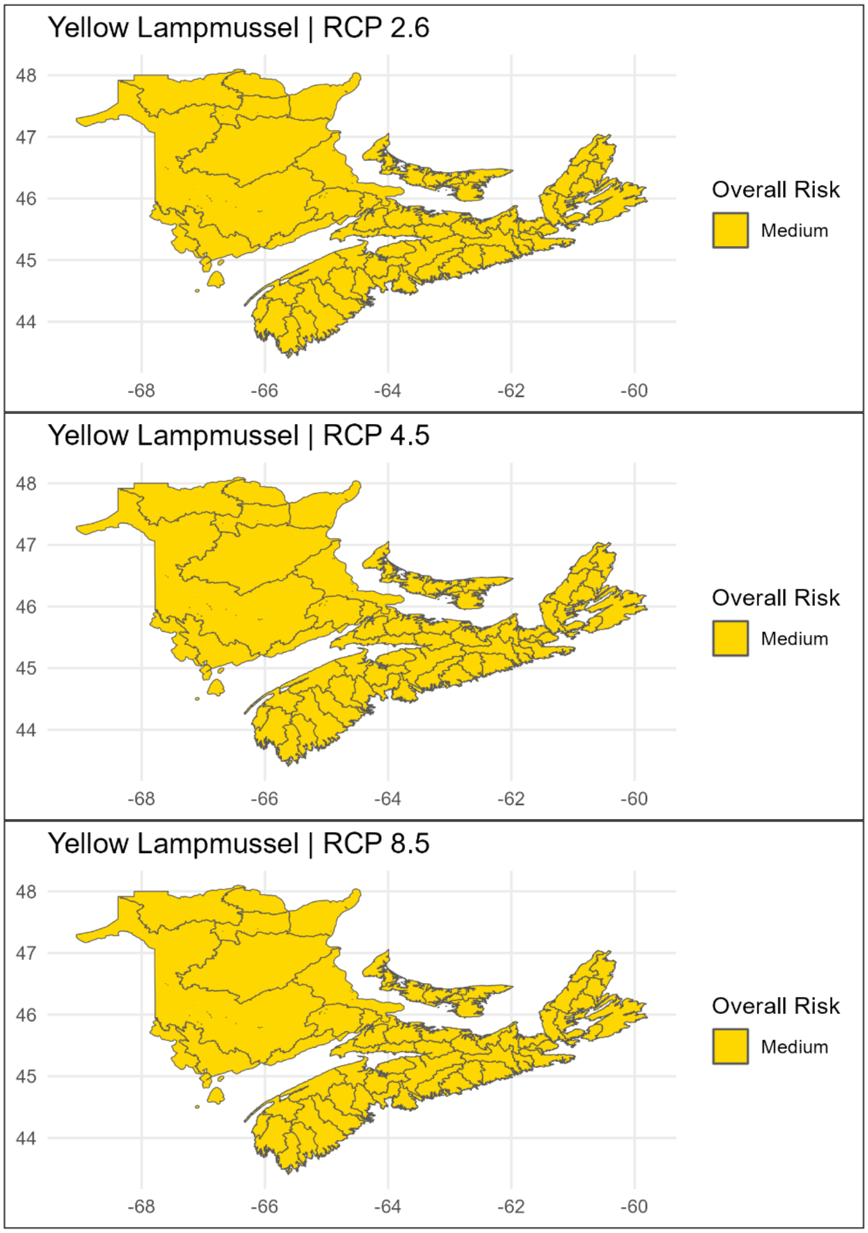
Appendix 18 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by shortnose sturgeon overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



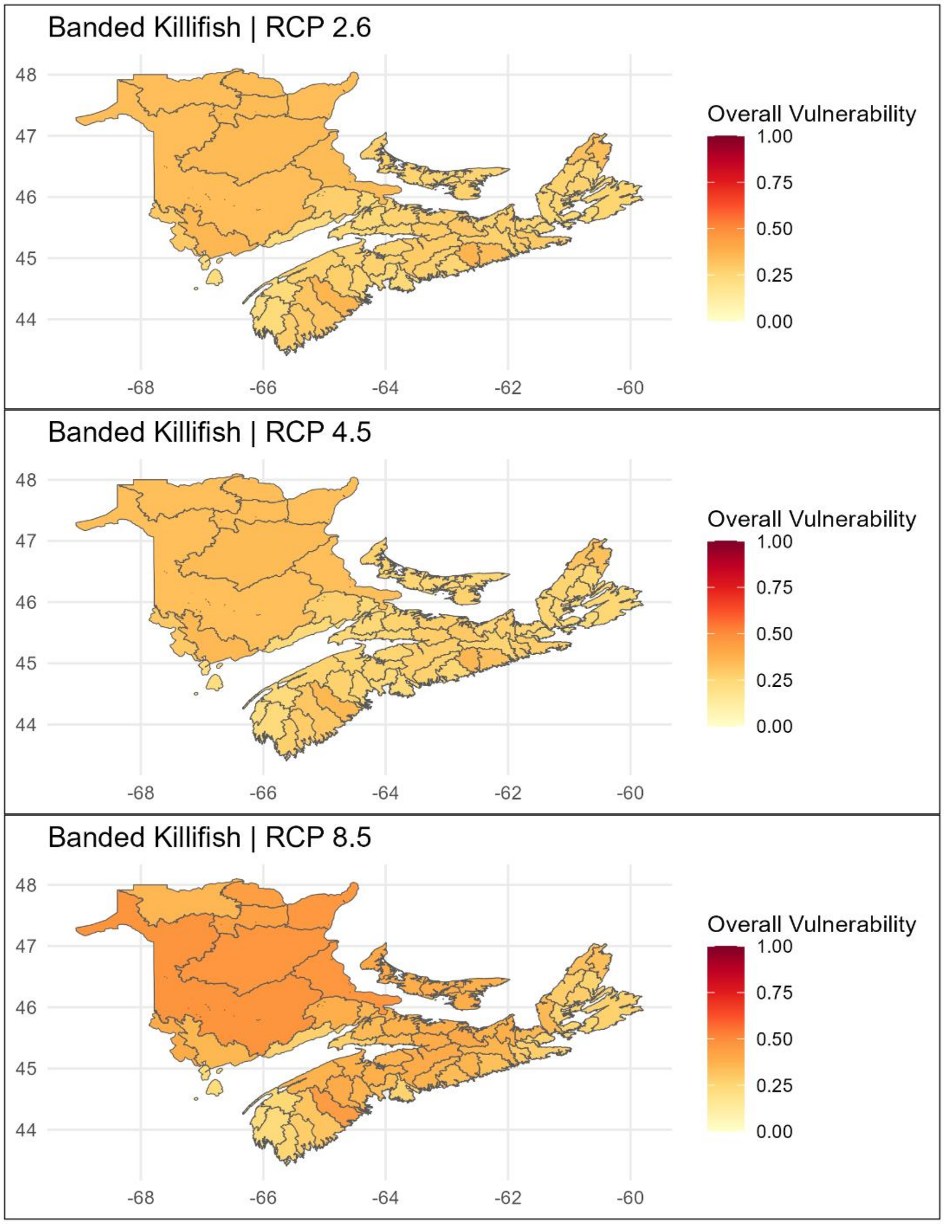
Appendix 19 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by shortnose sturgeon overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



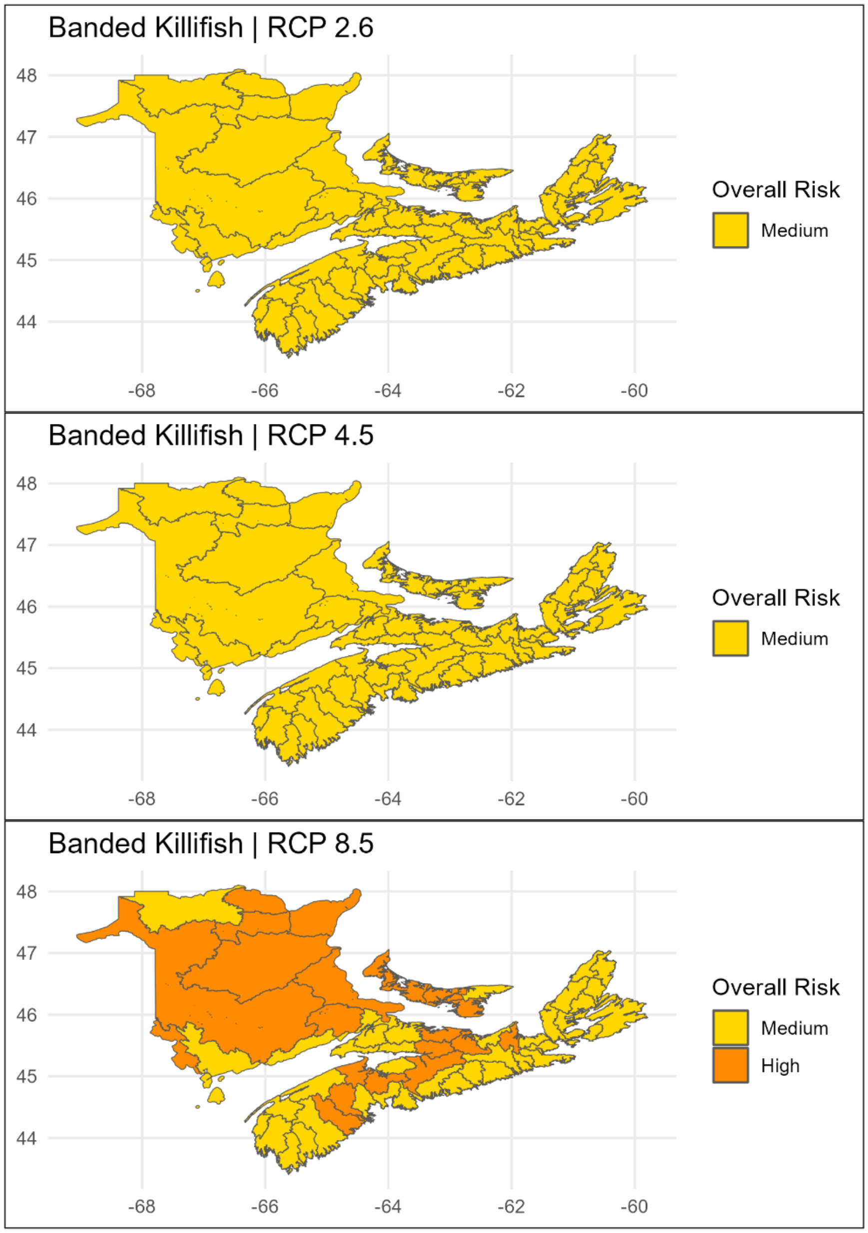
Appendix 20 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by yellow lampmussel overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



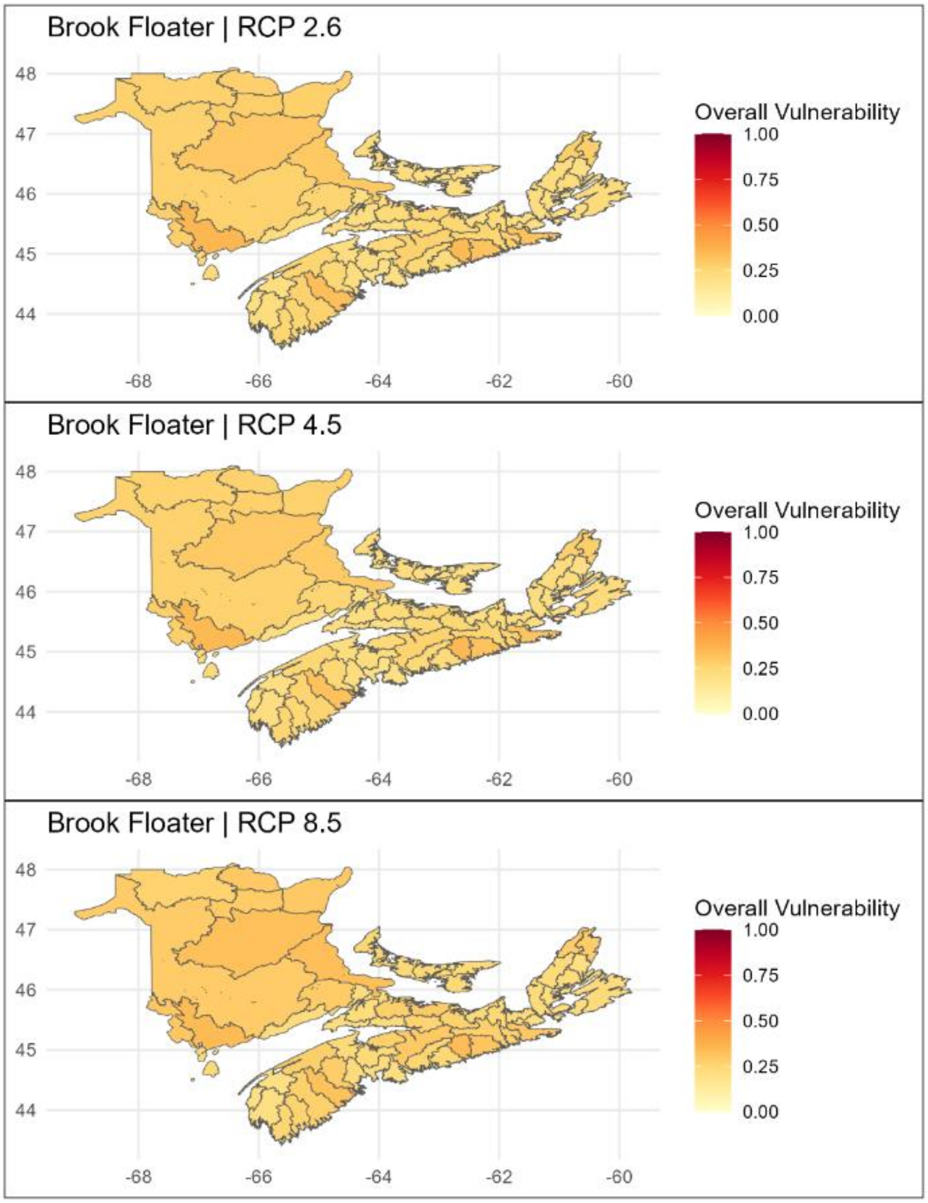
Appendix 21 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by yellow lampmussel overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



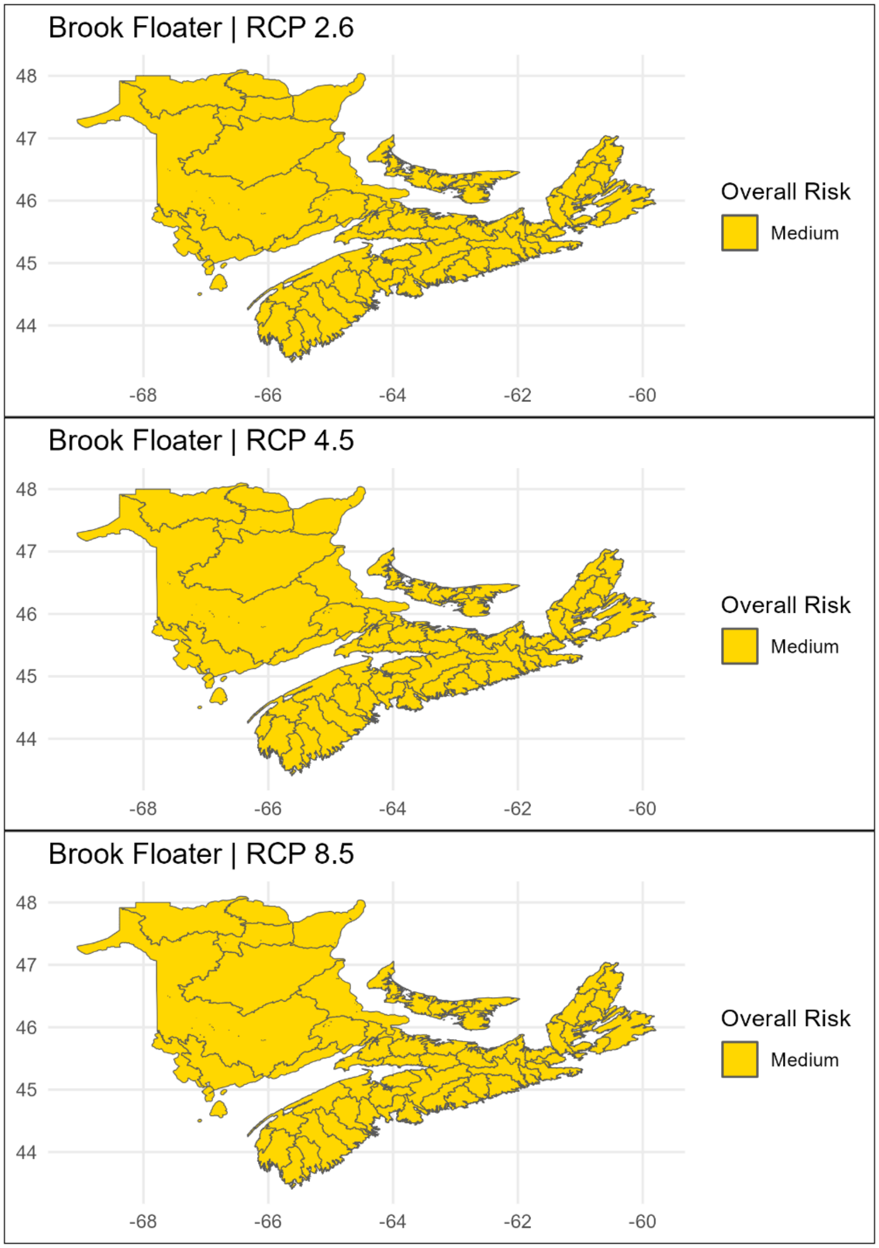
Appendix 22 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by banded killifish overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



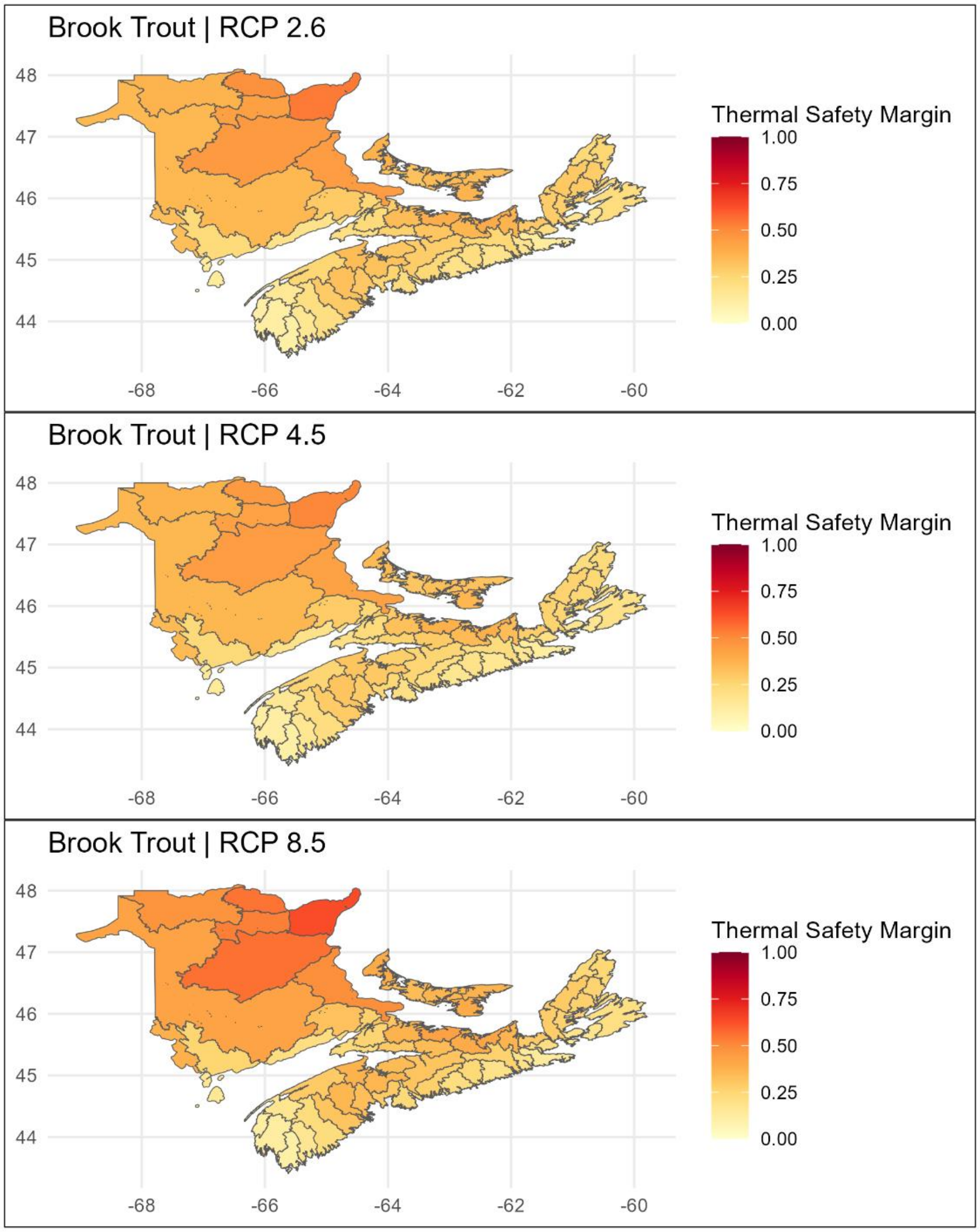
Appendix 23 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by banded killifish overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



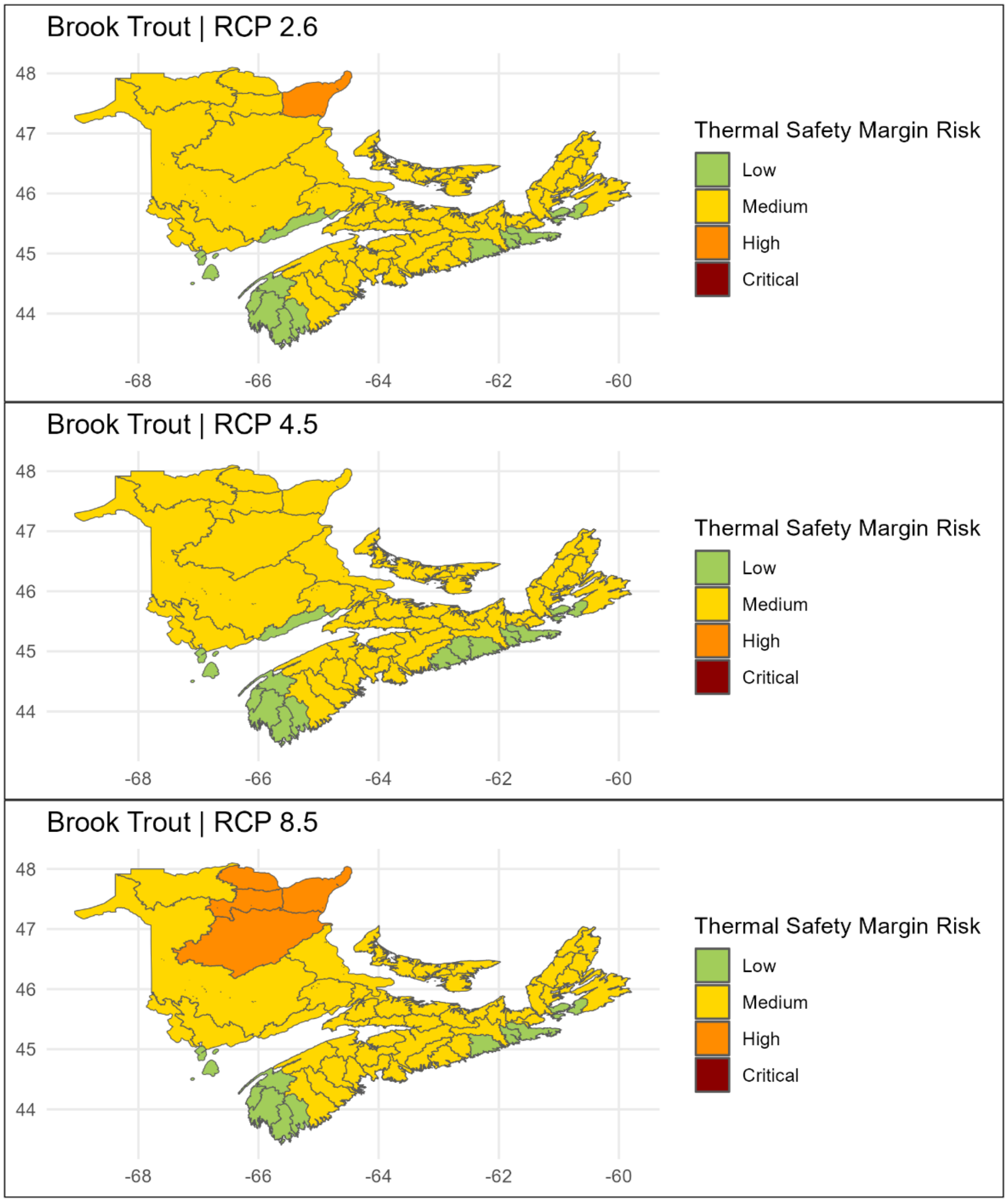
Appendix 24 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by brook floater overall vulnerability results from 0-1 for each of three RCPs (2.6, 4.5, 8.5).



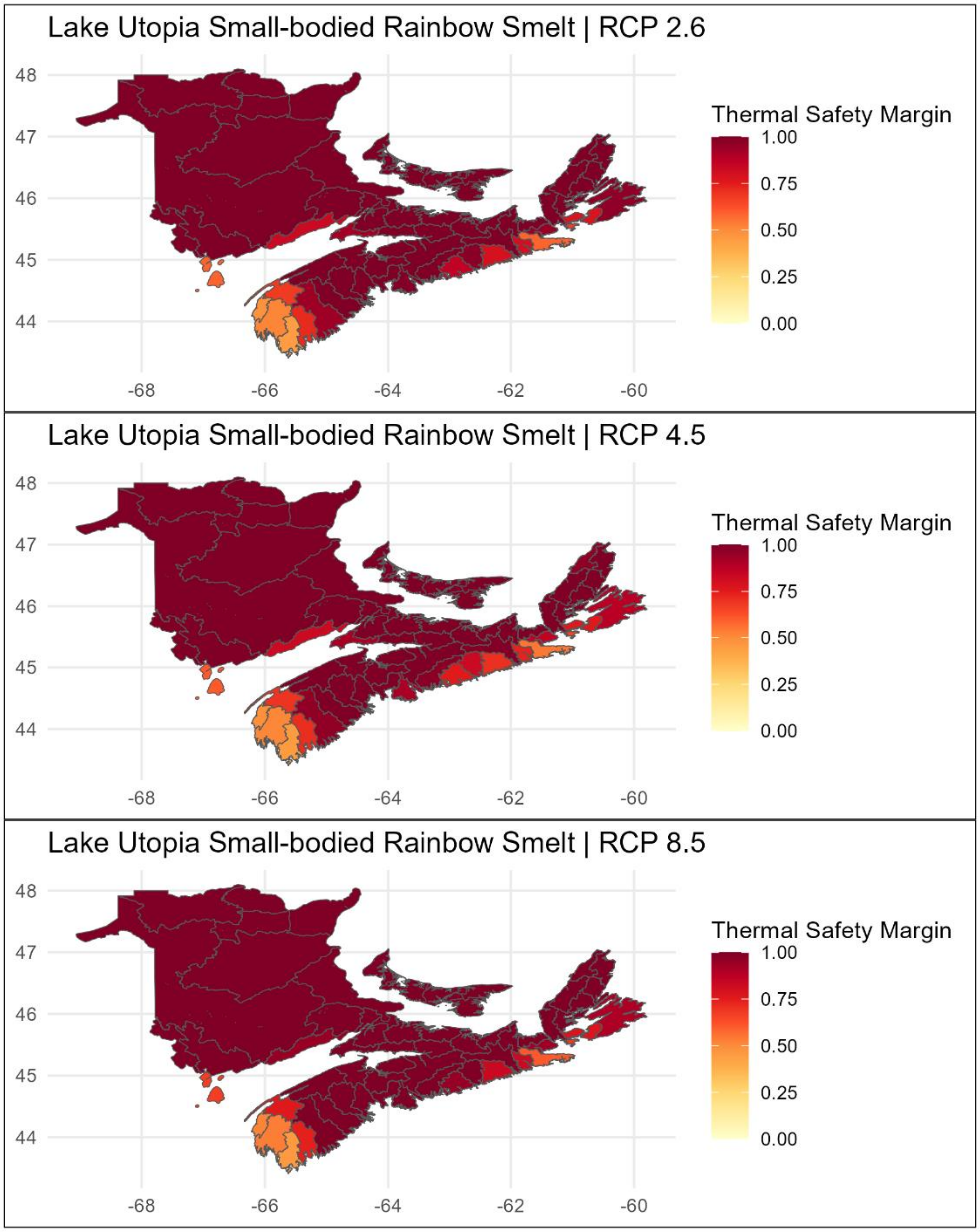
Appendix 25 Map of study area; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Map coloured by brook floater overall risk levels for each of three RCPs (2.6, 4.5, 8.5)



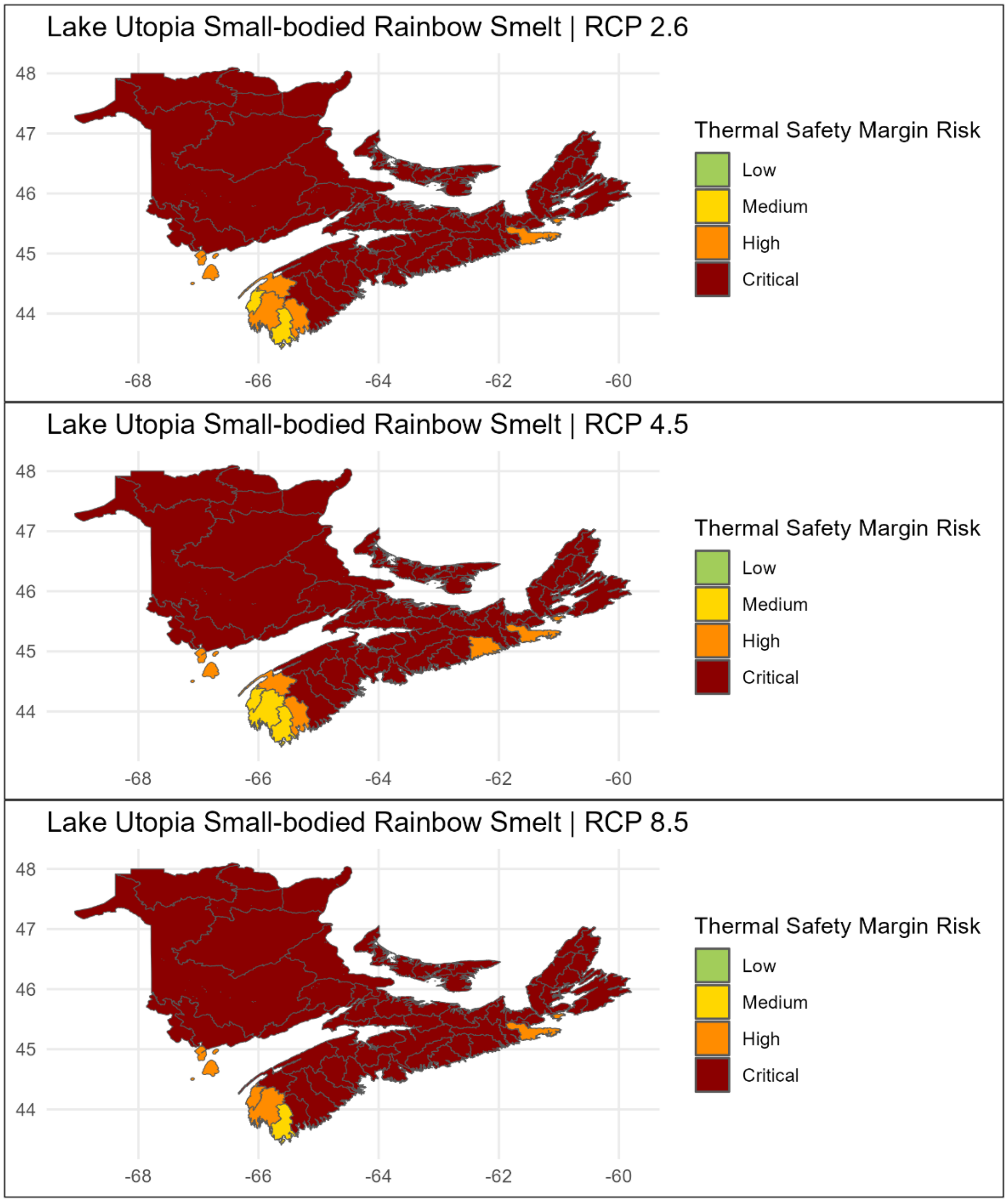
Appendix 26 Map of study area coloured by brook trout thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



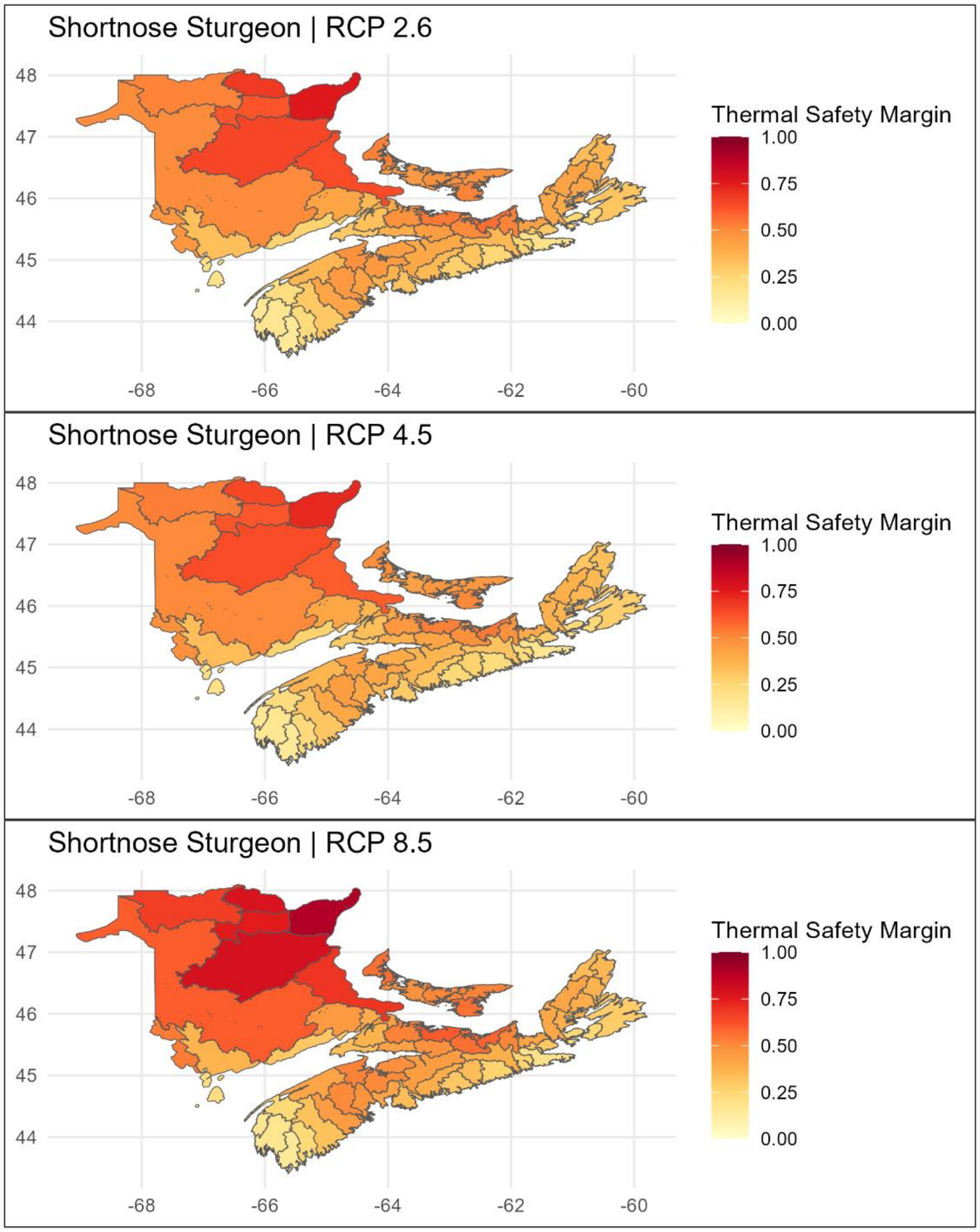
Appendix 27 Map of study area coloured by brook trout thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



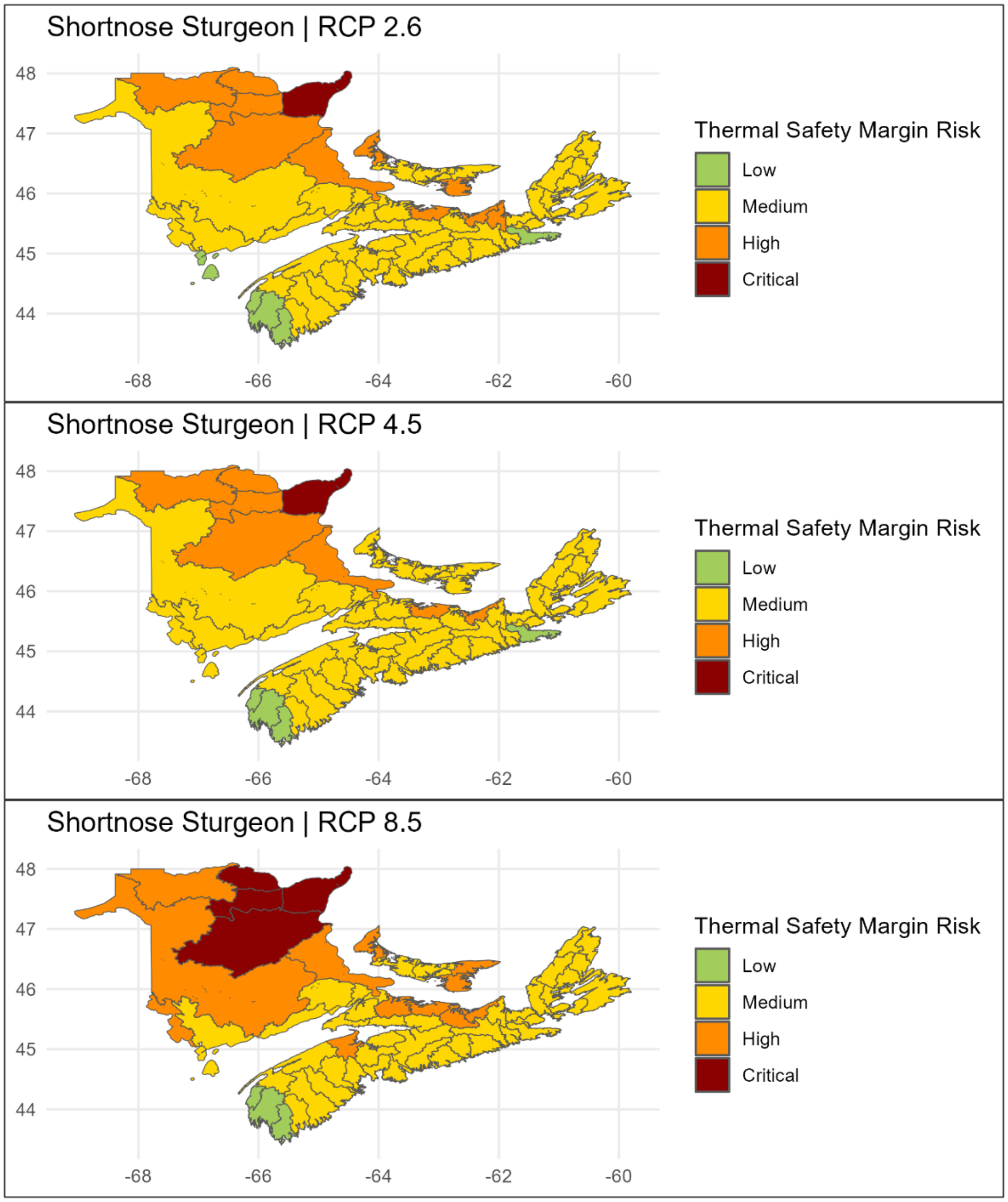
Appendix 28 Map of study area coloured by Lake Utopia small-bodie rainbow smelt thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



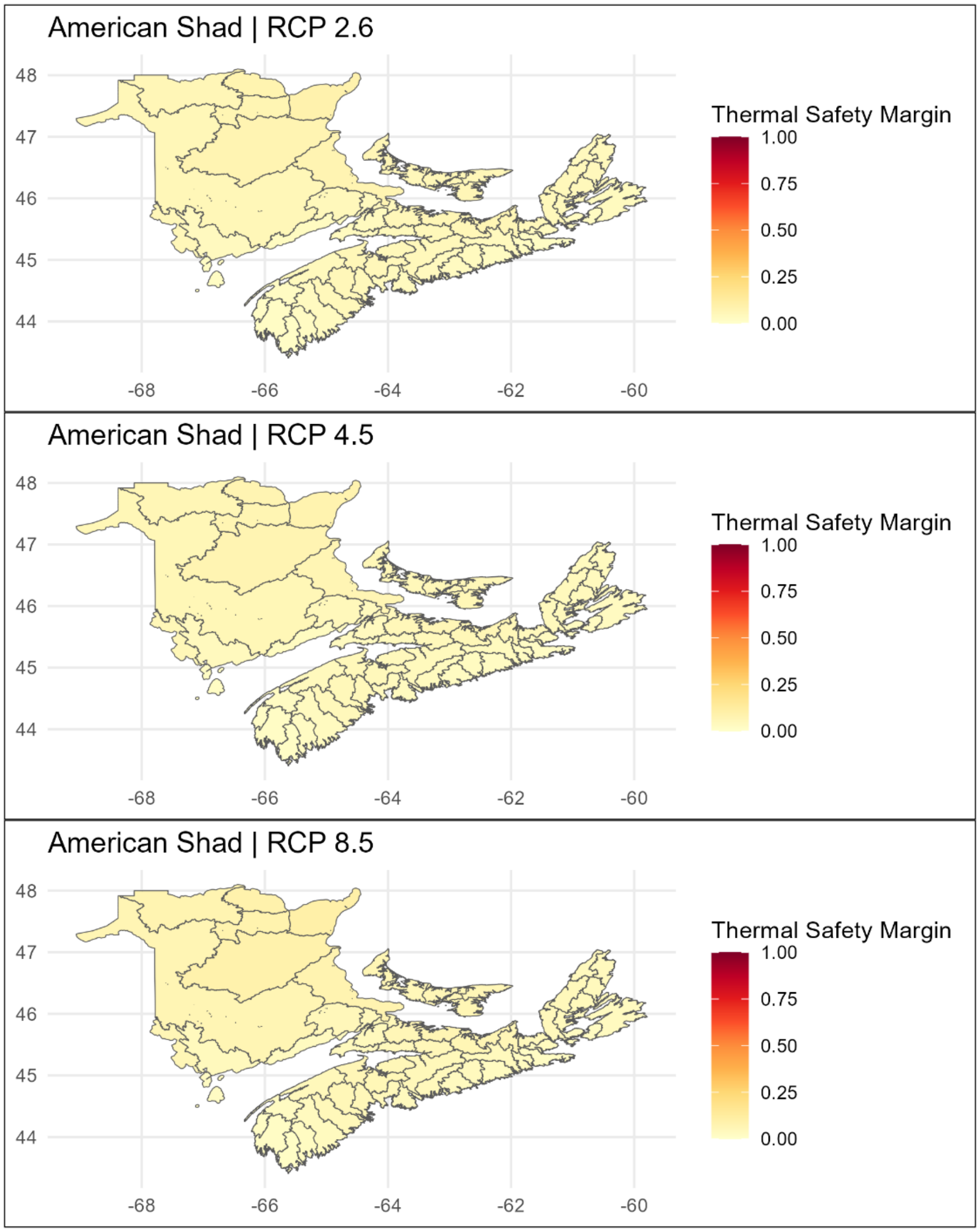
Appendix 29 Map of study area coloured by Lake Utopia small-bodied rainbow smelt thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



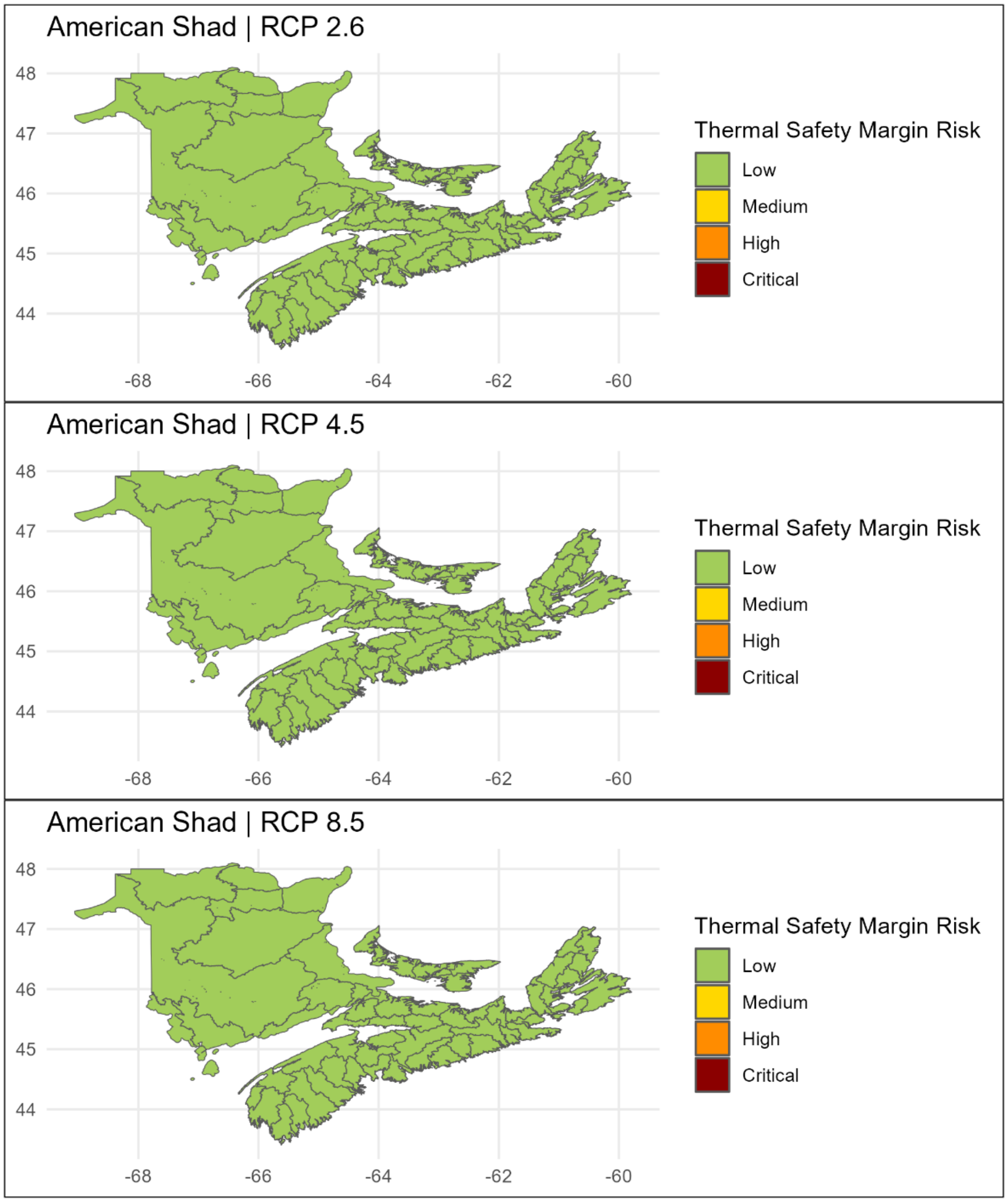
Appendix 30 Map of study area coloured by shortnose sturgeon thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



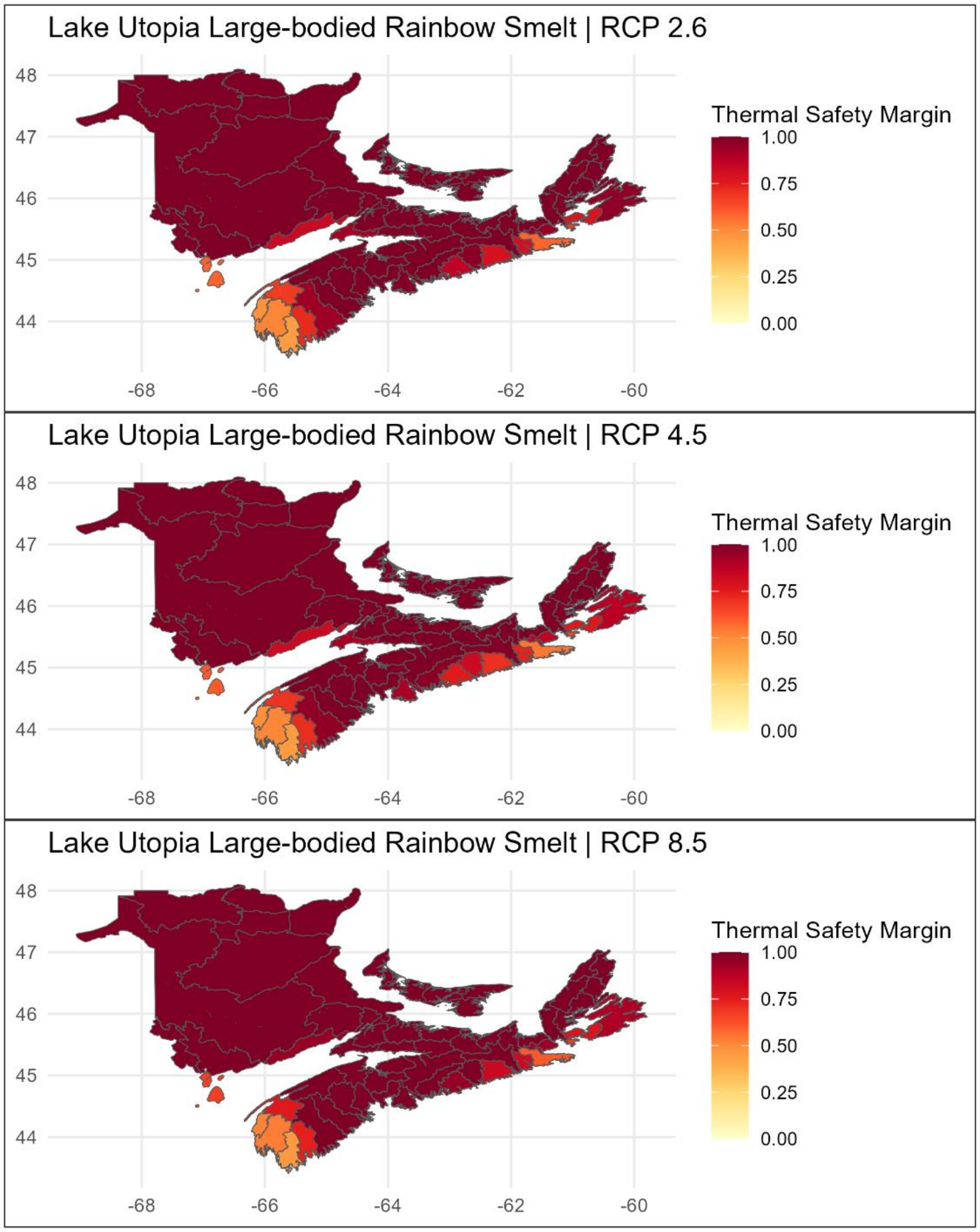
Appendix 31 Map of study area coloured by shortnose sturgeon thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



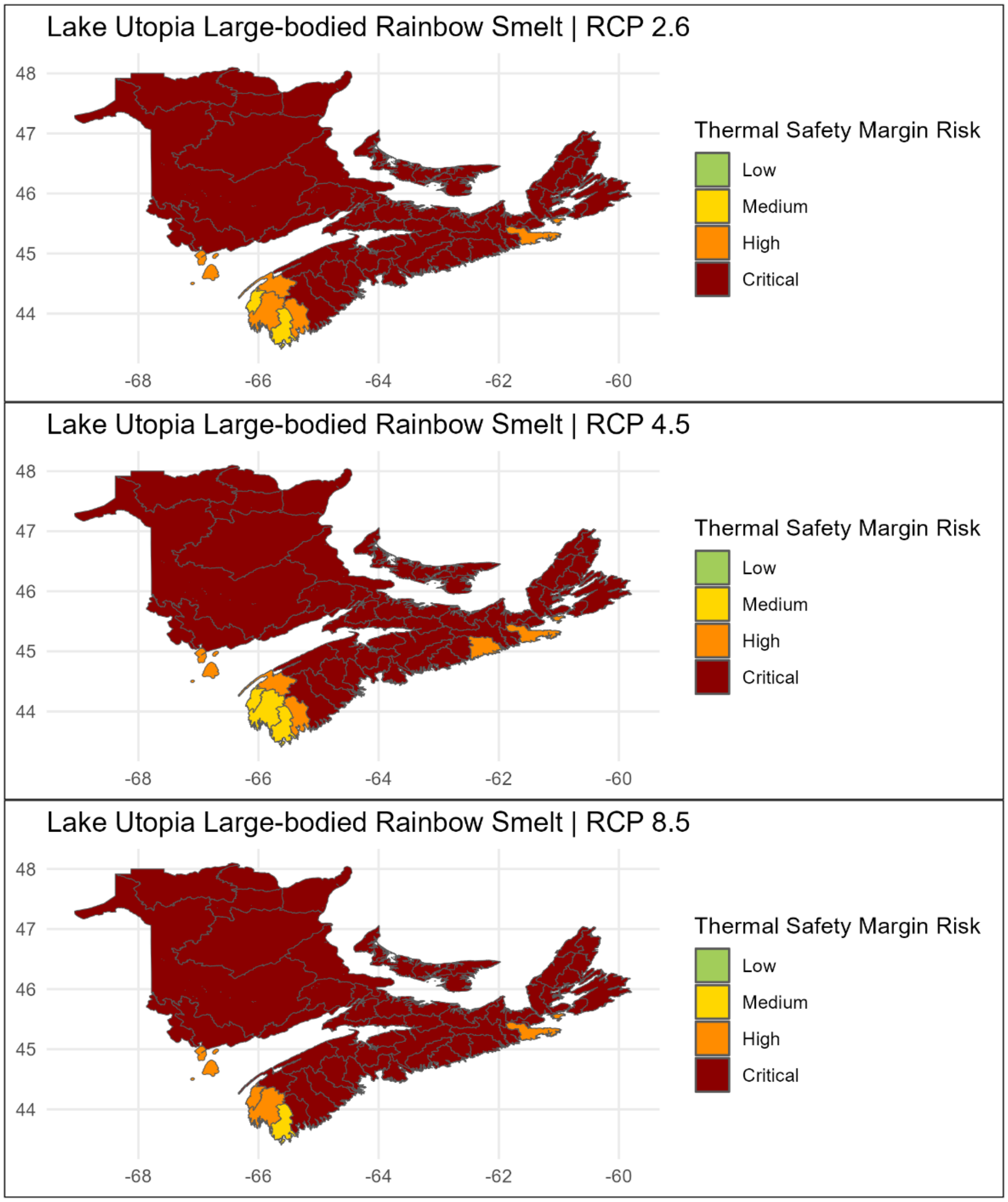
Appendix 32 Map of study area coloured by American shad thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



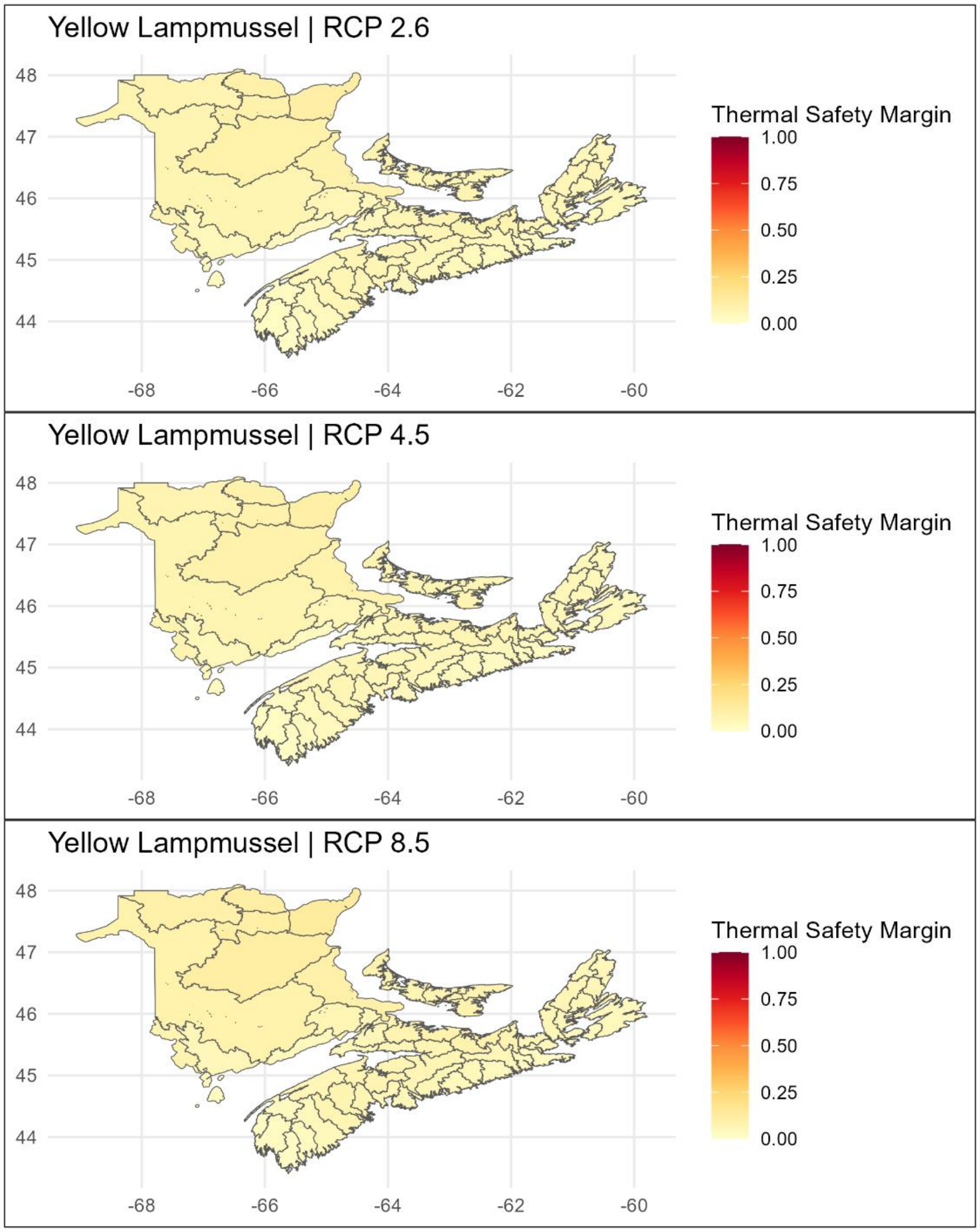
Appendix 33 Map of study area coloured by American shad thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



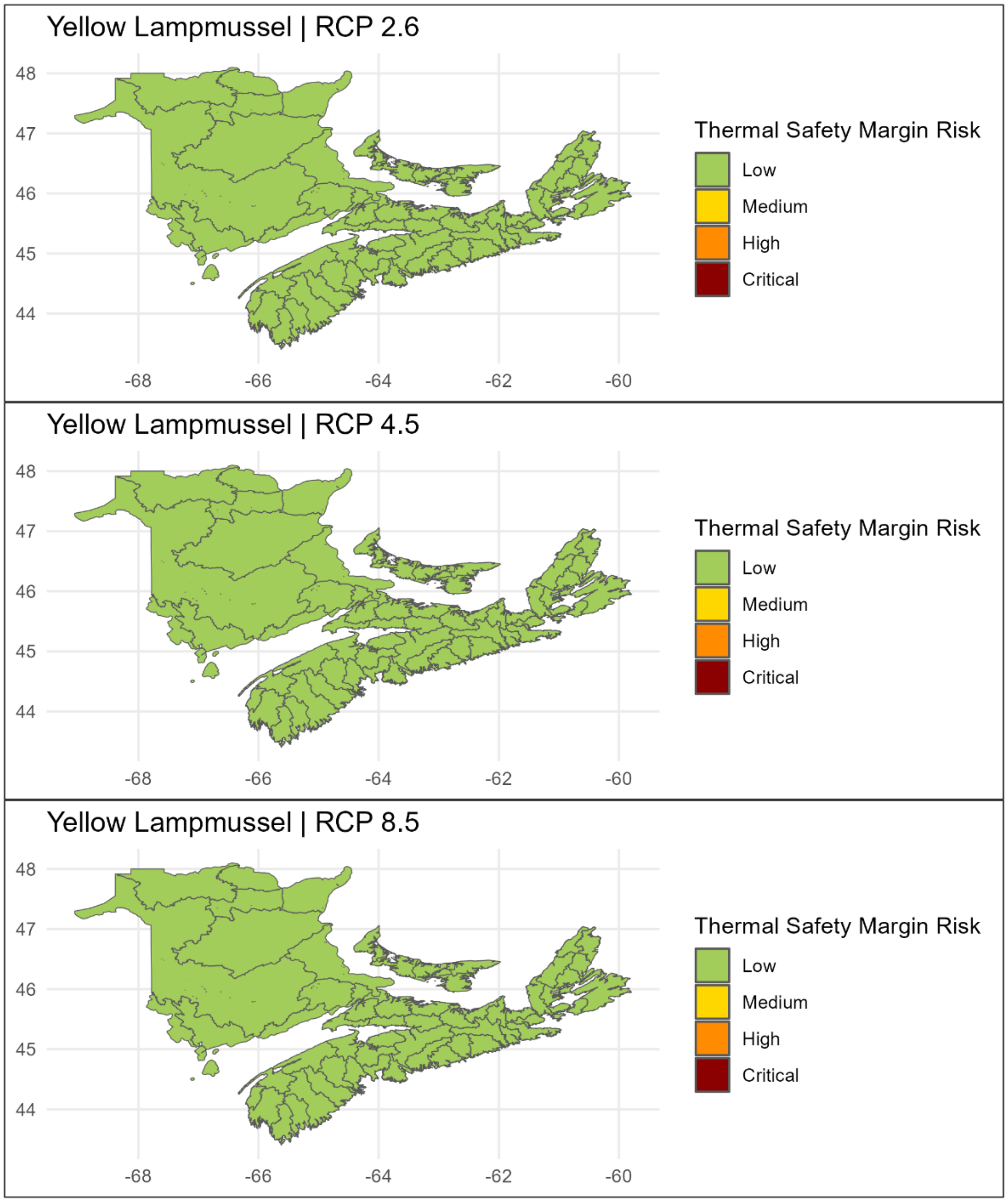
Appendix 34 Map of study area coloured by Lake Utopia large bodied rainbow smelt thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



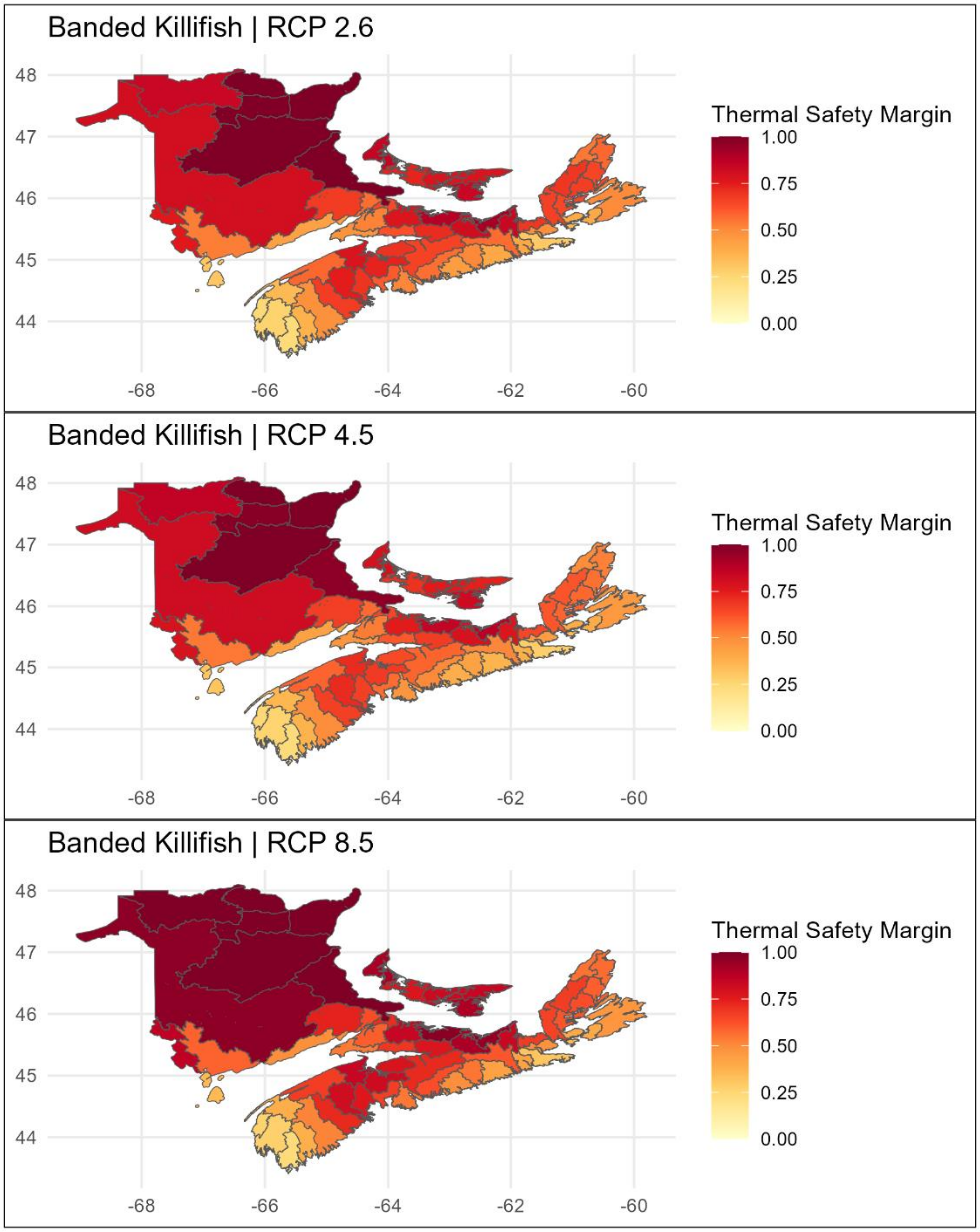
Appendix 35 Map of study area coloured by Lake Utopia large-bodied rainbow smelt thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



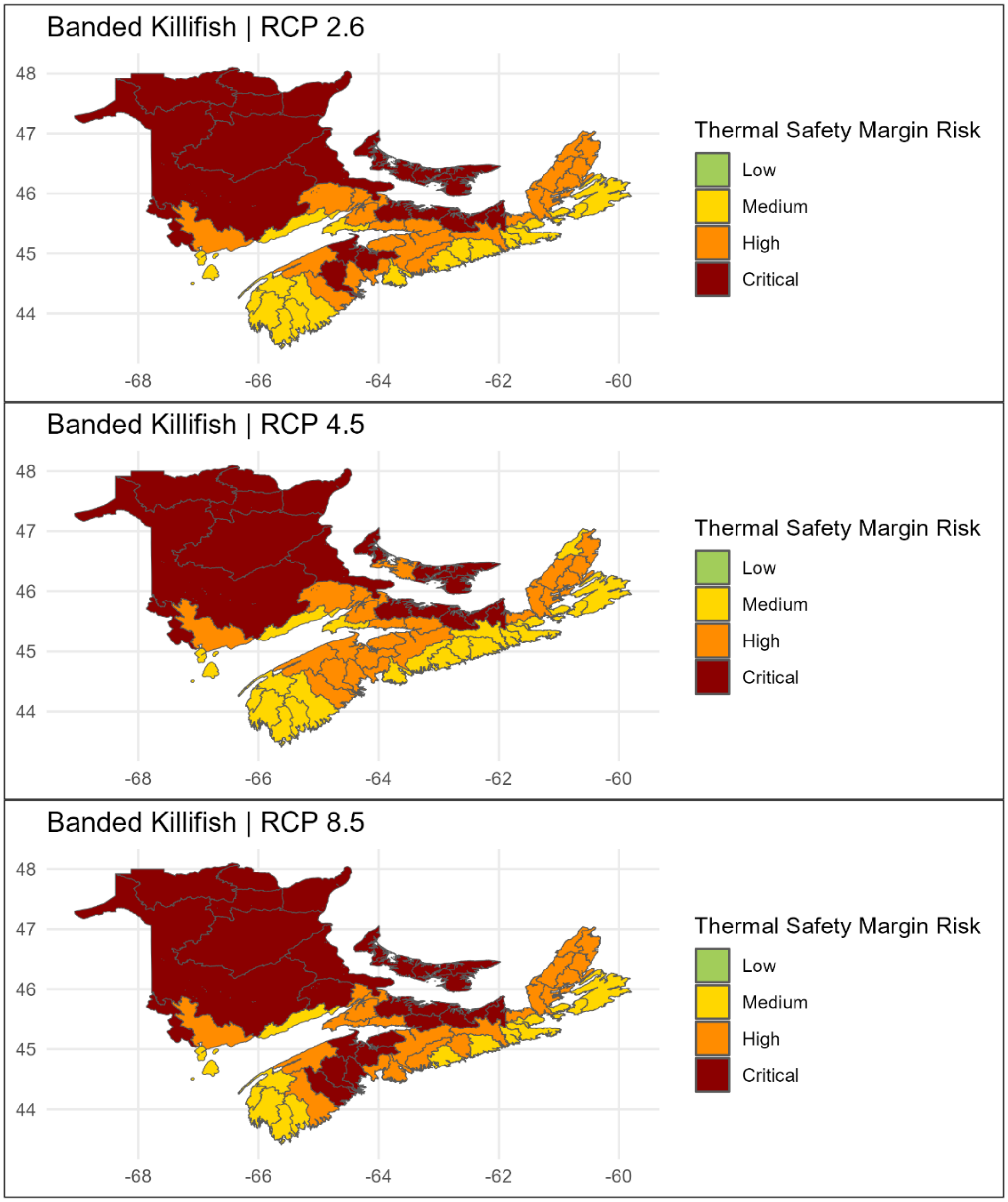
Appendix 36 Map of study area coloured by yellow lampmussel thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



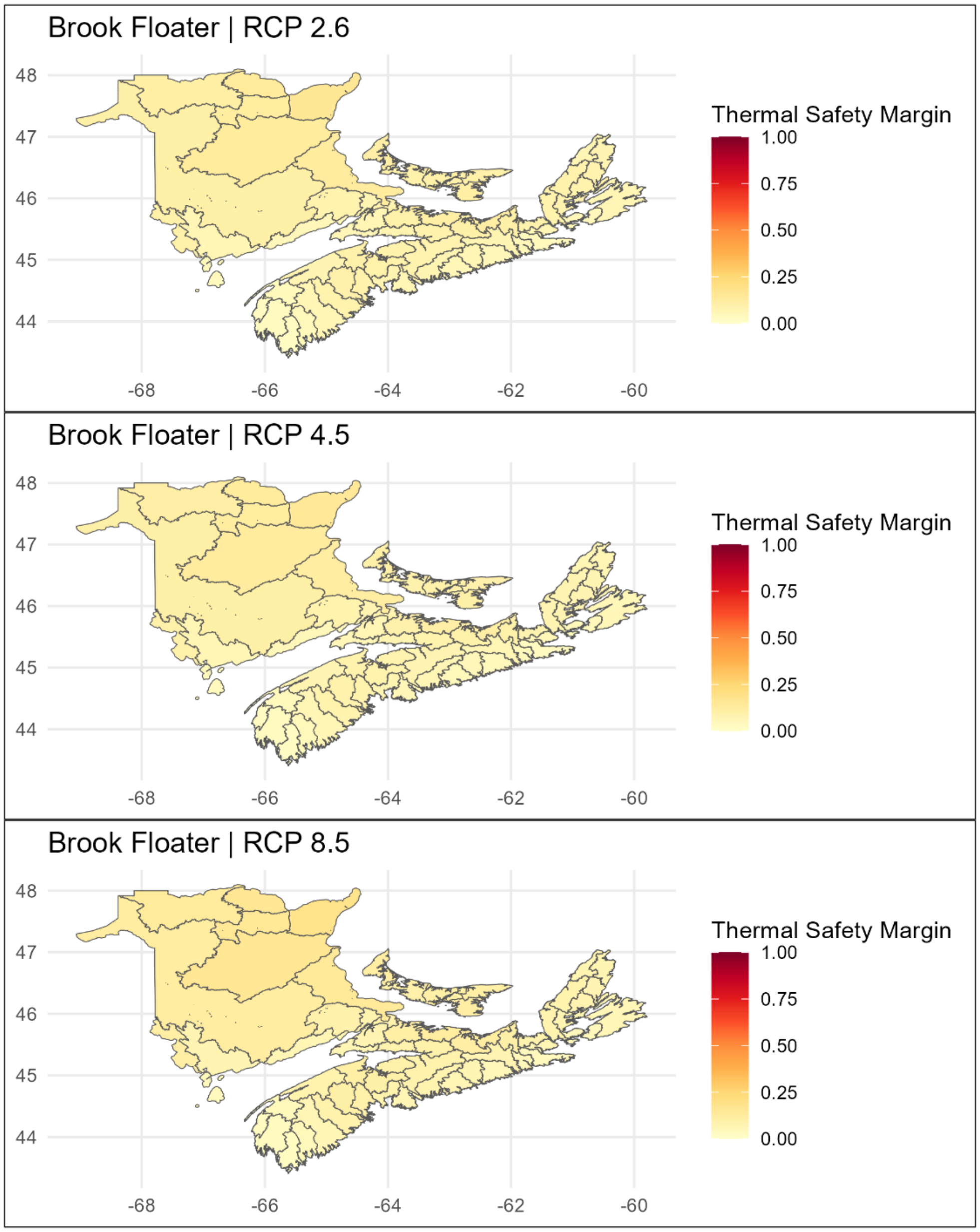
Appendix 37 Map of study area coloured by yellow lampmussel thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



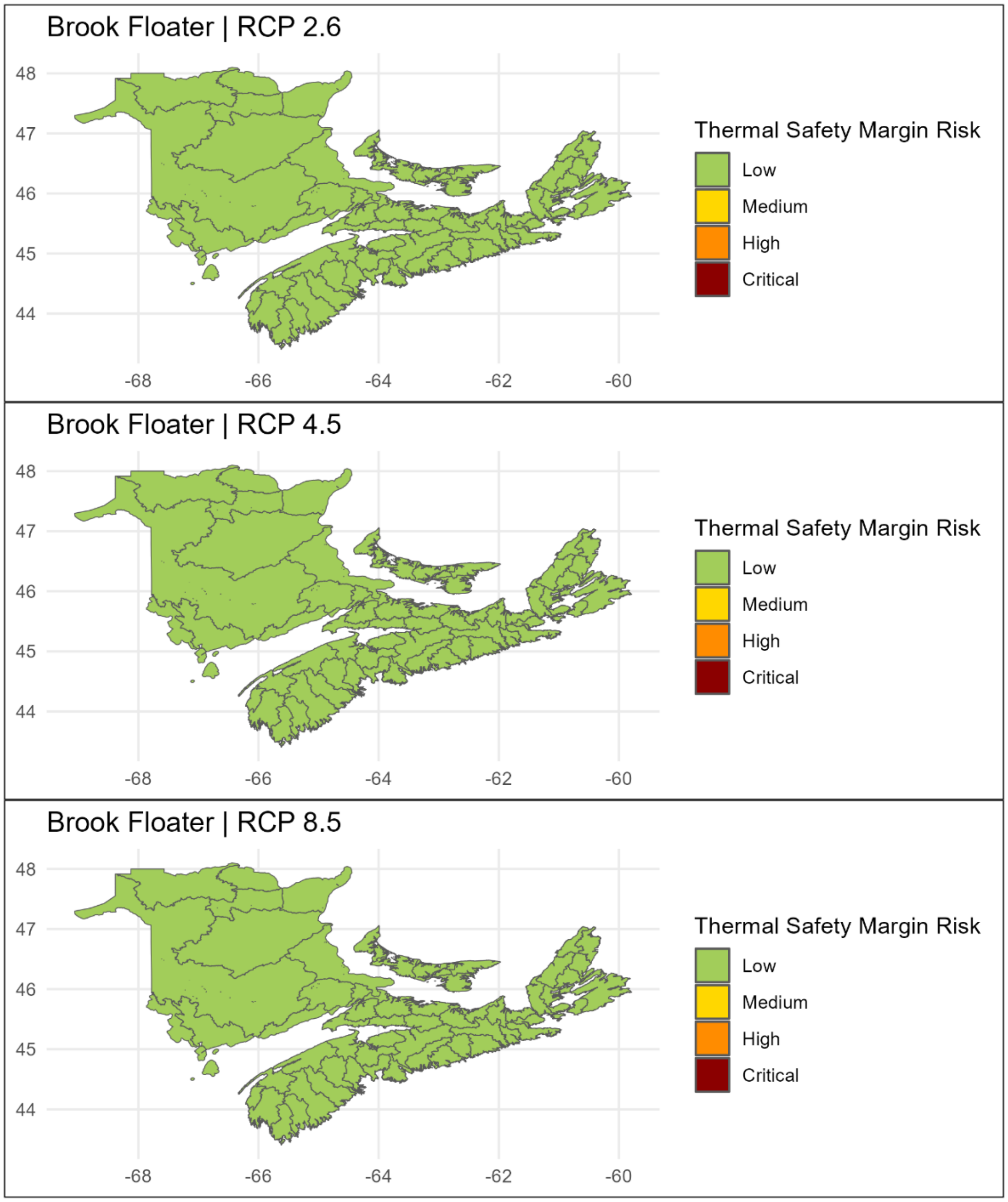
Appendix 38 Map of study area coloured by banded killifish thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



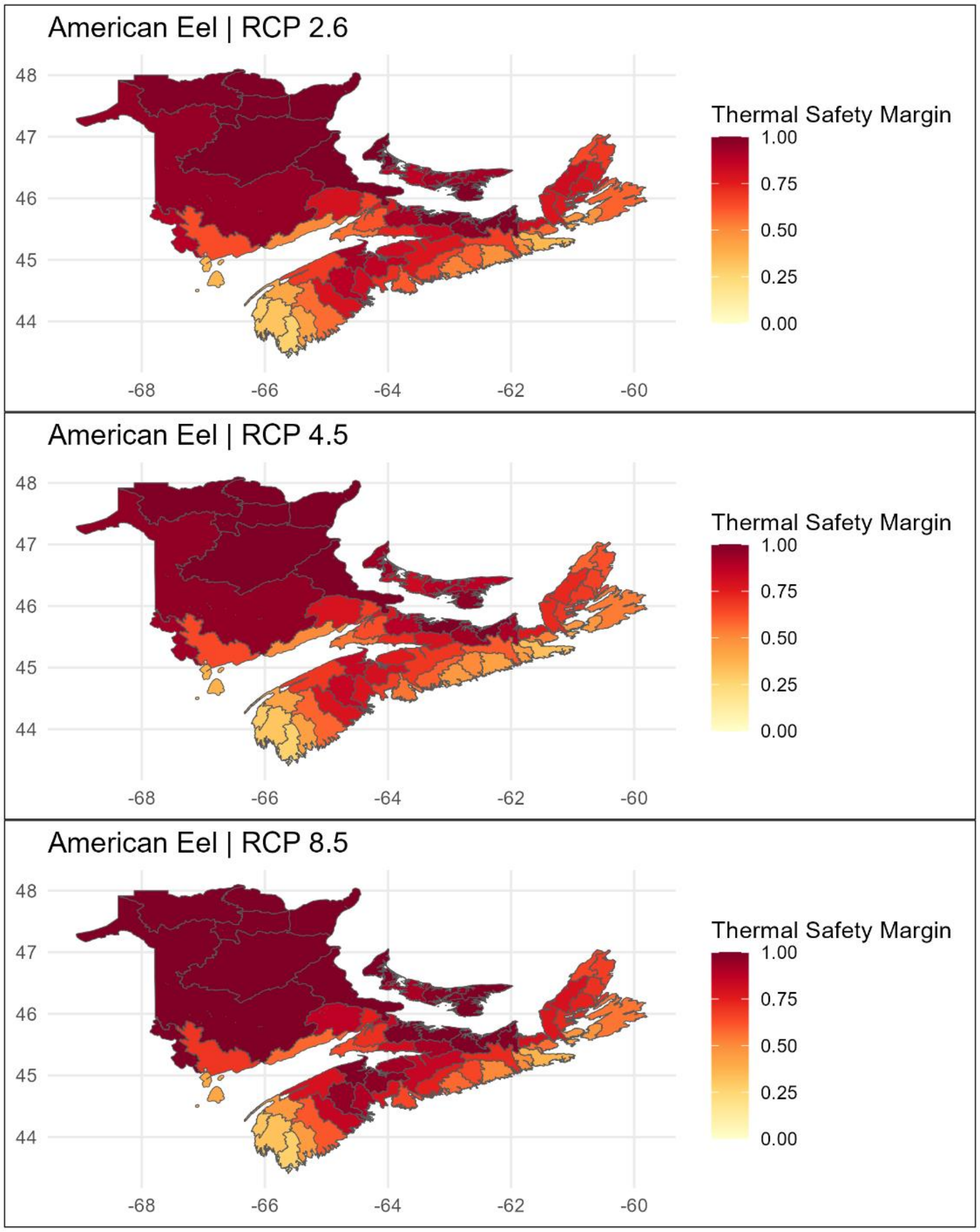
Appendix 39 Map of study area coloured by banded killifish thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



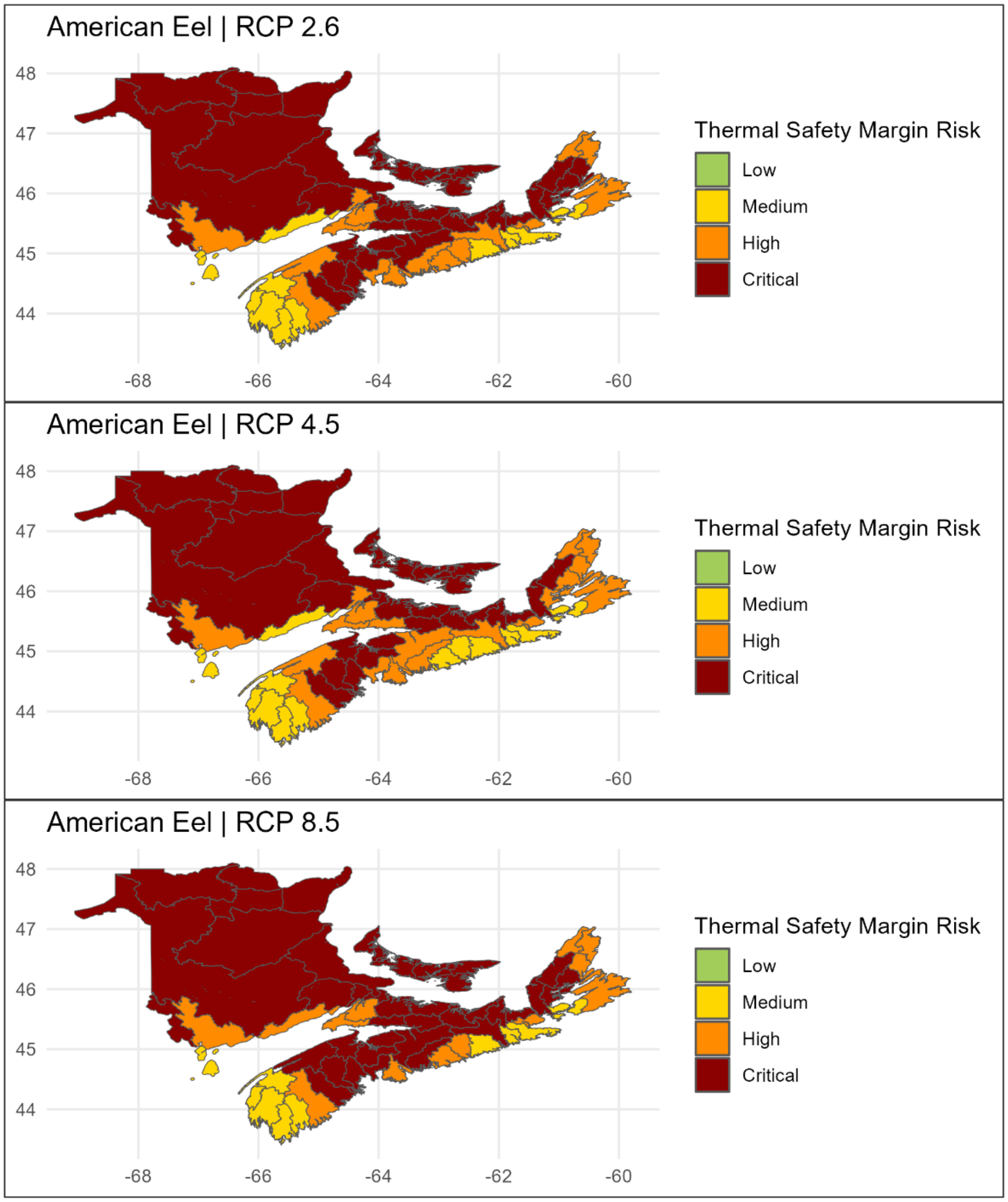
Appendix 40 Map of study area coloured by brook floater thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



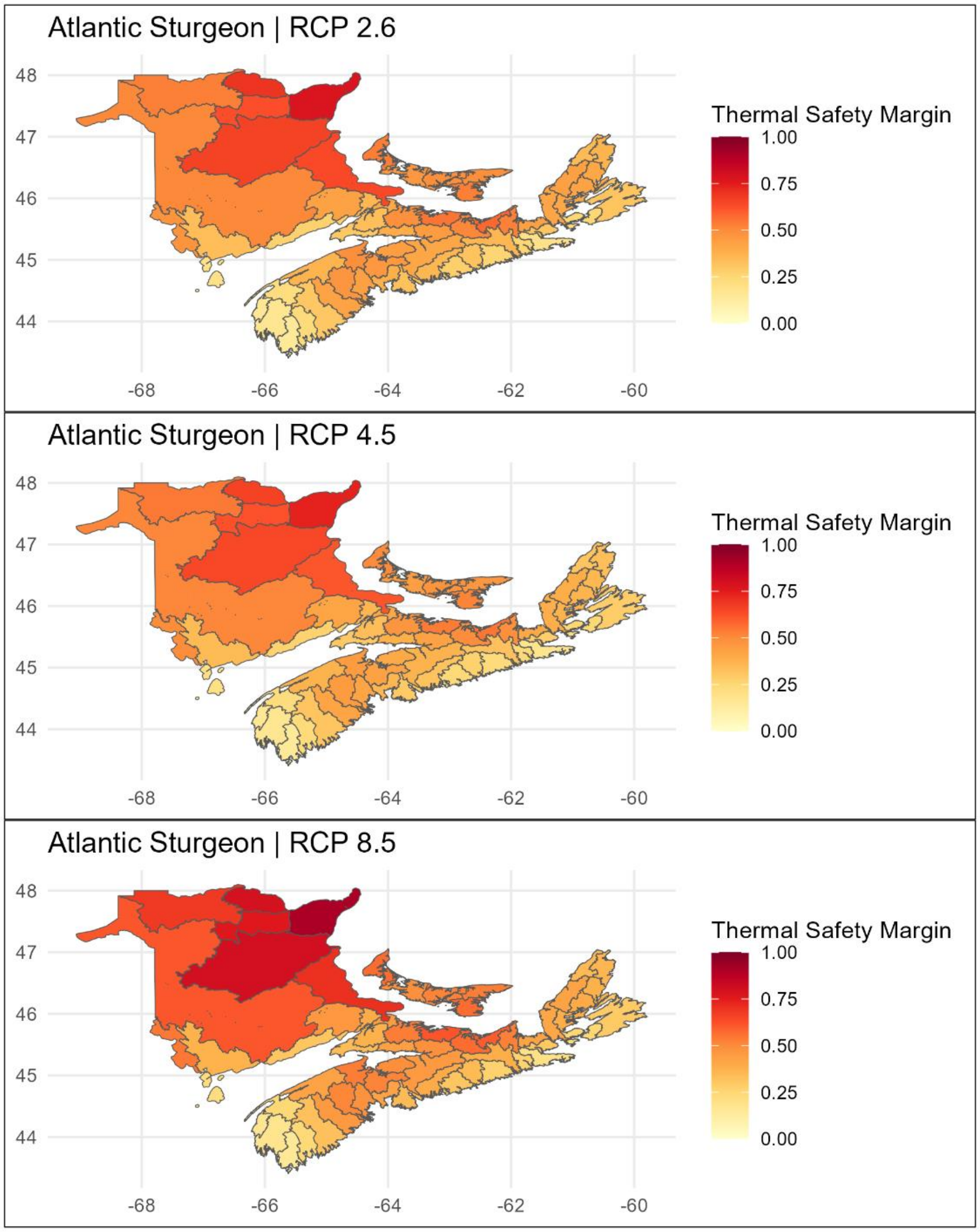
Appendix 41 Map of study area coloured by brook floater thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



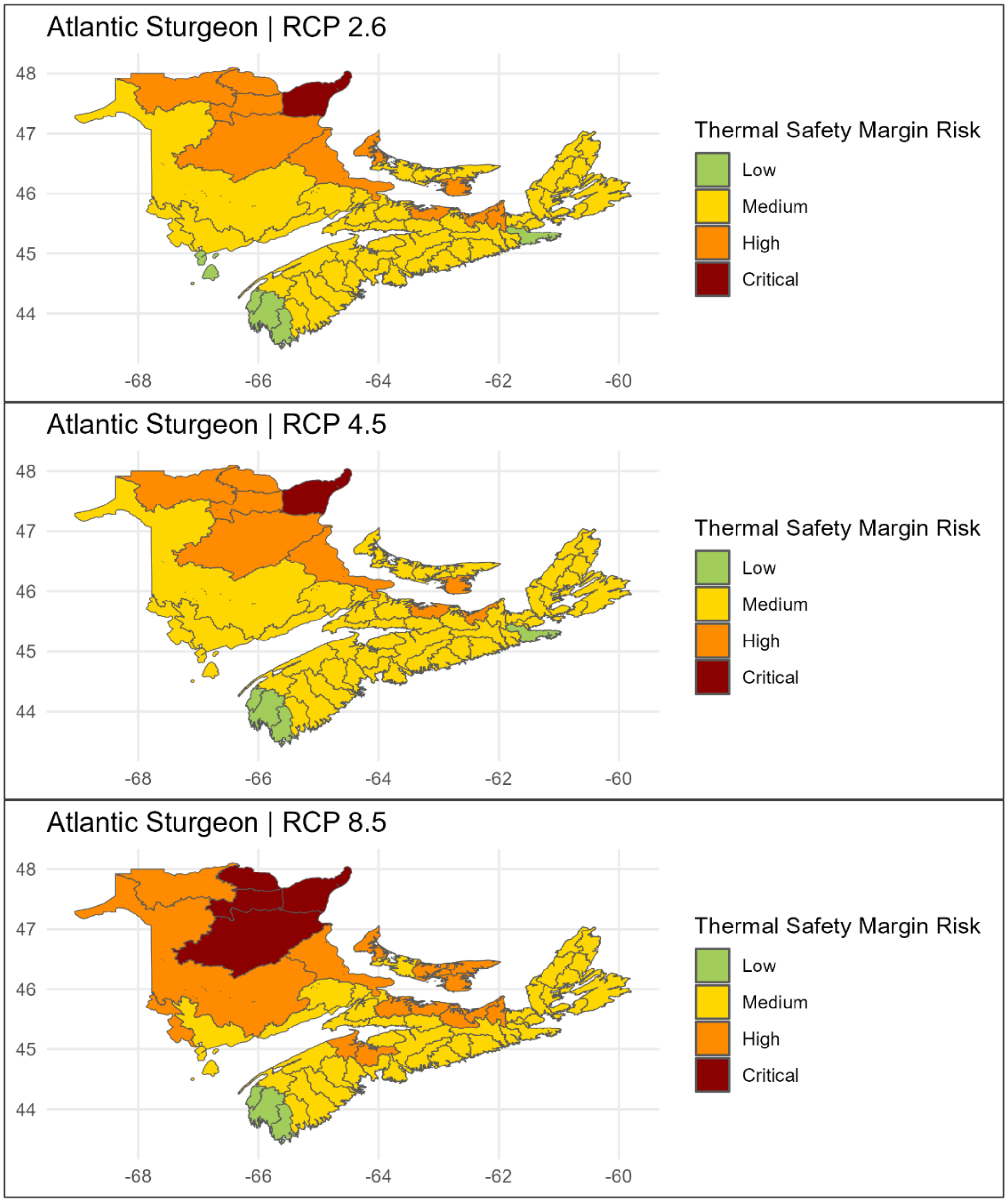
Appendix 42 Map of study area coloured by American eel thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



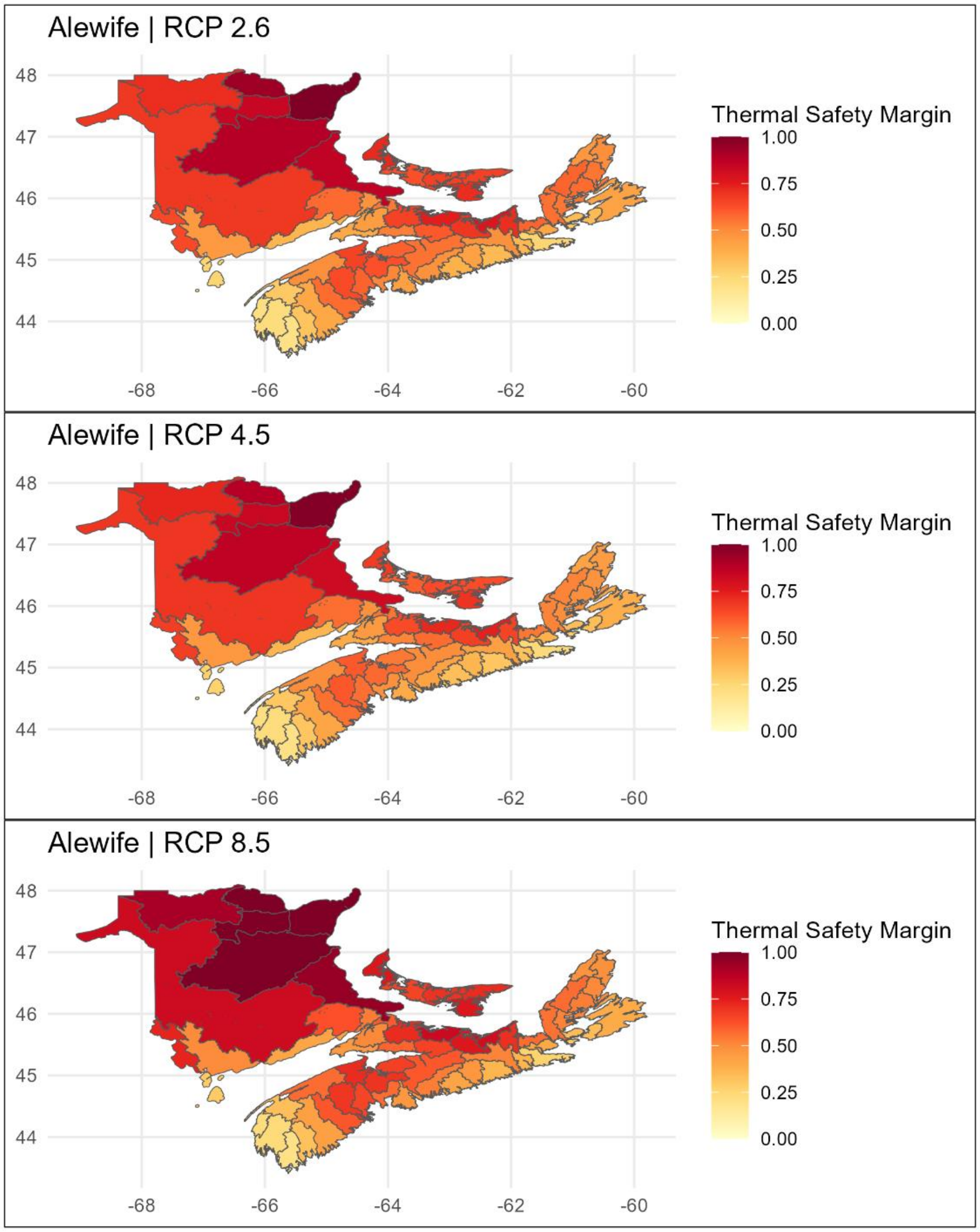
Appendix 43 Map of study area coloured by American eel thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



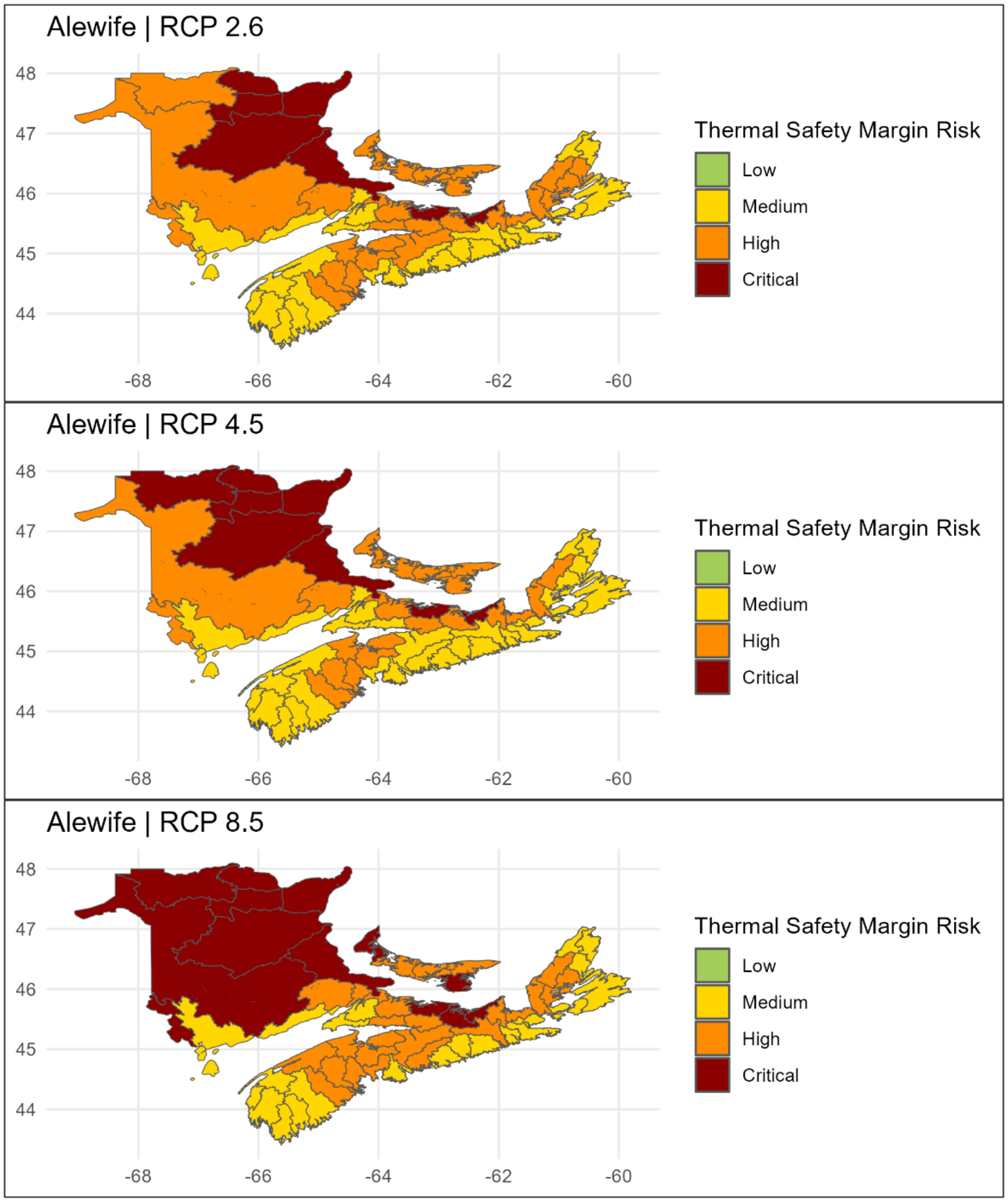
Appendix 44 Map of study area coloured by Atlantic sturgeon thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



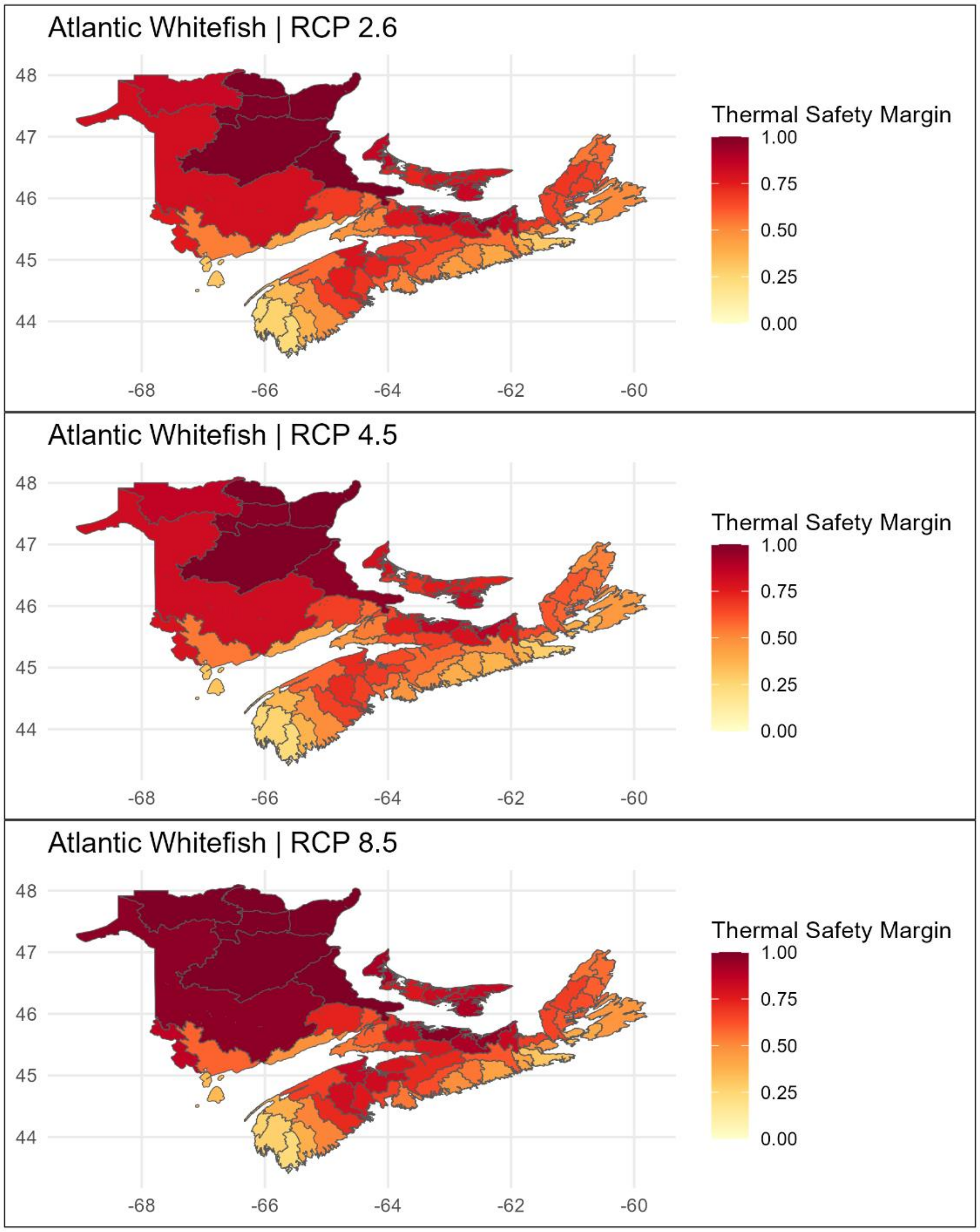
Appendix 45 Map of study area coloured by Atlantic sturgeon thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



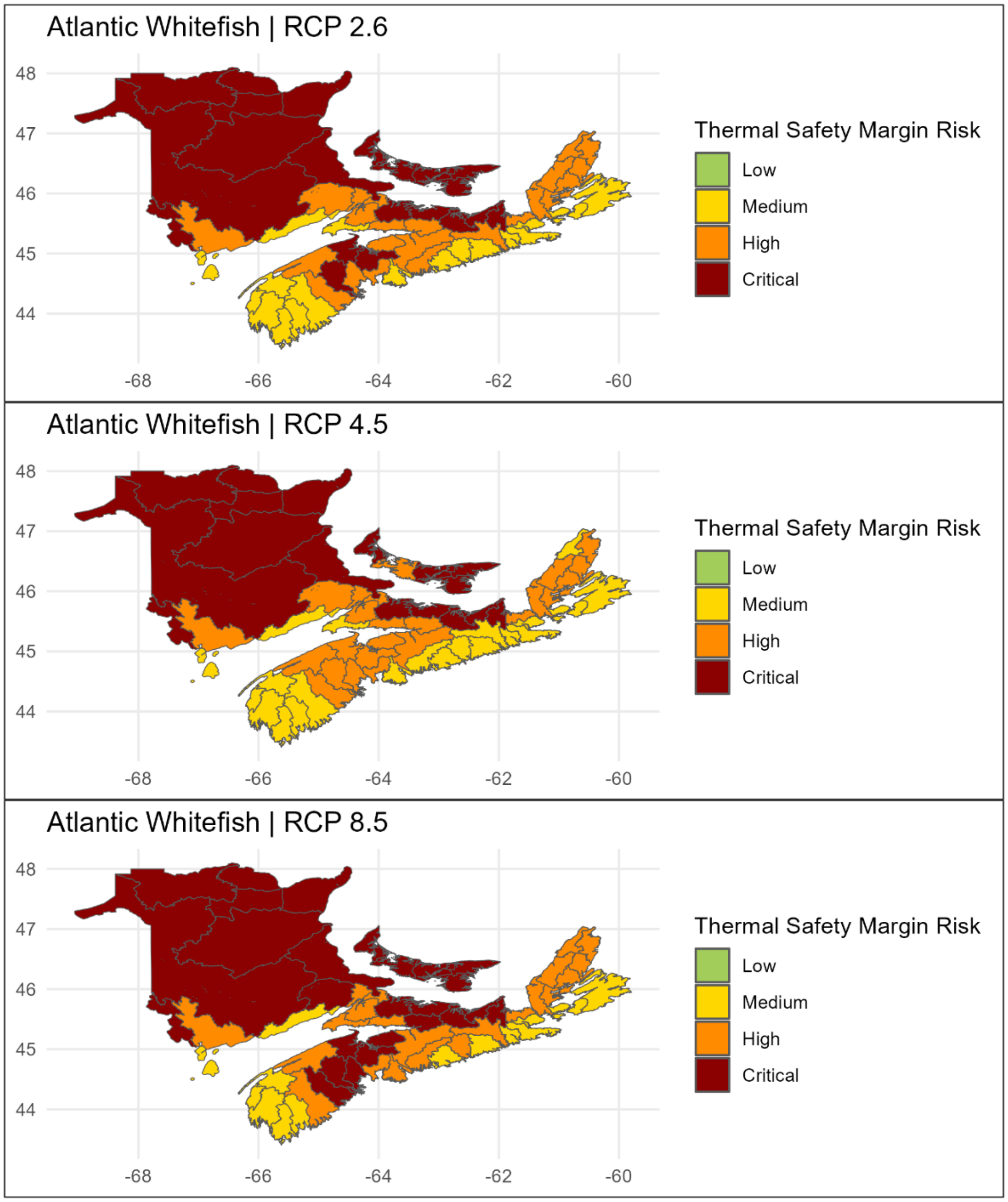
Appendix 46 Map of study area coloured by alewife thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



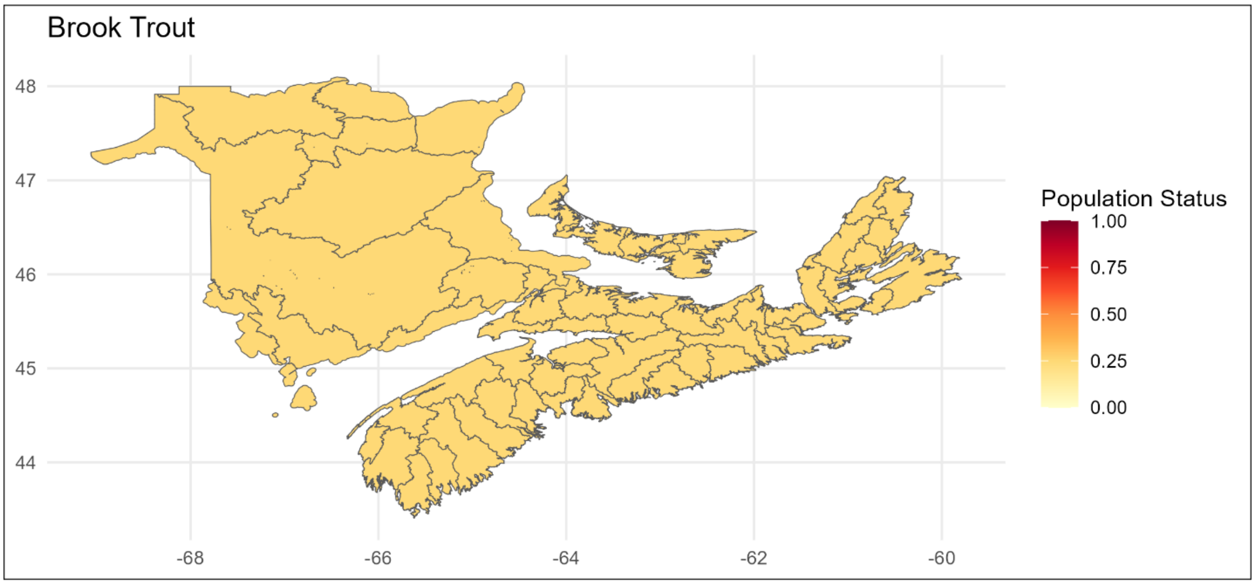
Appendix 47 Map of study area coloured by alewife thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



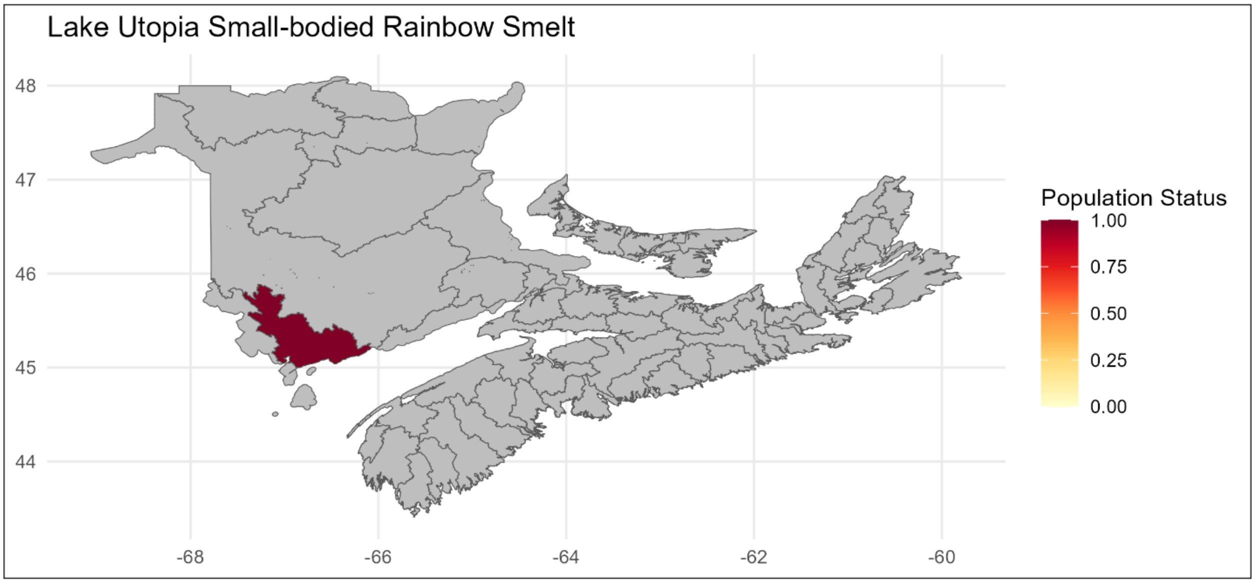
Appendix 48 Map of study area coloured by Atlantic whitefish thermal safety margin index scores from 0-1 for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



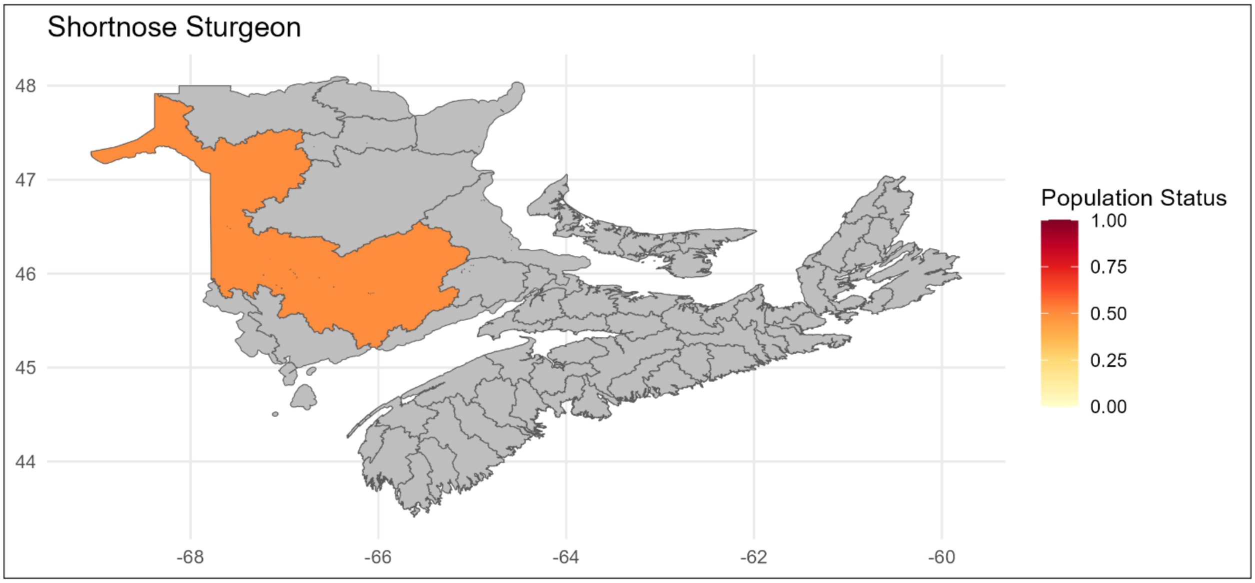
Appendix 49 Map of study area coloured by Atlantic whitefish thermal safety margin index risk levels for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



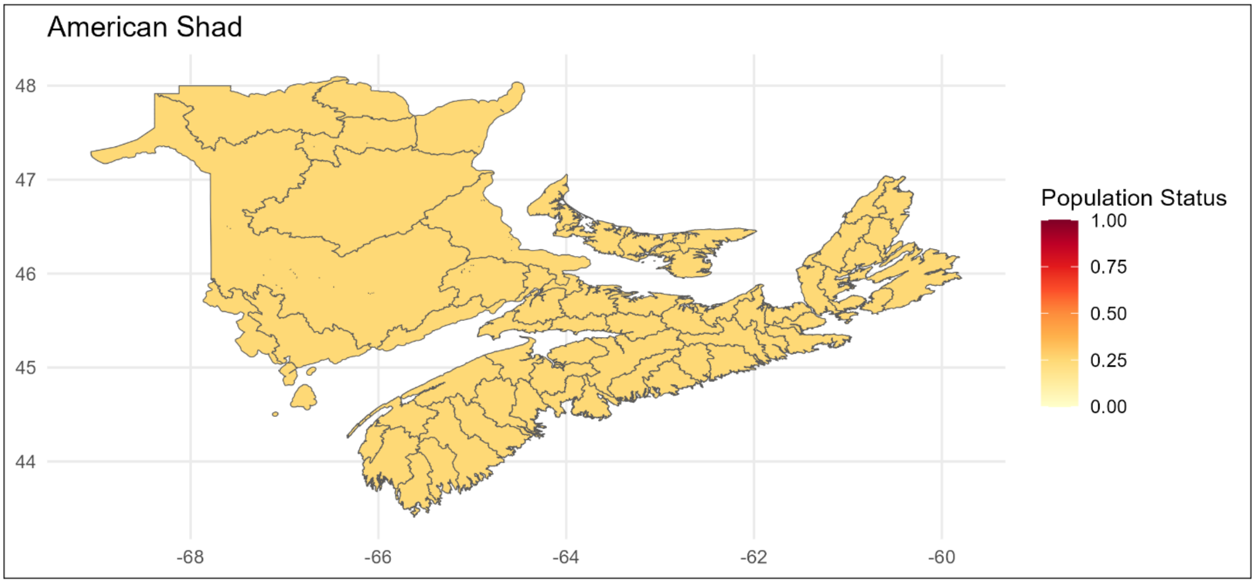
Appendix 50 Map of study area coloured by brook trout population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



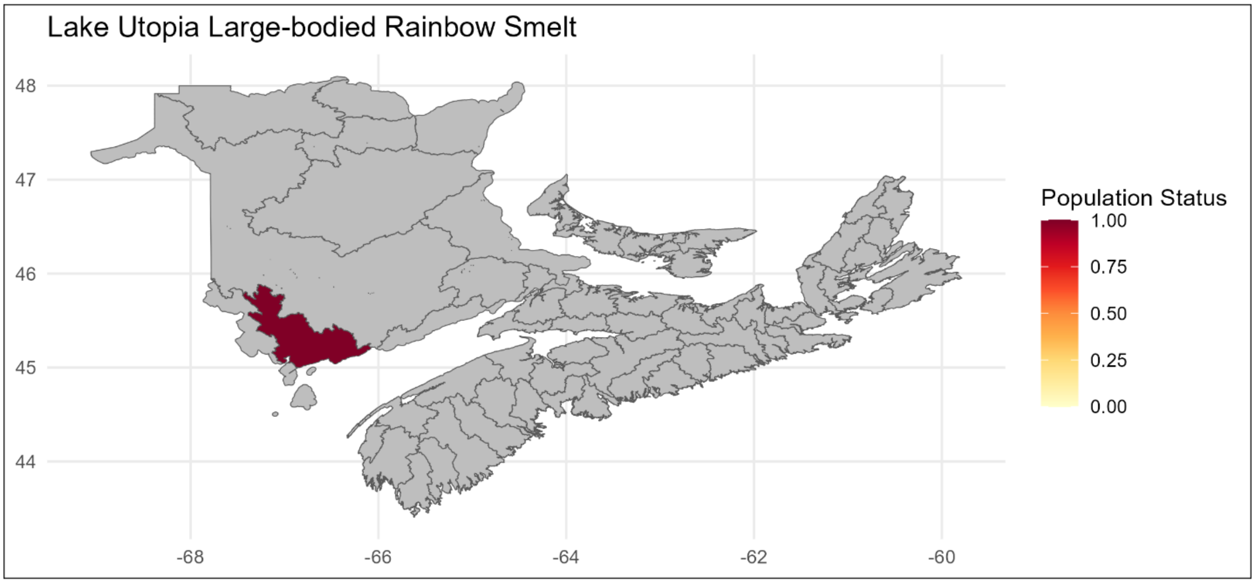
Appendix 51 Map of study area coloured by Lake Utopia small-bodied rainbow smelt population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



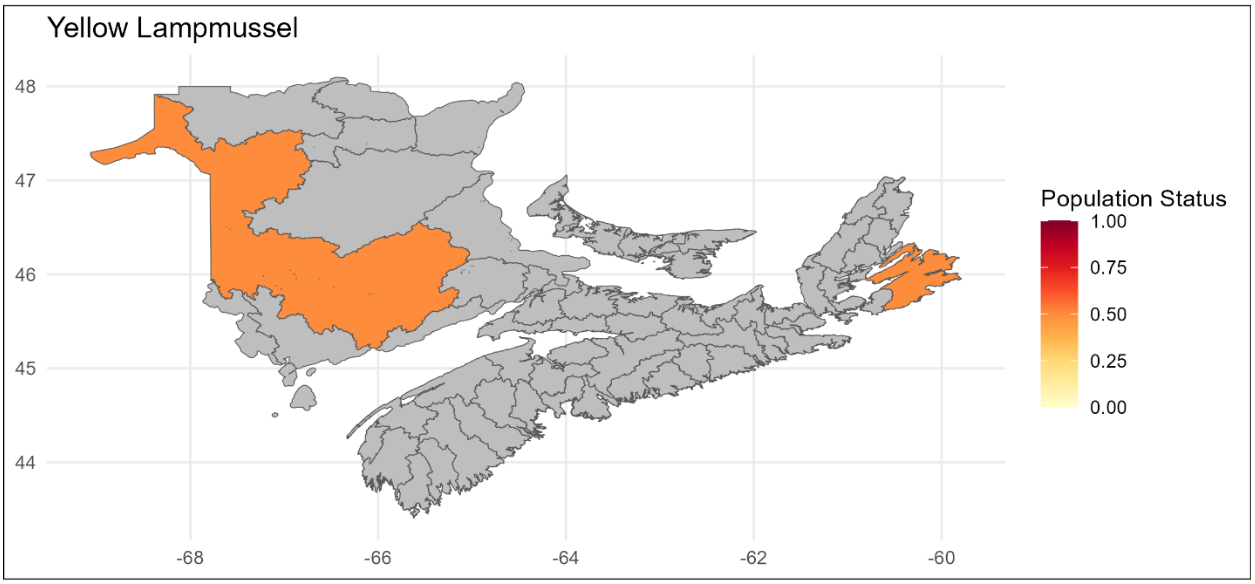
Appendix 52 Map of study area coloured by shortnose sturgeon population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



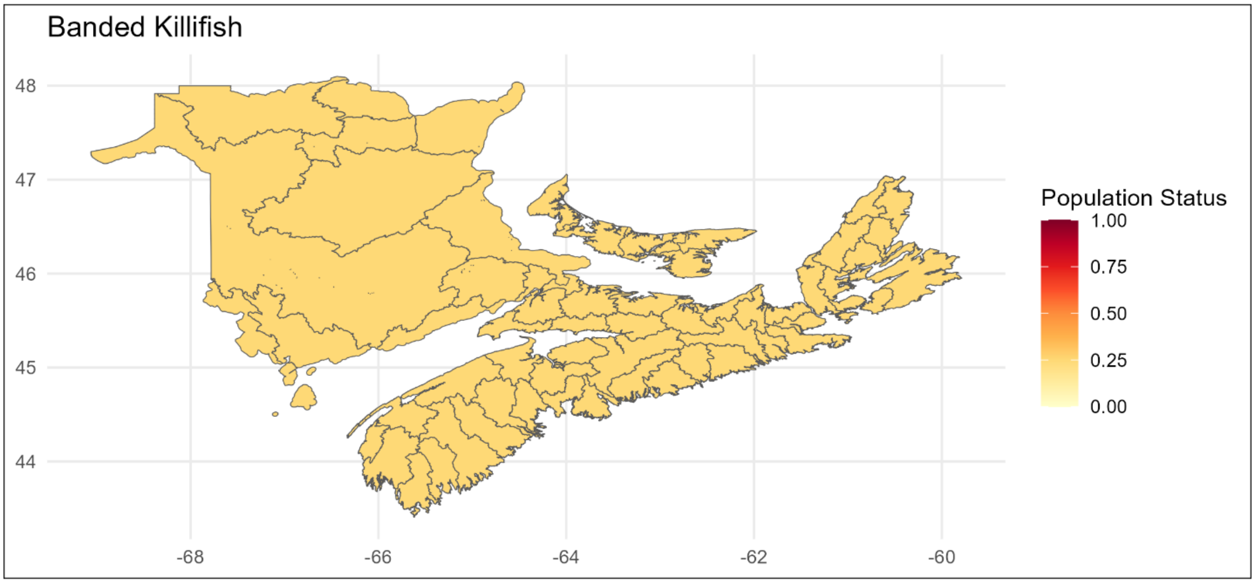
Appendix 53 Map of study area coloured by American shad population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



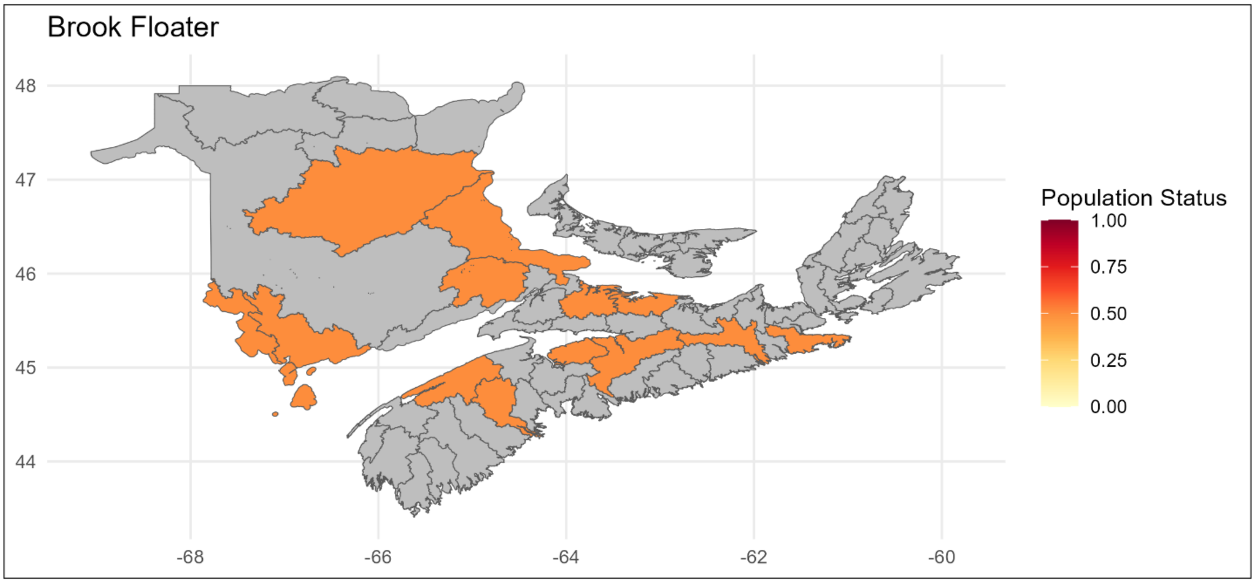
Appendix 54 Map of study area coloured by Lake Utopia large-bodied rainbow smelt population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



Appendix 55 Map of study area coloured by yellow lampmussel population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.

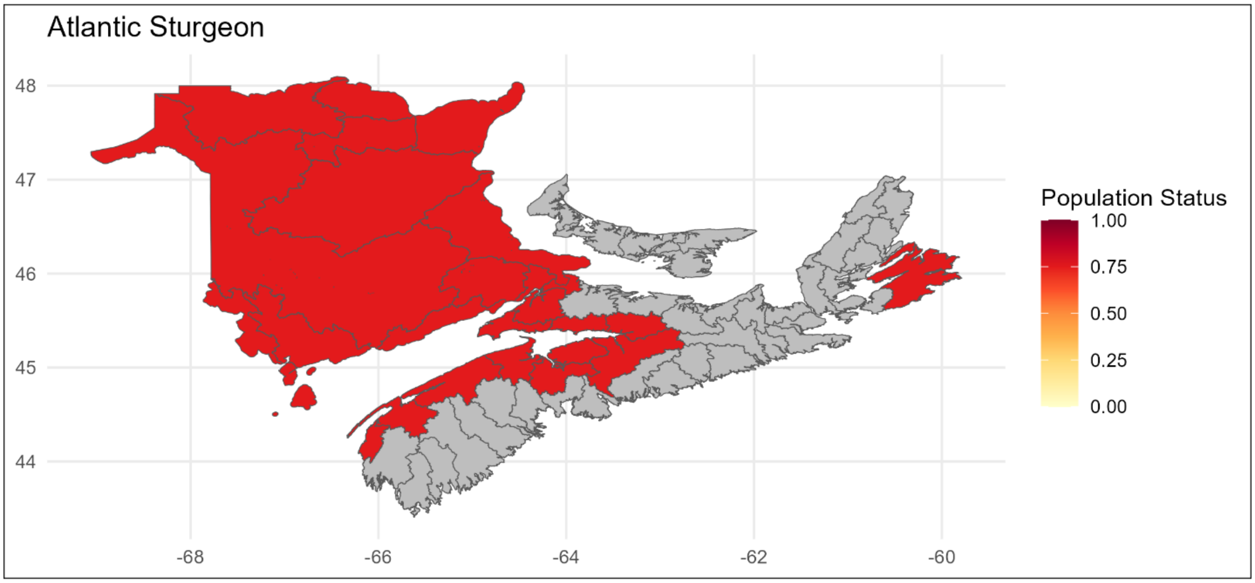


Appendix 56 Map of study area coloured by banded killifish population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.

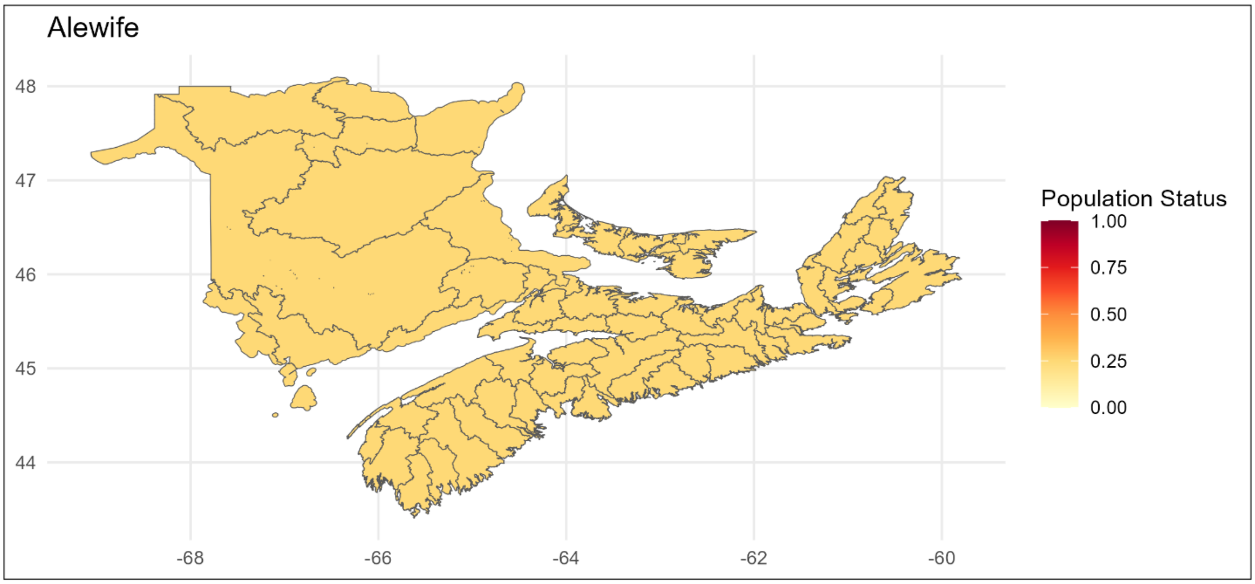


Appendix 57 Map of study area coloured by brook floater population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.

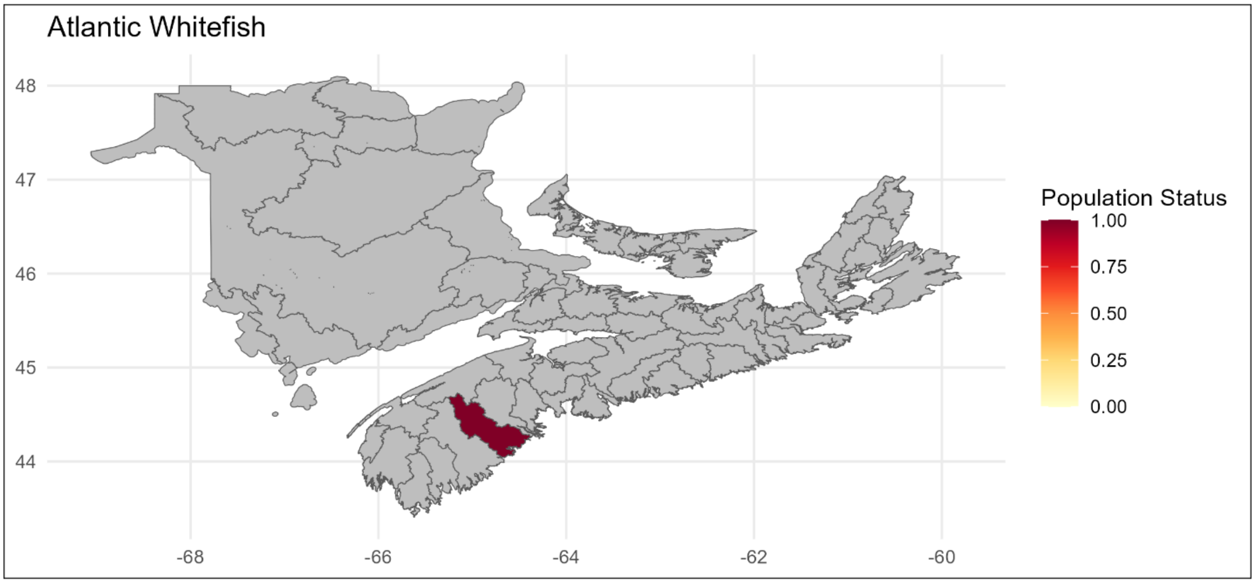
Appendix 58 Map of study area coloured by American eel population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



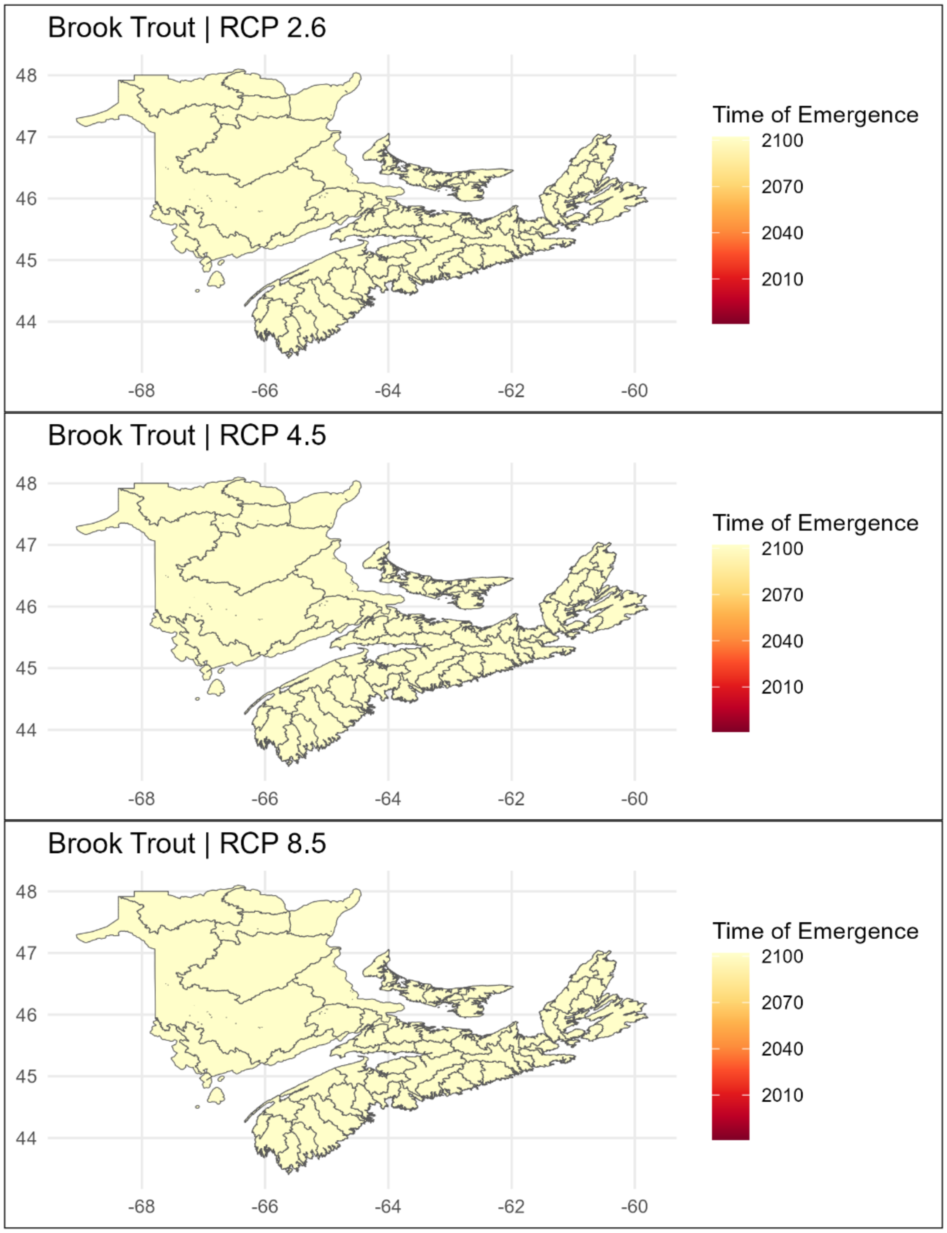
Appendix 59 Map of study area coloured by Atlantic sturgeon population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



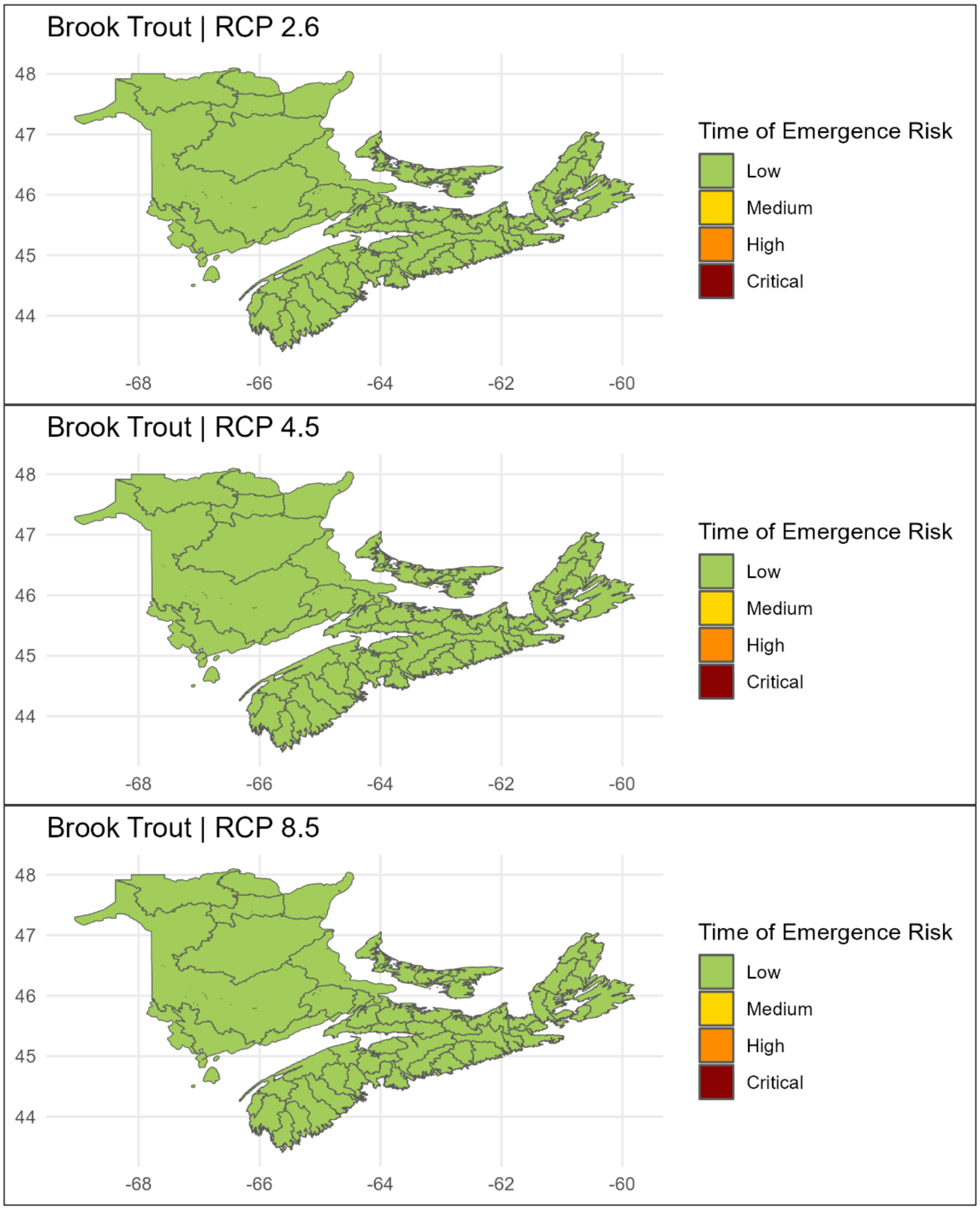
Appendix 60 Map of study area coloured by alewife population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



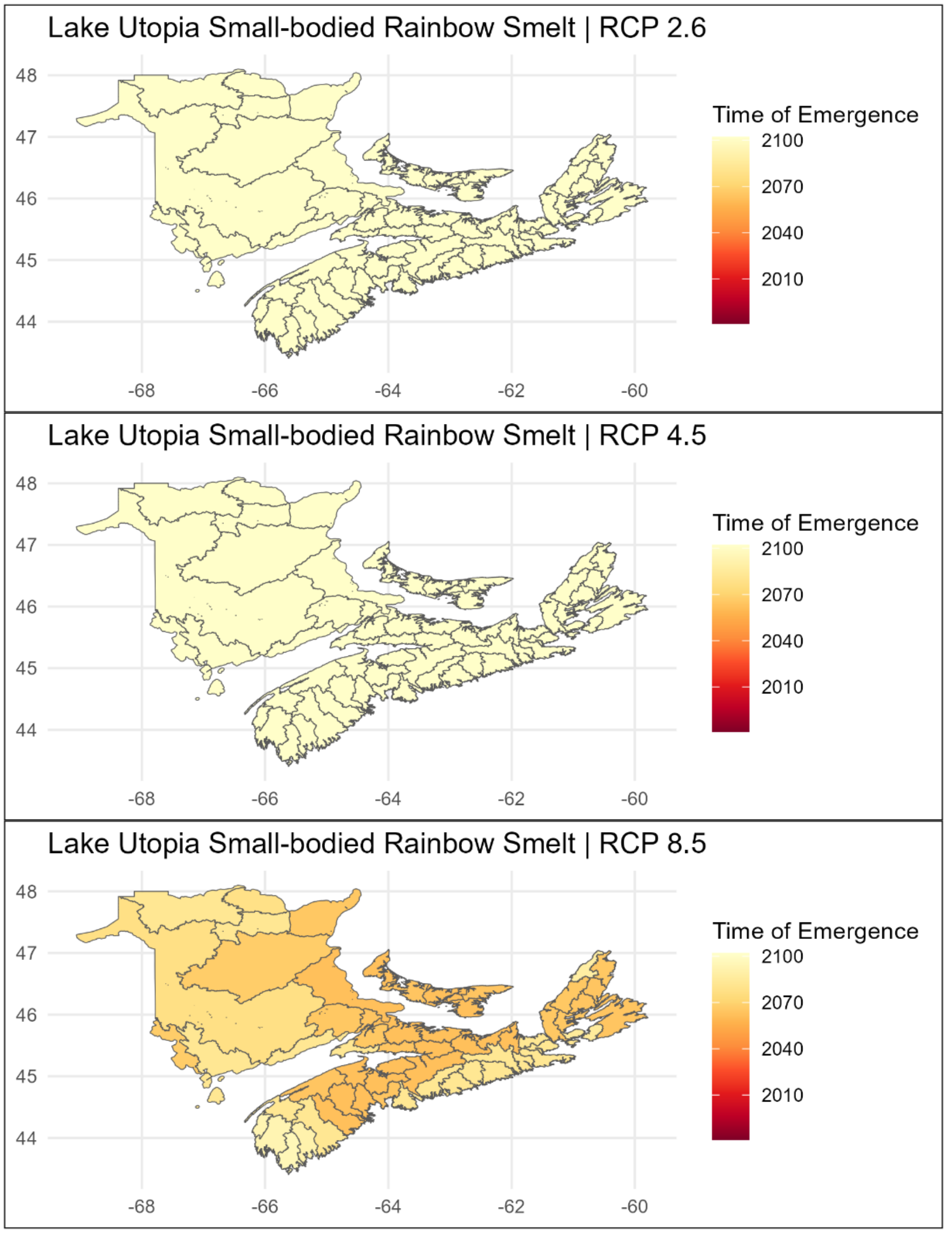
Appendix 61 Map of study area coloured by Atlantic whitefish population status index scores from 0-1; Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level. Grey colouring indicates the species is not documented. Scores are defined as follows: Secure = 0, Unranked = 0.1, Candidate for COSEWIC Assessment = 0.25, Special Concern = 0.5, Threatened = 0.75, Endangered = 1.



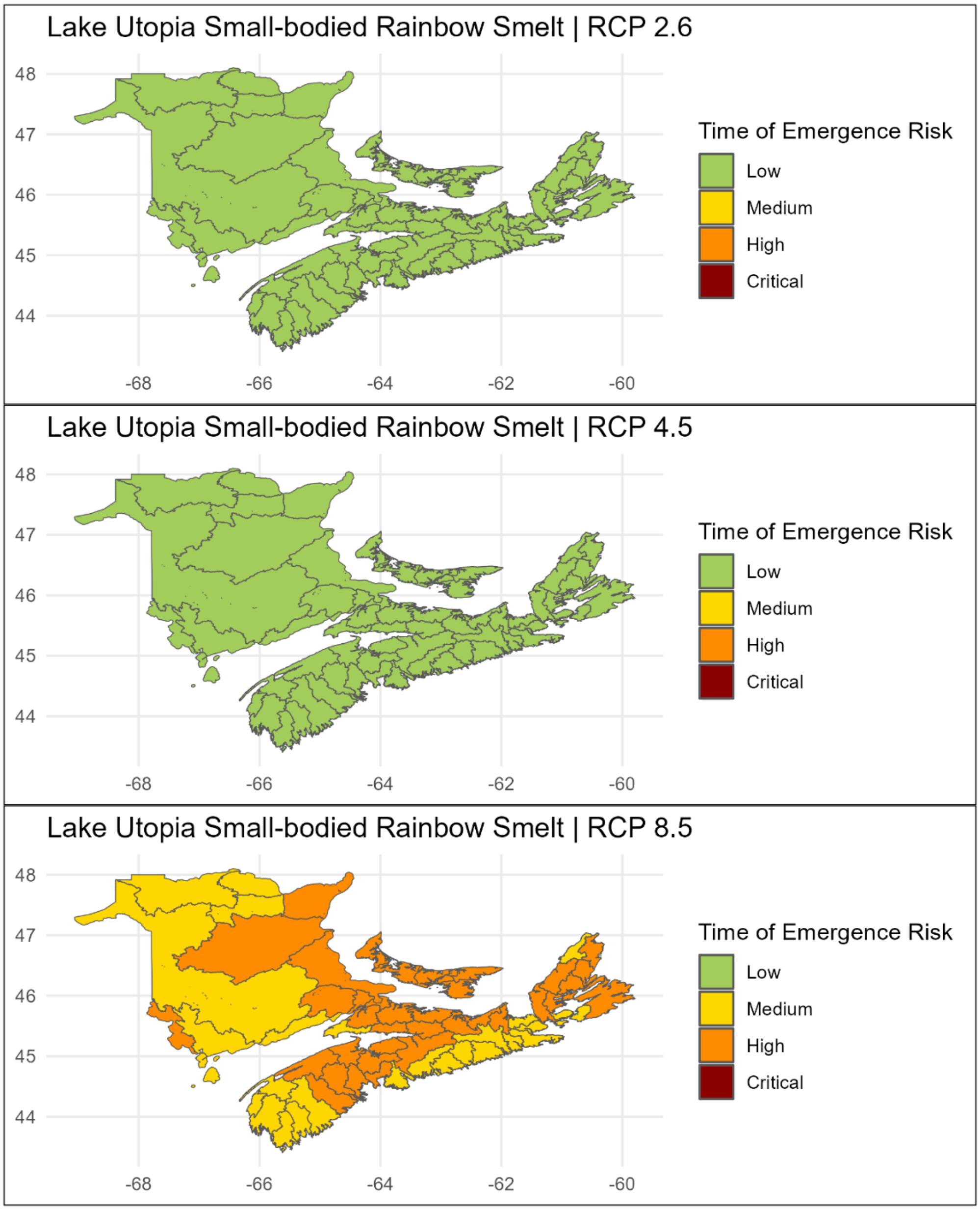
Appendix 62 Map of study area coloured by brook trout time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



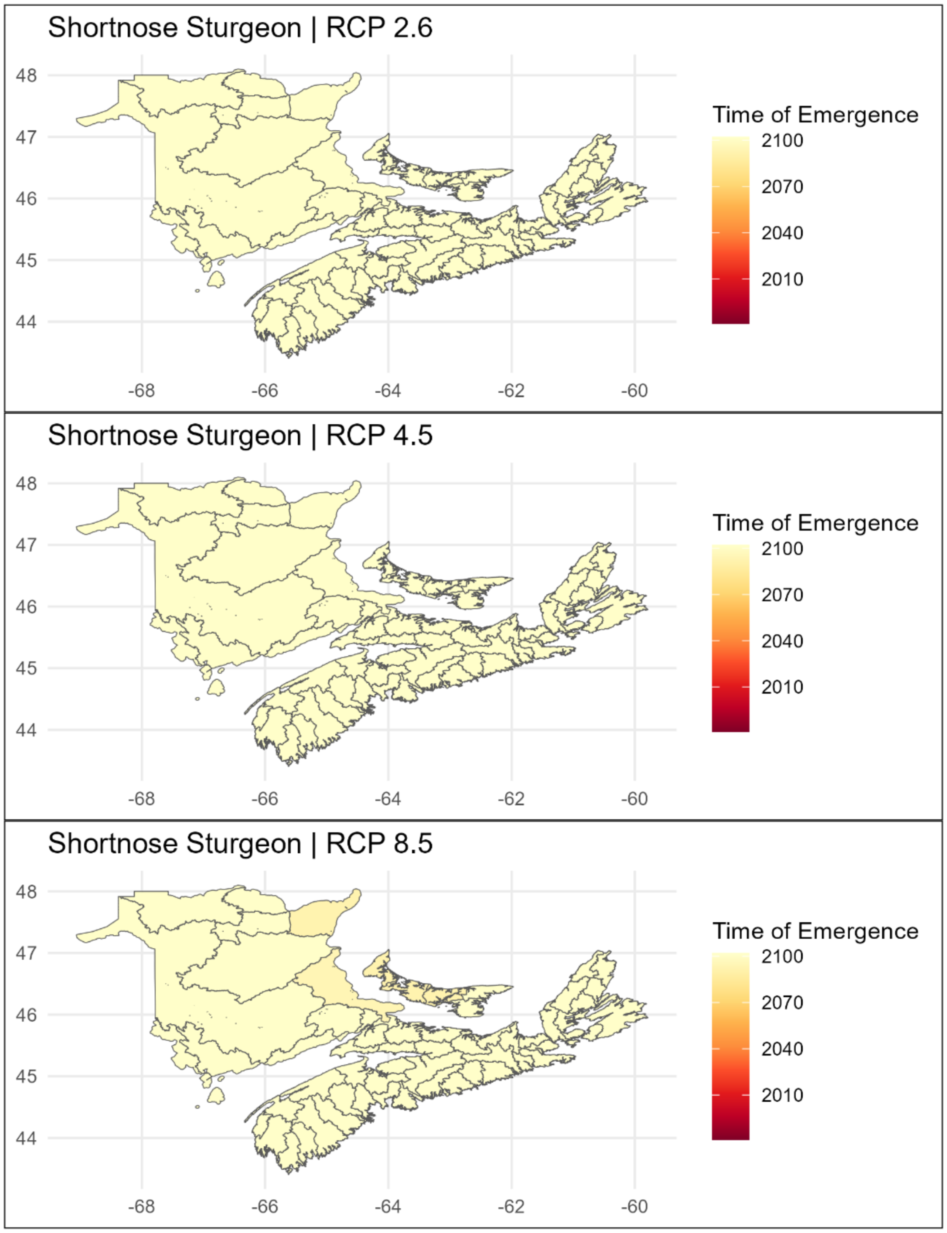
Appendix 63 Map of study area coloured by brook trout time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



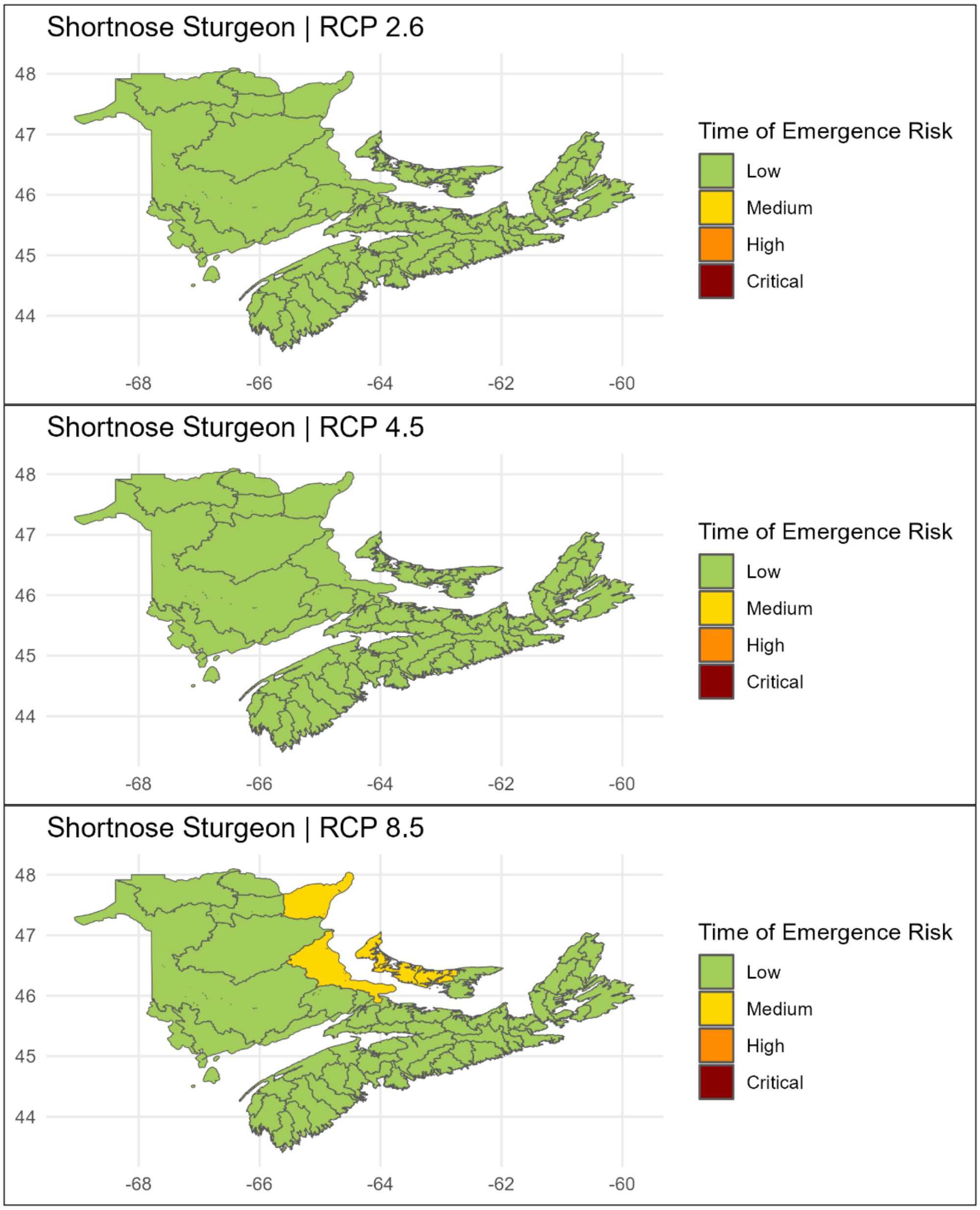
Appendix 64 Map of study area coloured by Lake Utopia small-bodied rainbow smelt time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



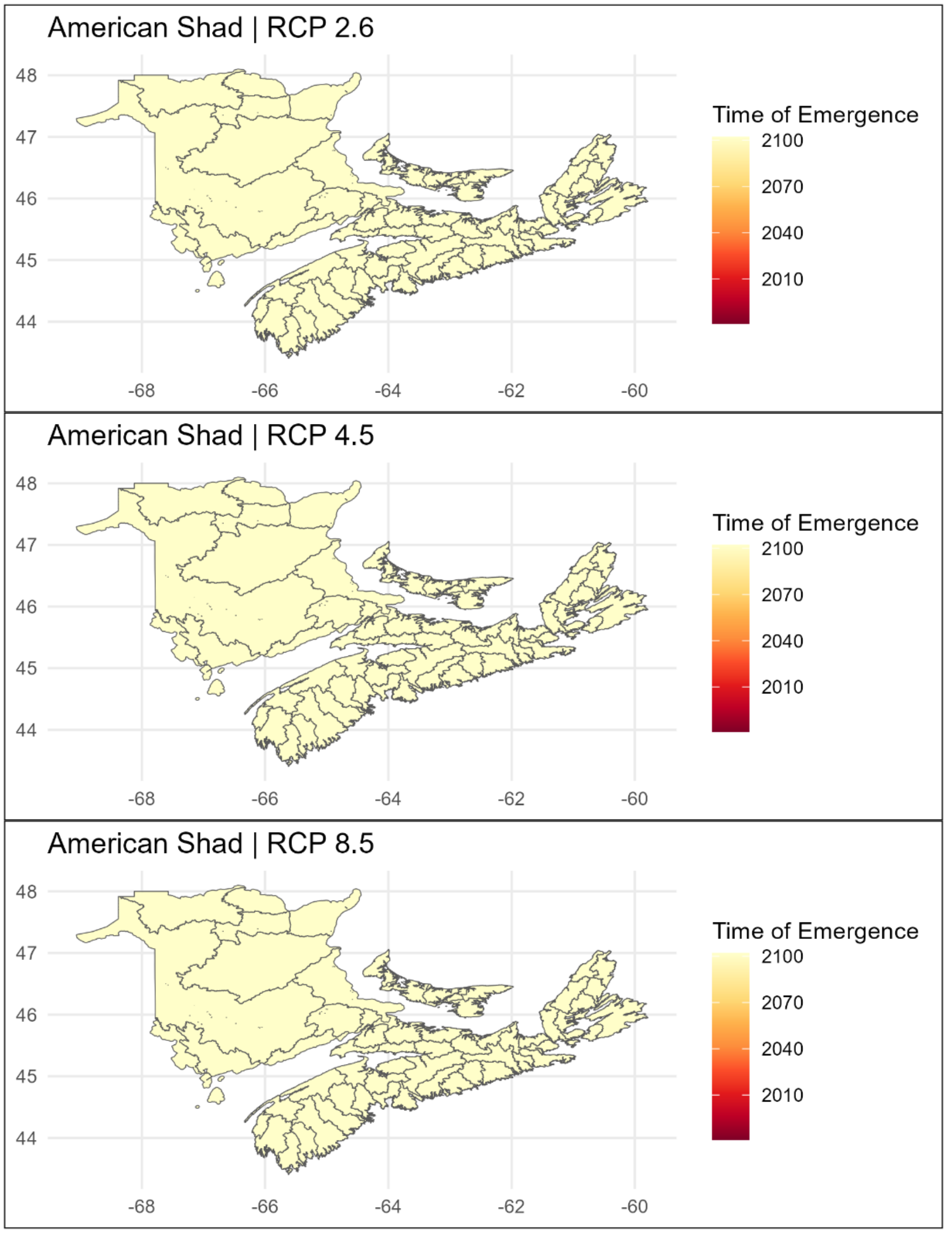
Appendix 65 Map of study area coloured by Lake Utopia small-bodied rainbow smelt time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



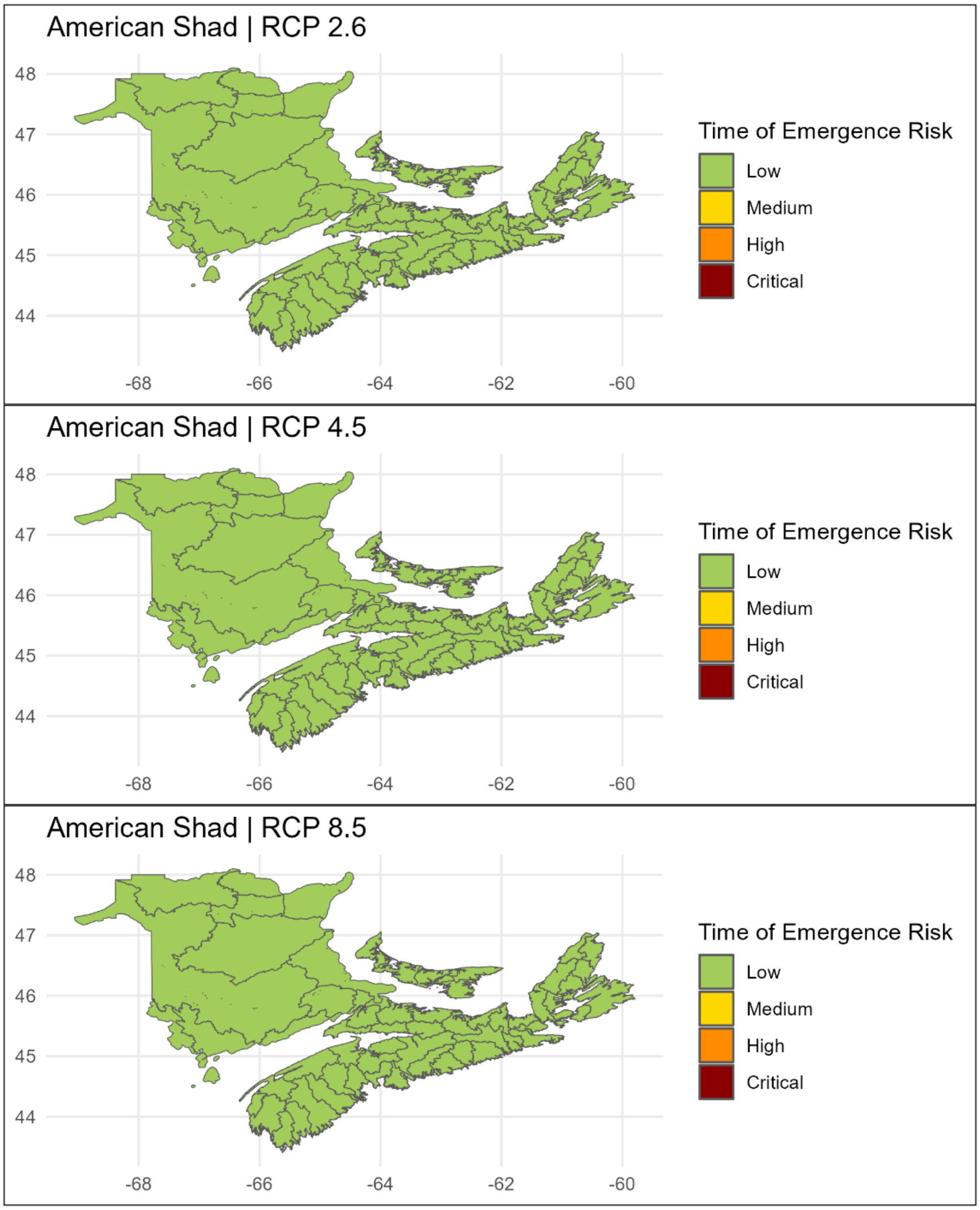
Appendix 66 Map of study area coloured by shortnose sturgeon time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



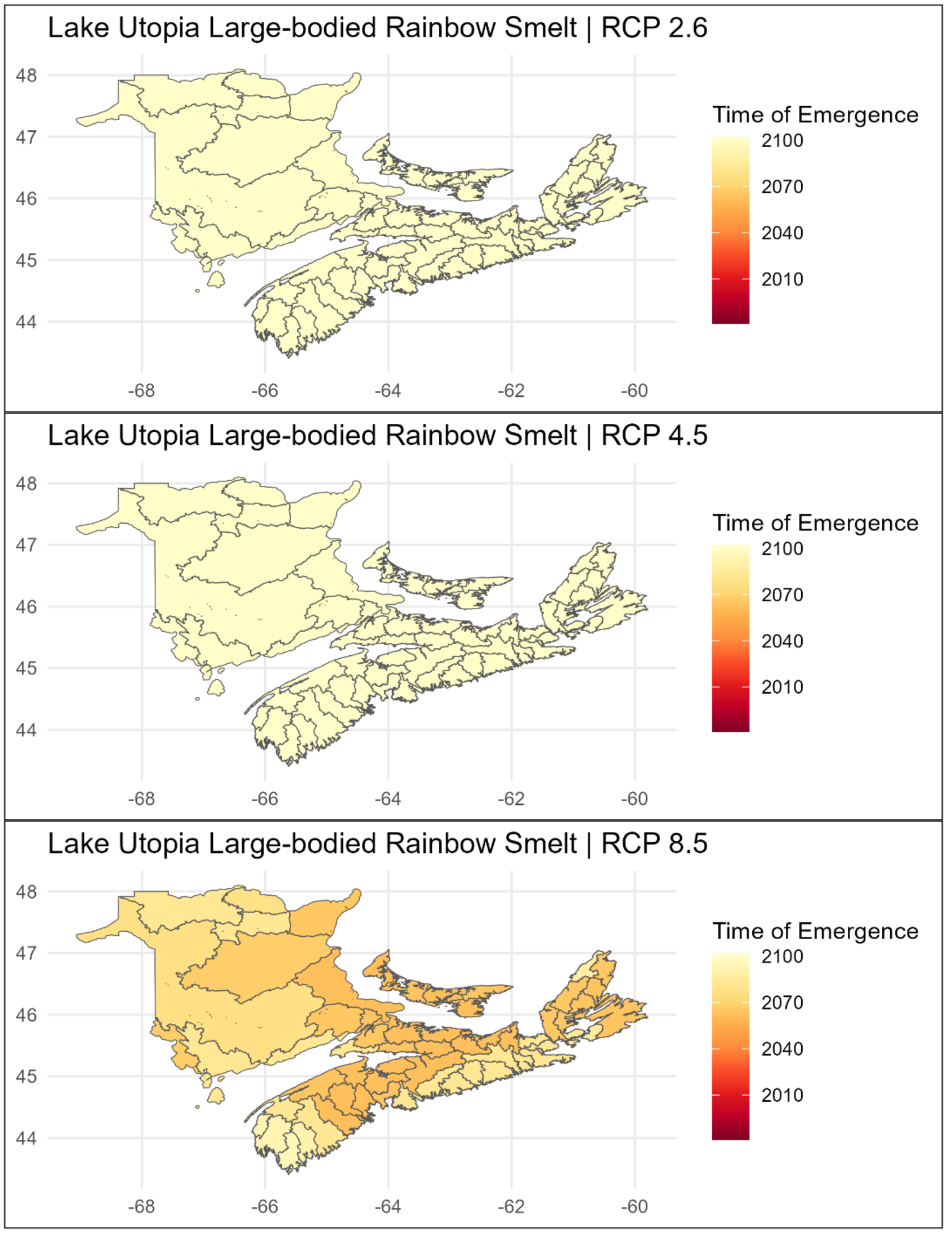
Appendix 67 Map of study area coloured by shortnose sturgeon time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



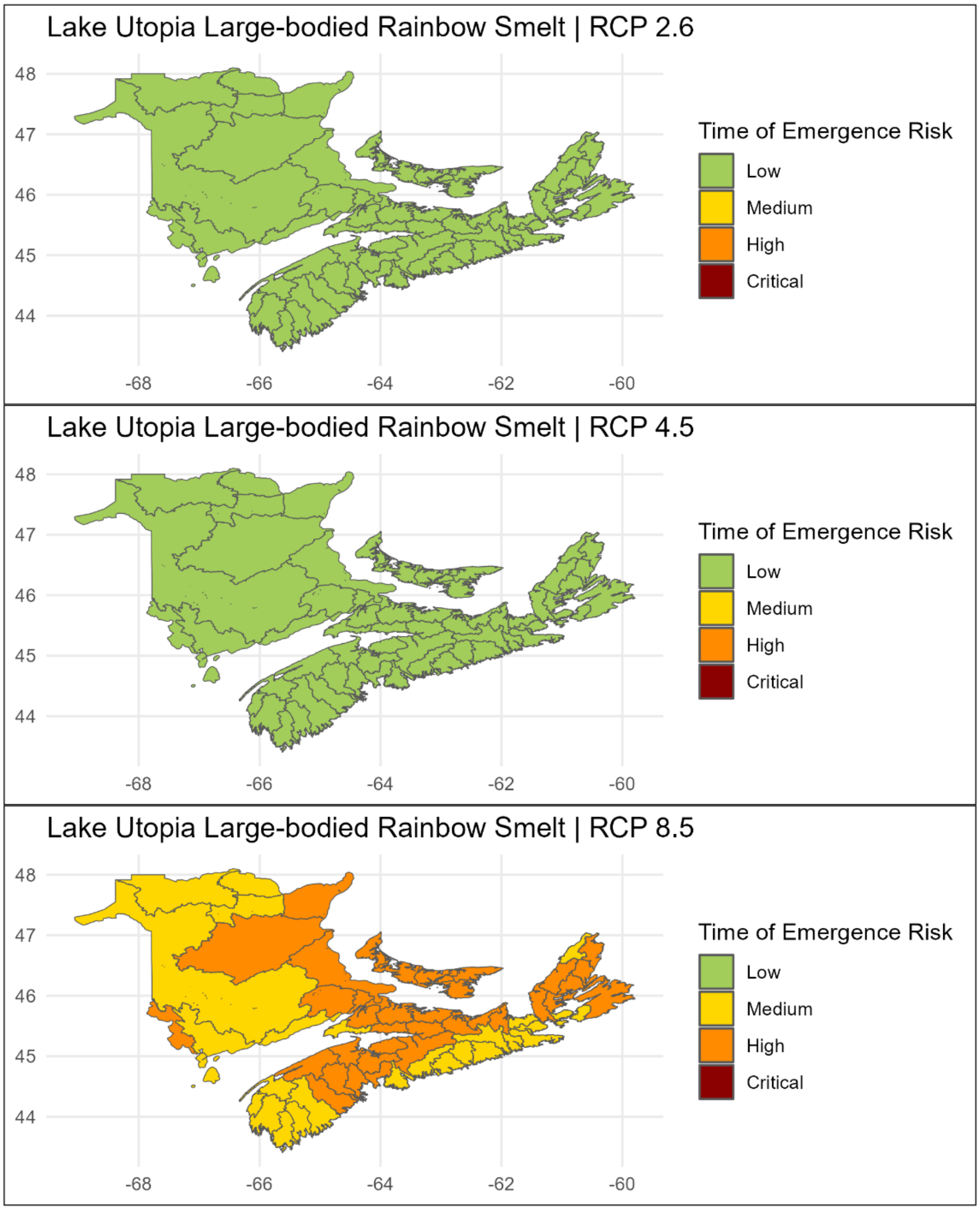
Appendix 68 Map of study area coloured by American shad time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



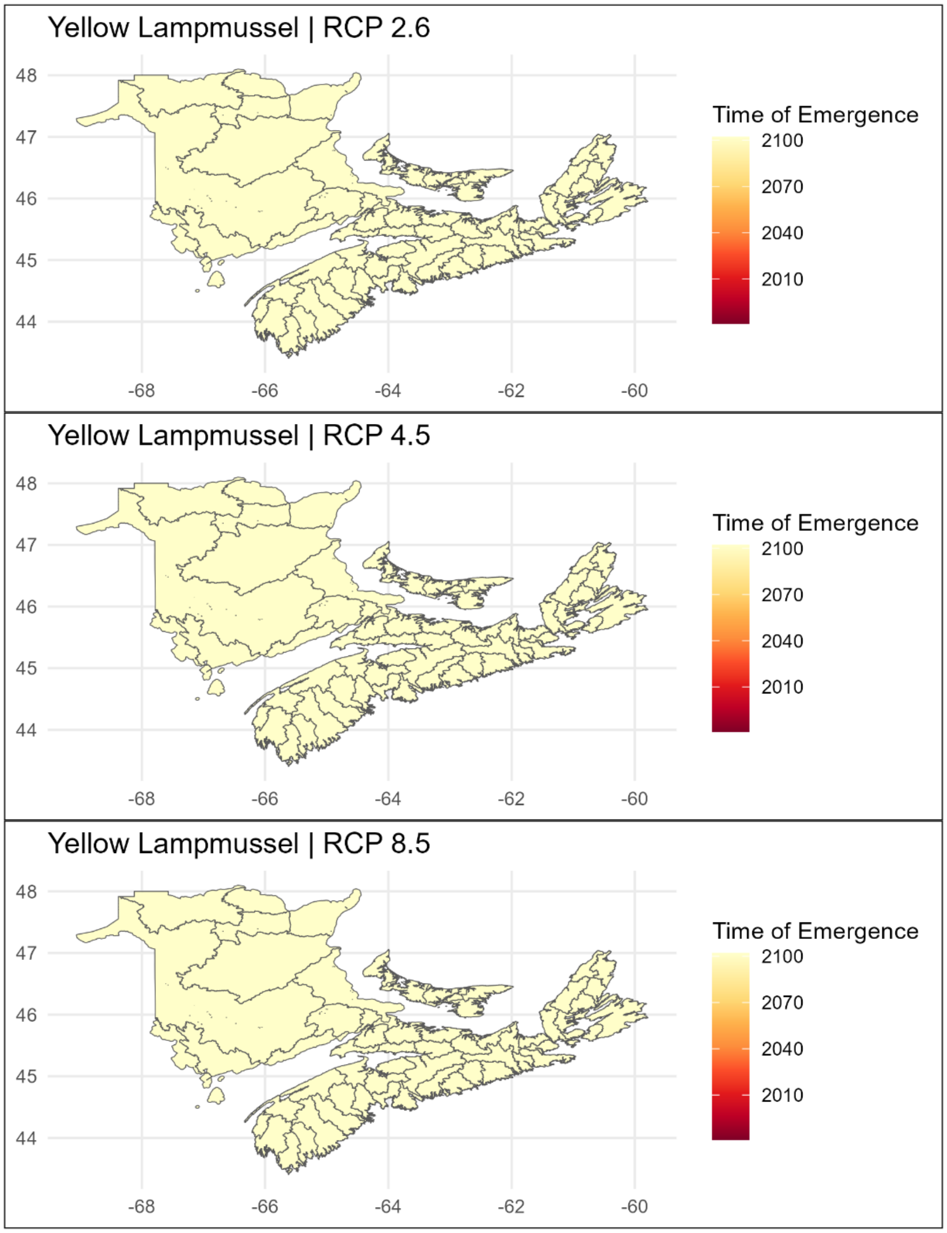
Appendix 69 Map of study area coloured by American shad time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



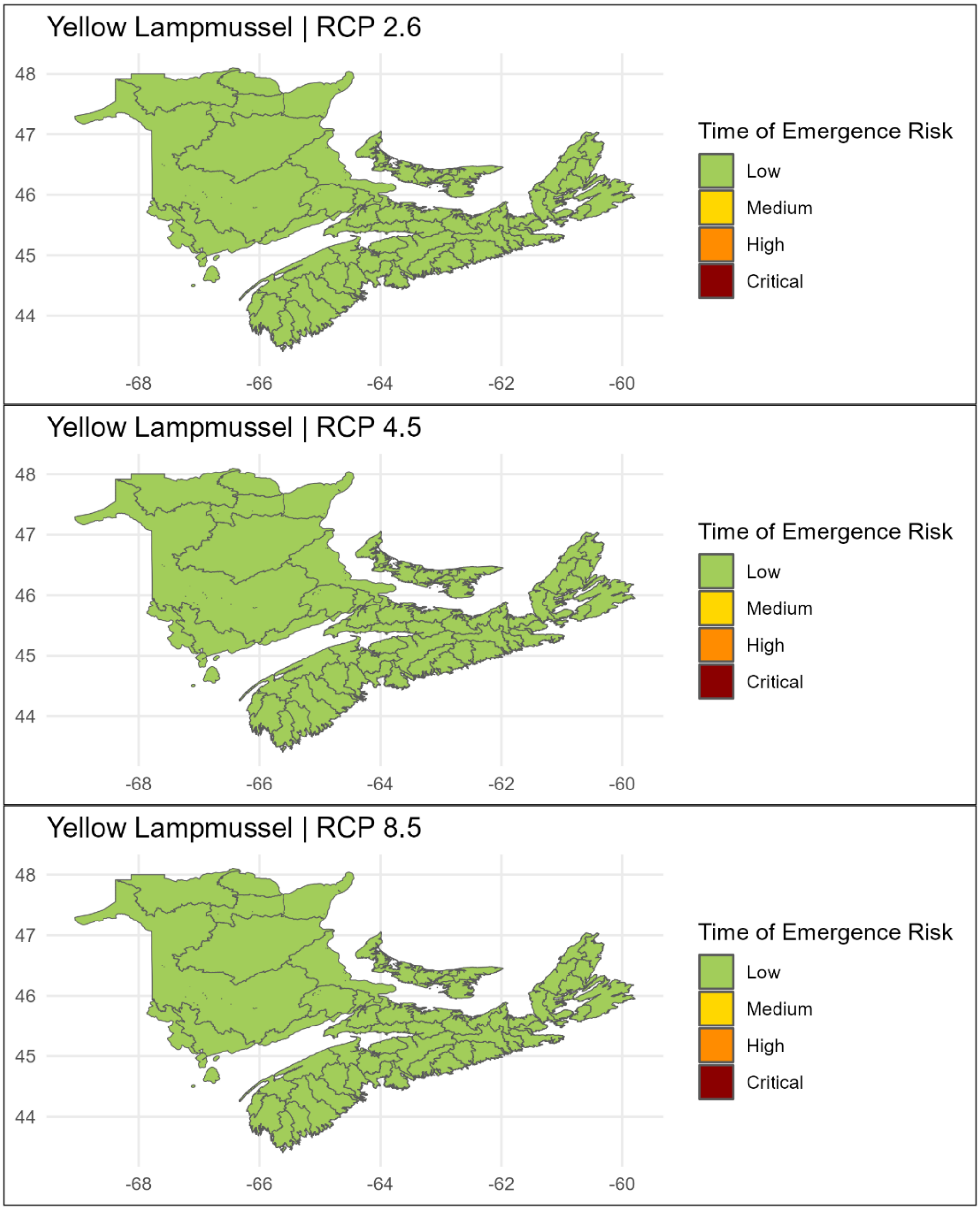
Appendix 70 Map of study area coloured by Lake Utopia large-bodied rainbow smelt time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



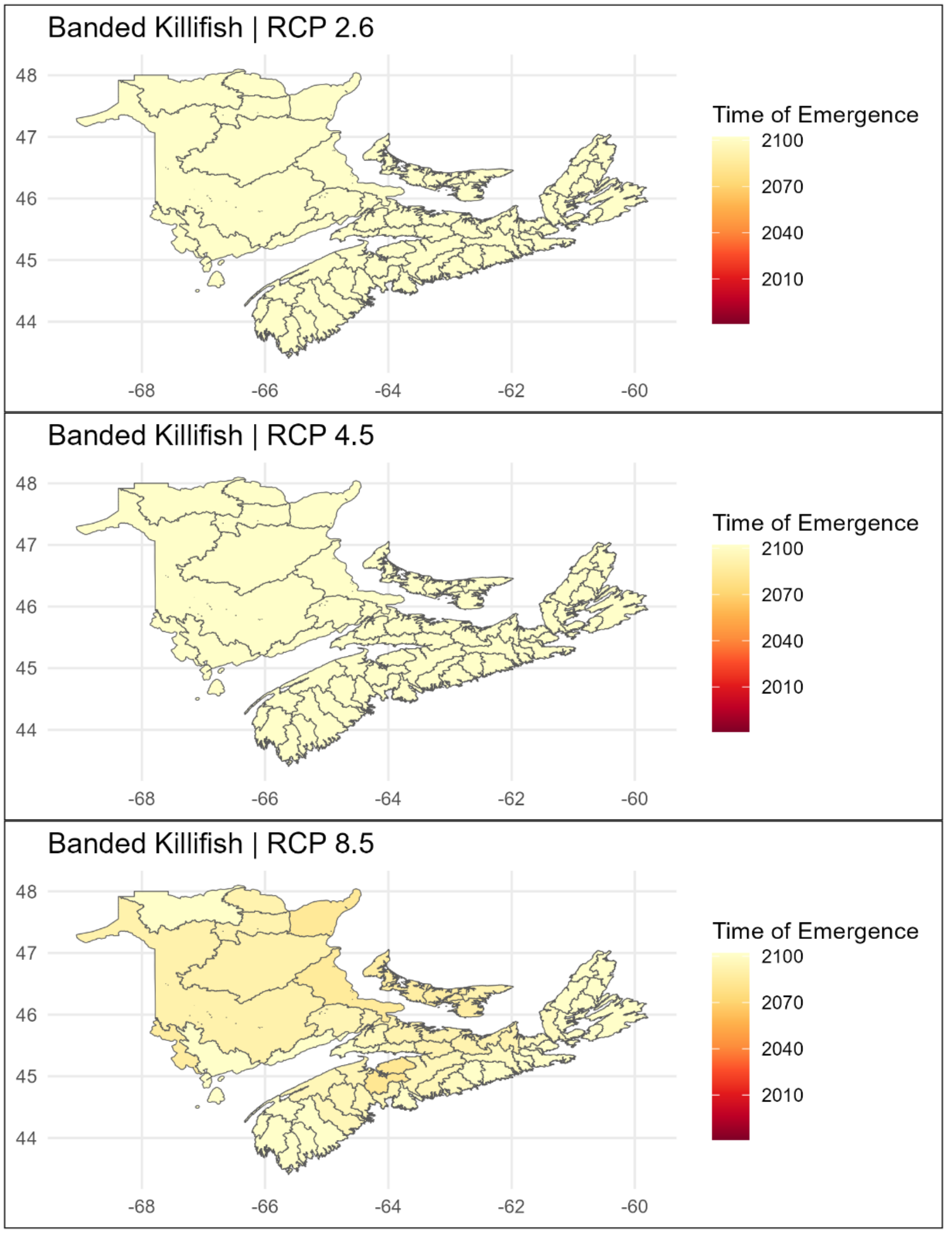
Appendix 71 Map of study area coloured by Lake Utopia large-bodied rainbow smelt time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



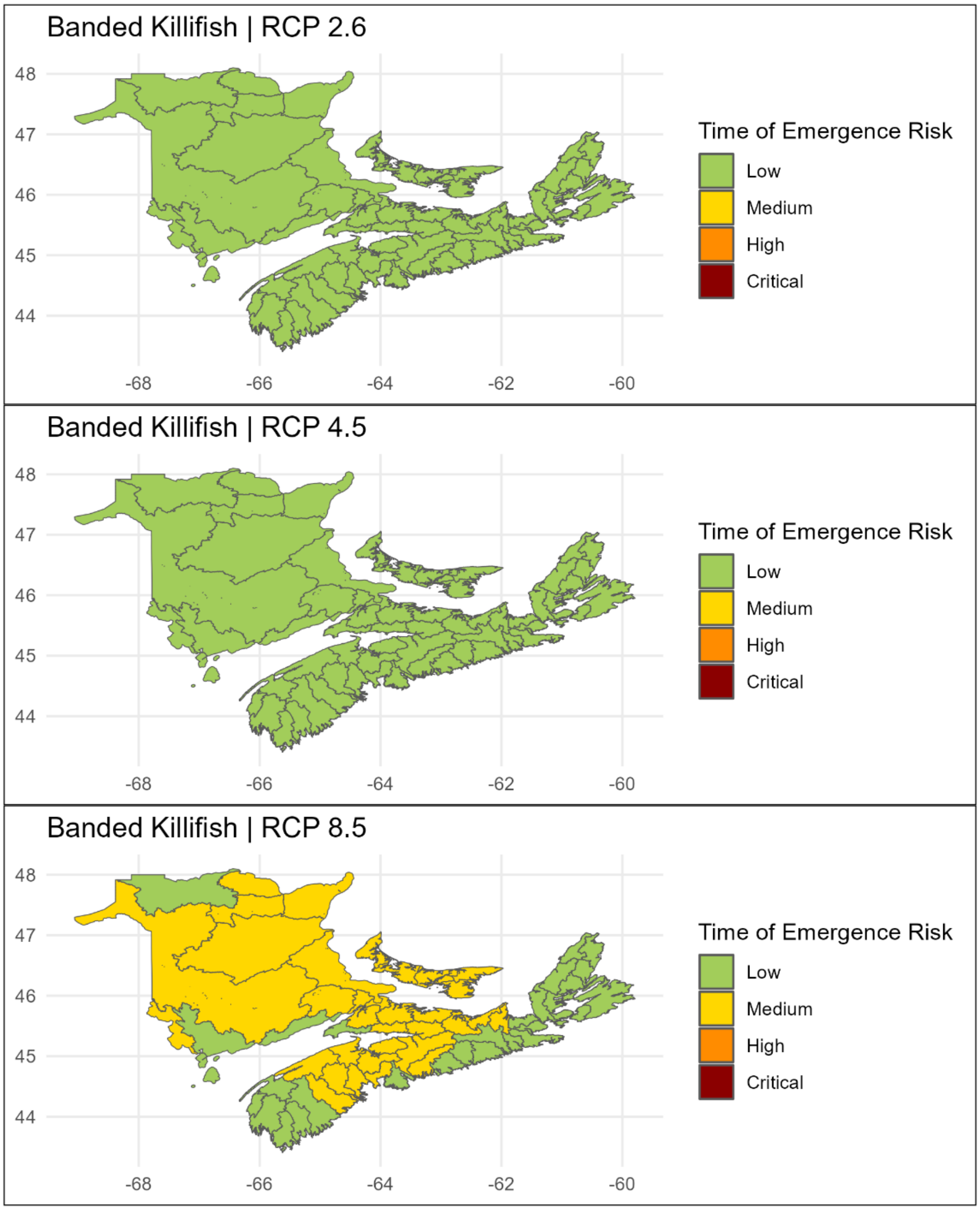
Appendix 72 Map of study area coloured by yellow lampmussel time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



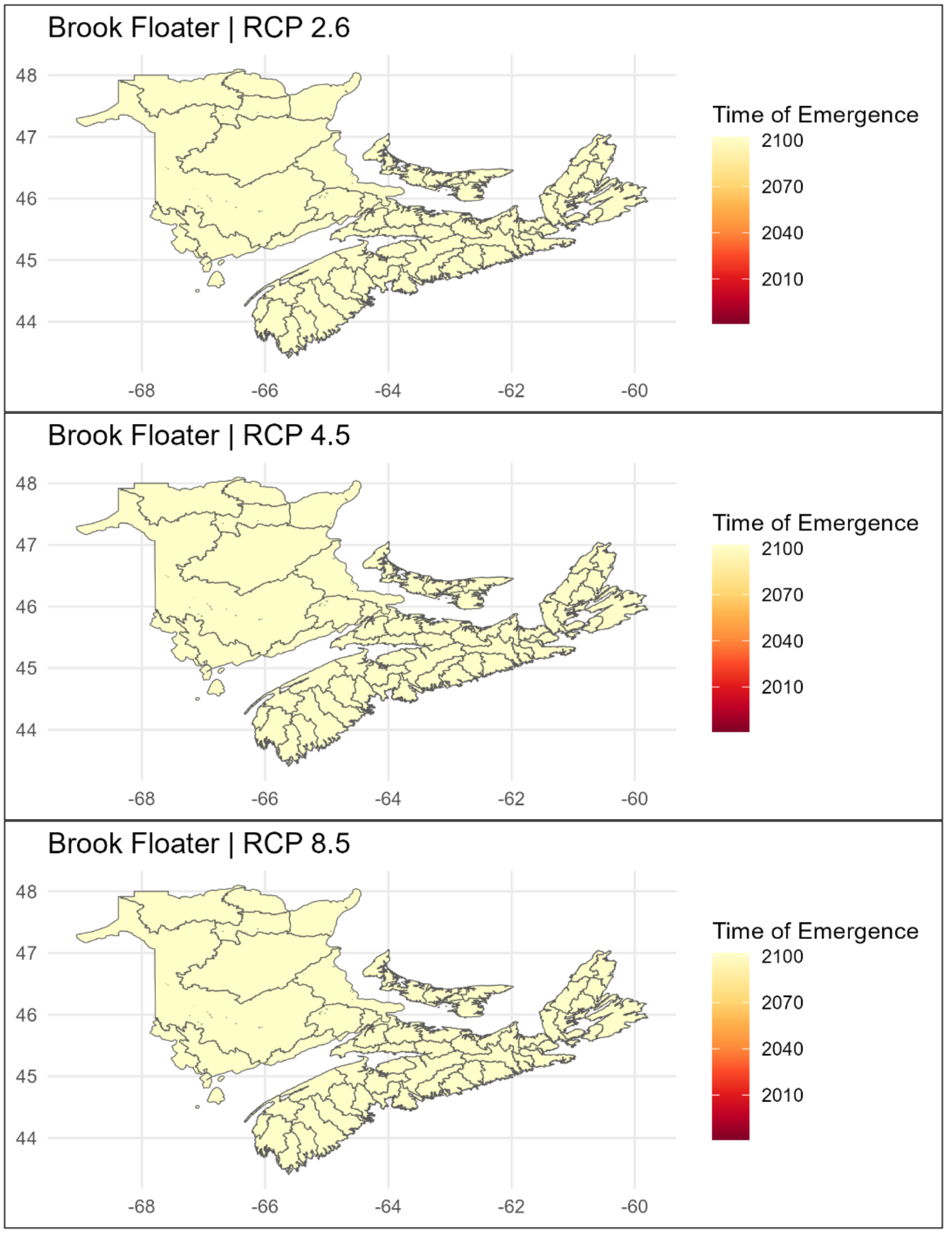
Appendix 73 Map of study area coloured by yellow lampmussel time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



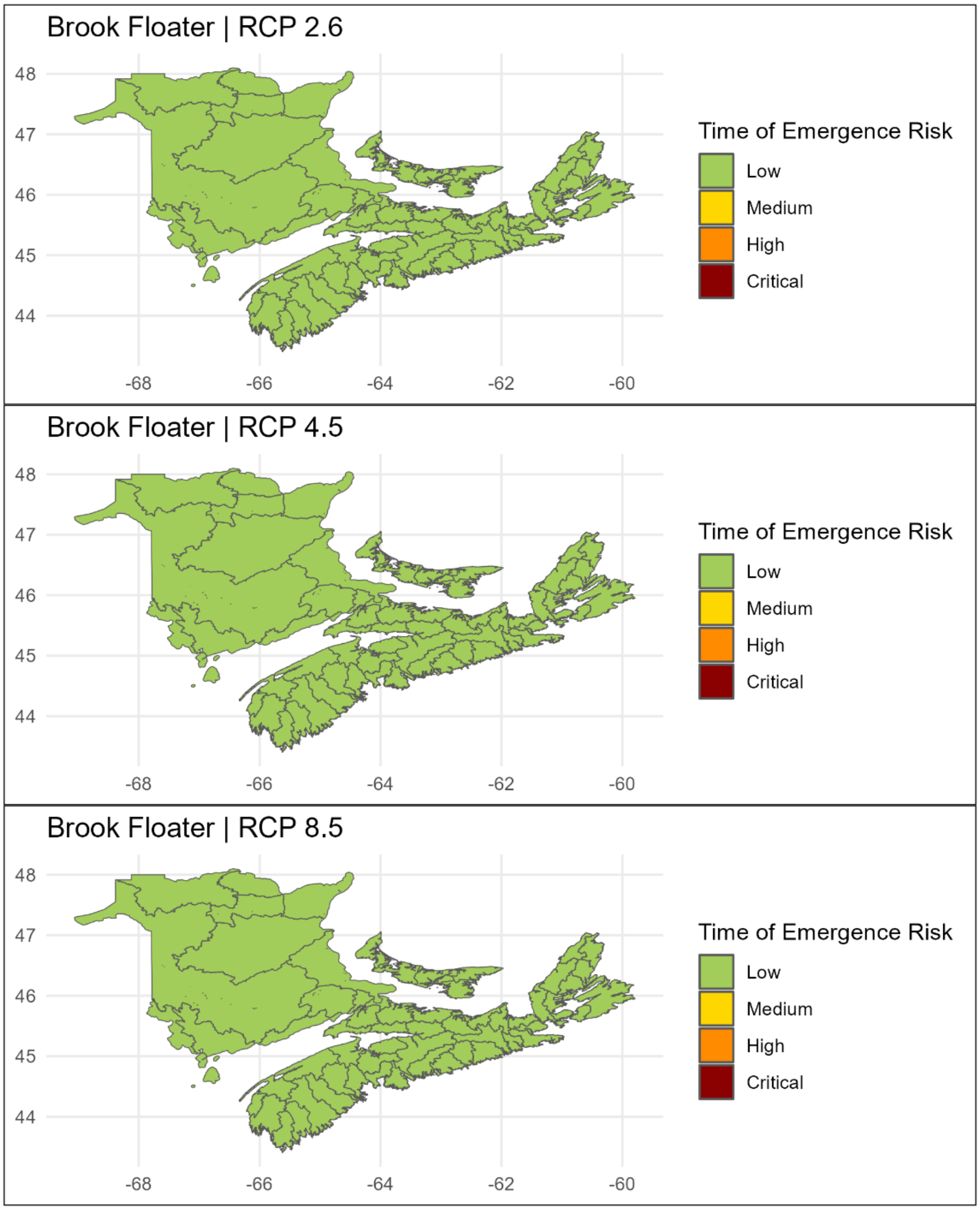
Appendix 74 Map of study area coloured by banded killifish time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



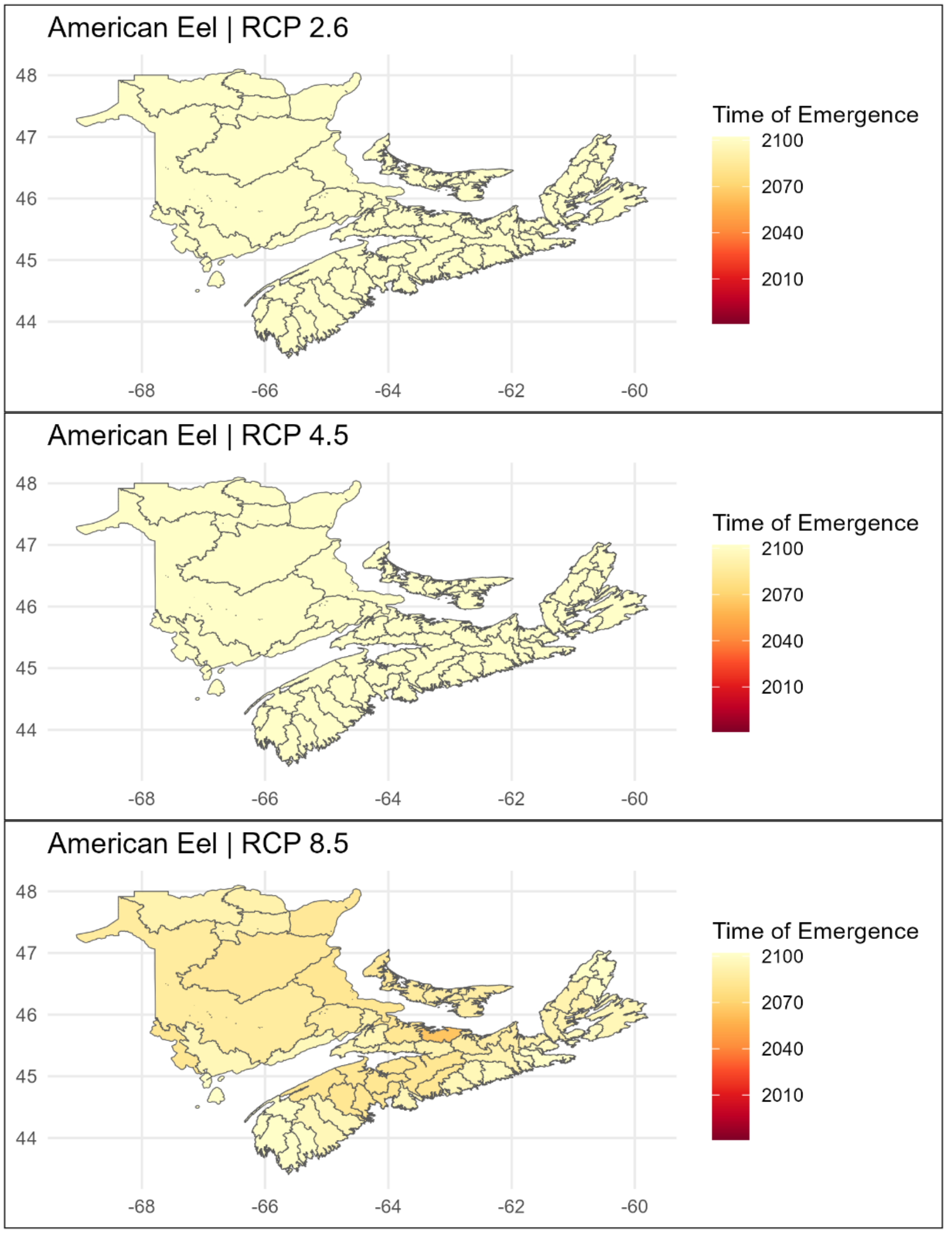
Appendix 75 Map of study area coloured by banded killifish time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



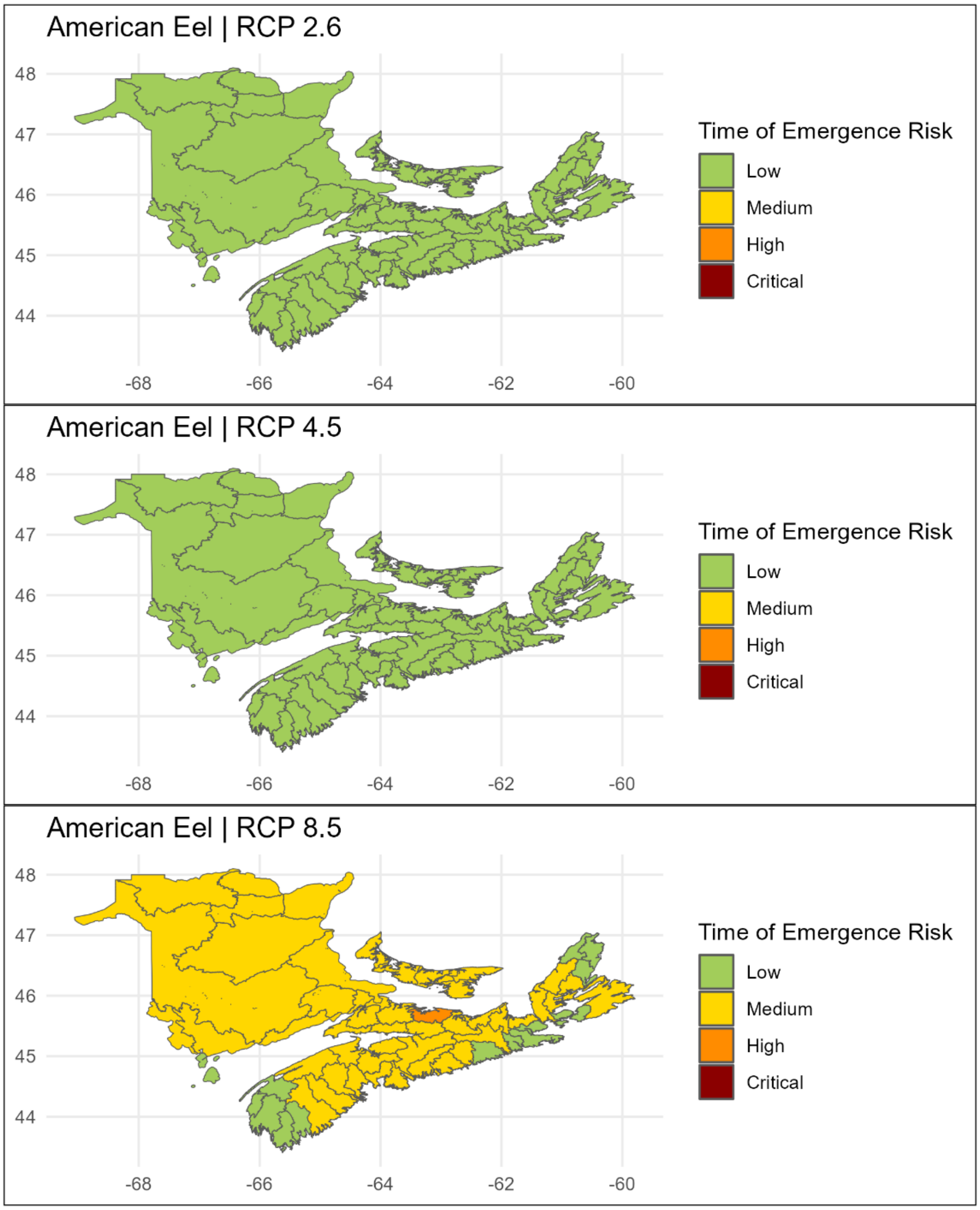
Appendix 76 Map of study area coloured by brook floater time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



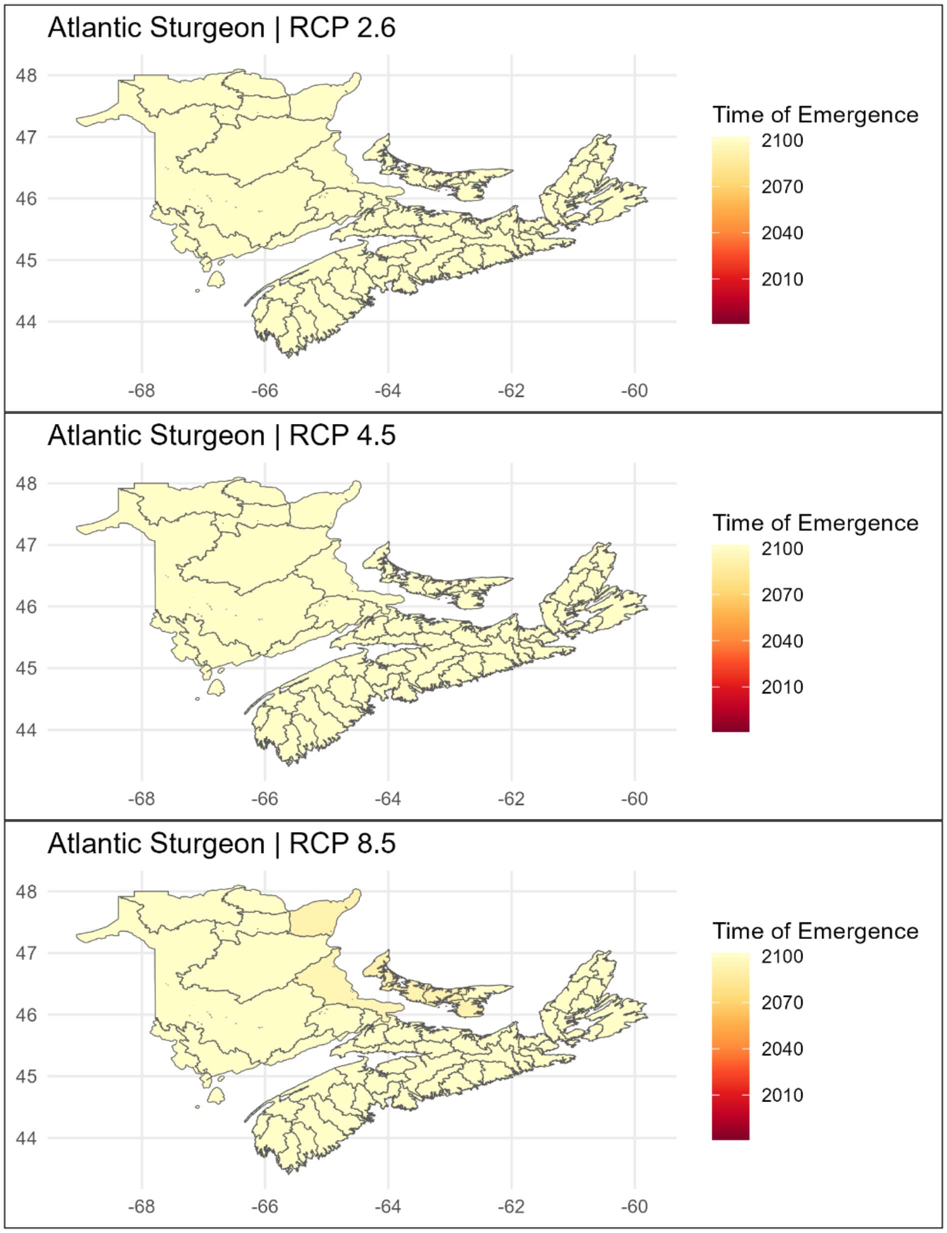
Appendix 77 Map of study area coloured by brook floater time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



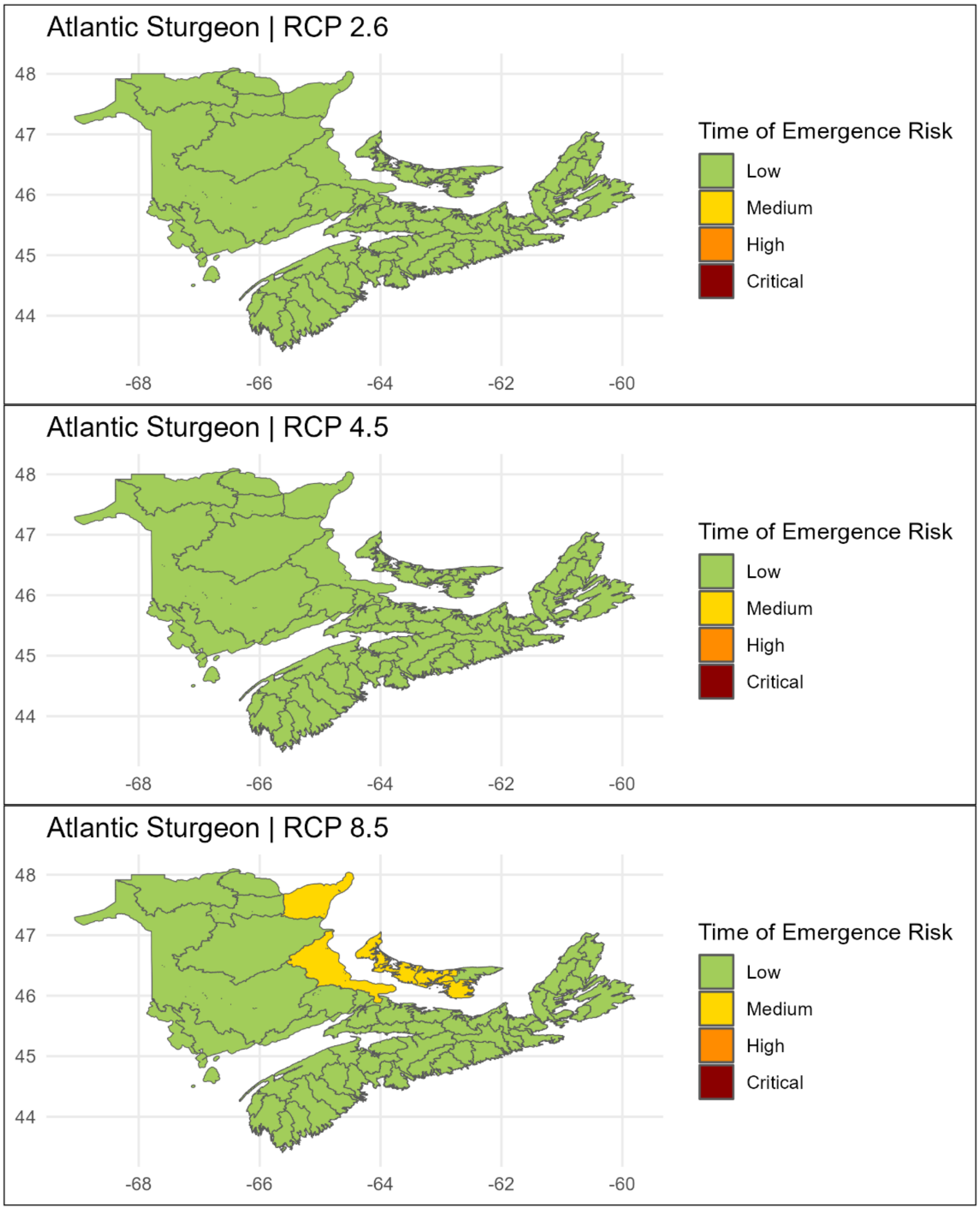
Appendix 78 Map of study area coloured by American eel time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



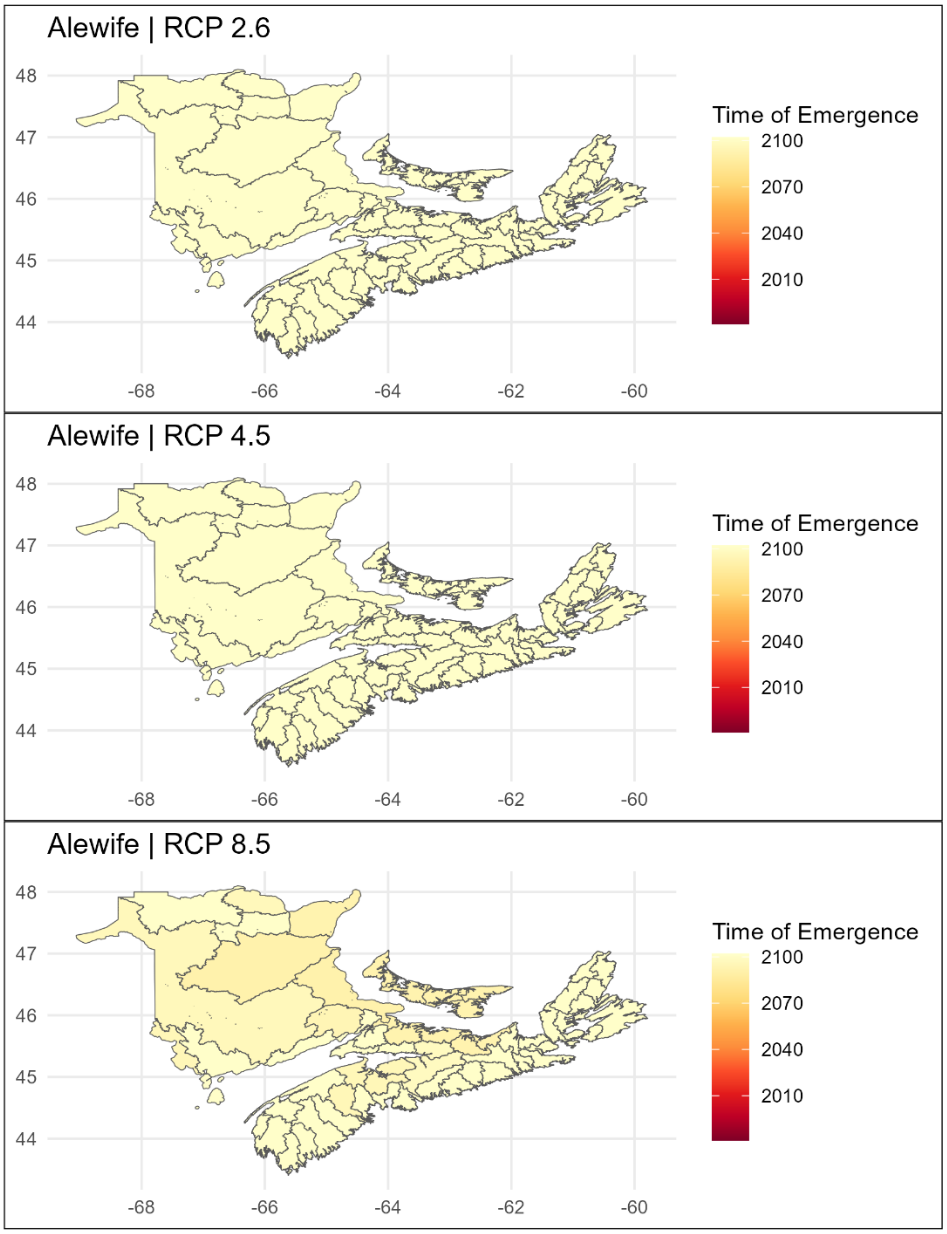
Appendix 79 Map of study area coloured by American eel time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



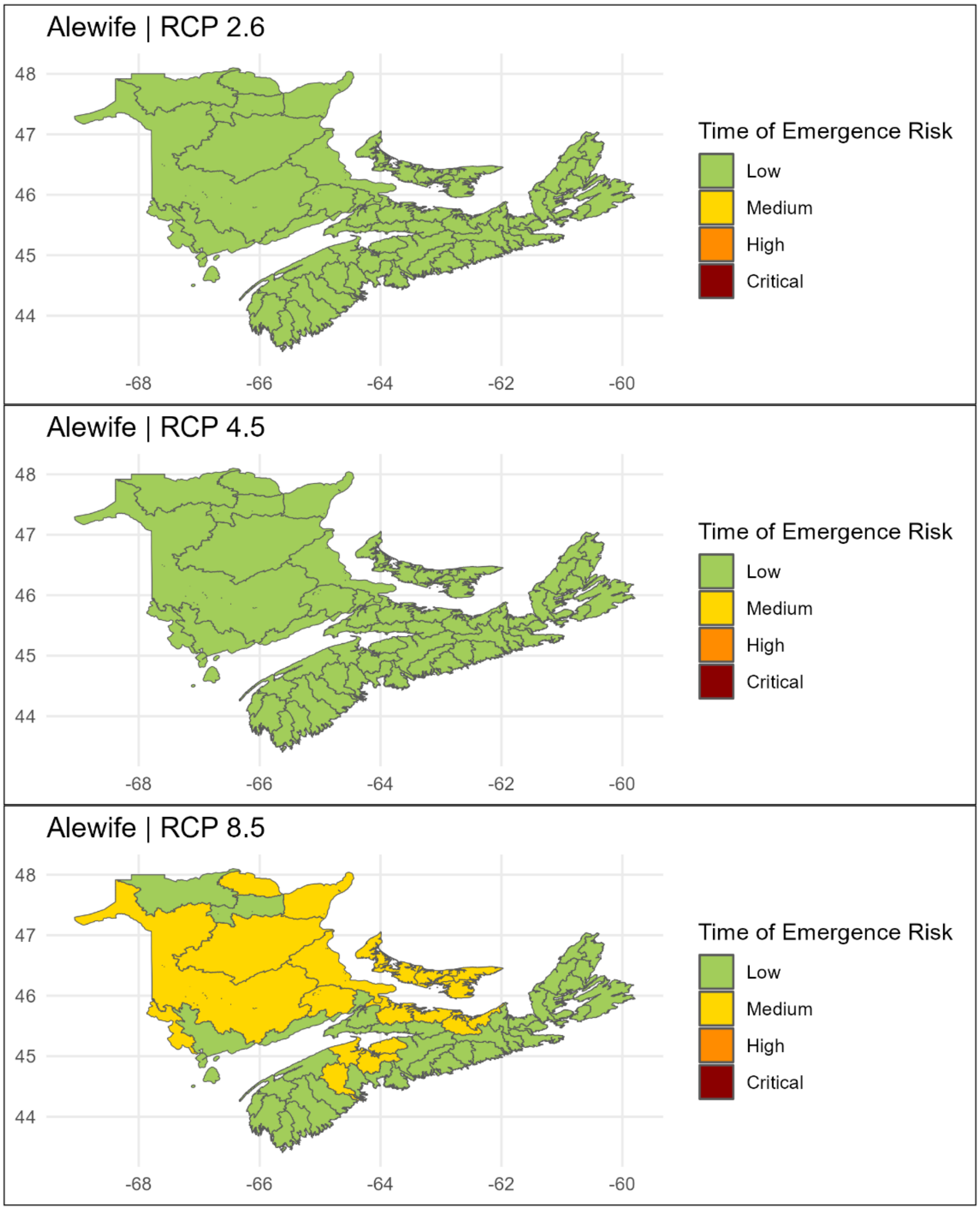
Appendix 80 Map of study area coloured by Atlantic sturgeon time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



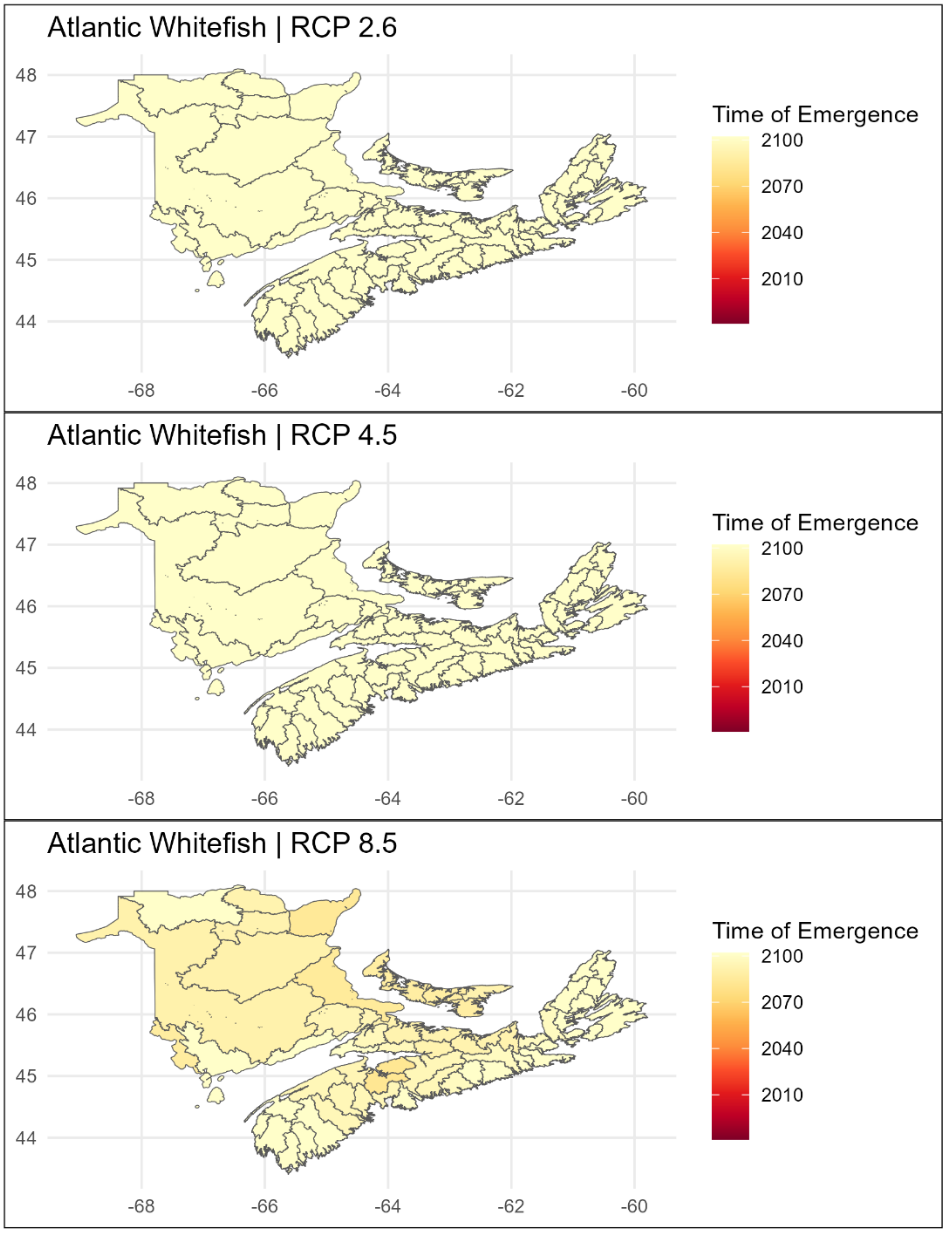
Appendix 81 Map of study area coloured by Atlantic sturgeon time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



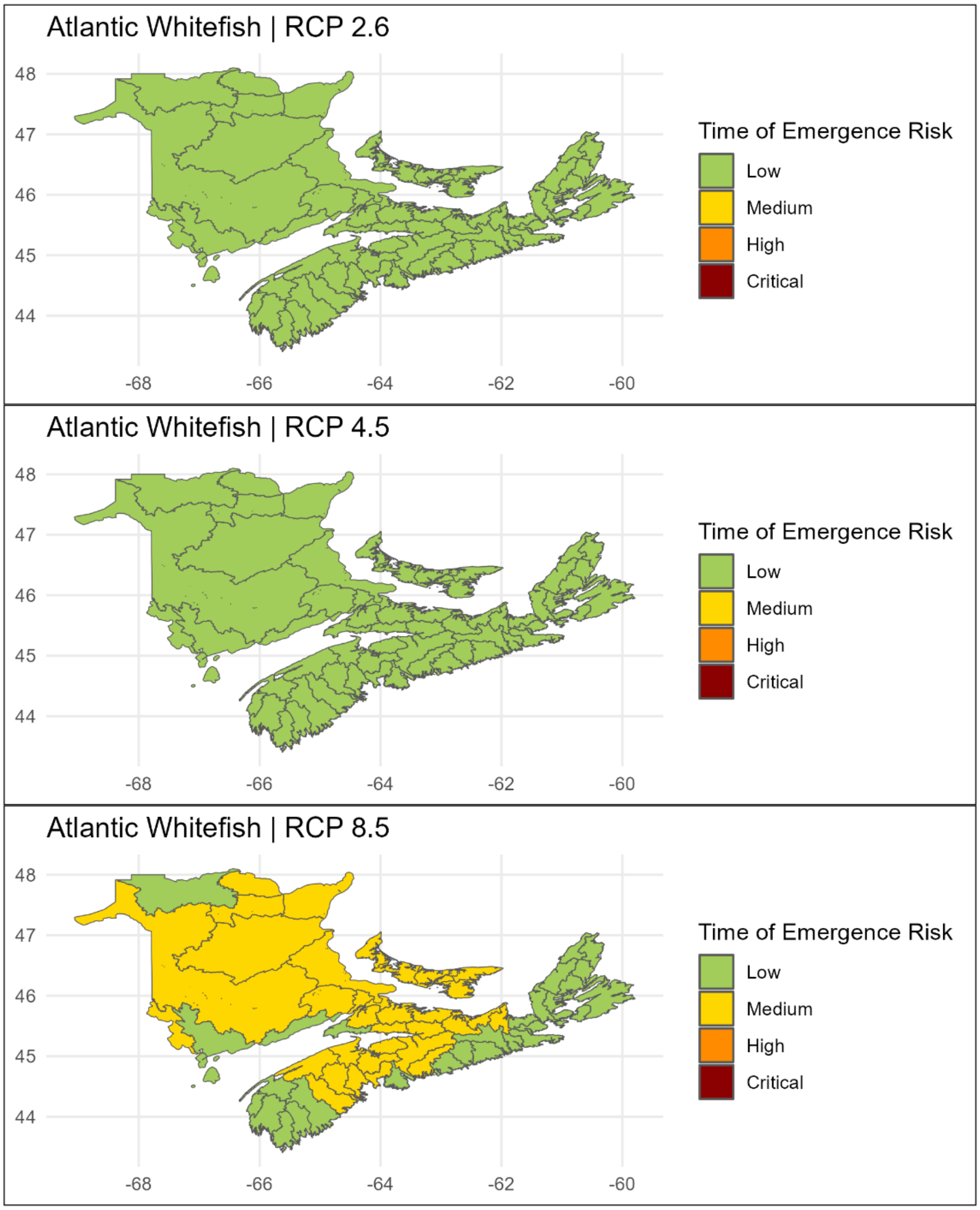
Appendix 82 Map of study area coloured by alewife time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



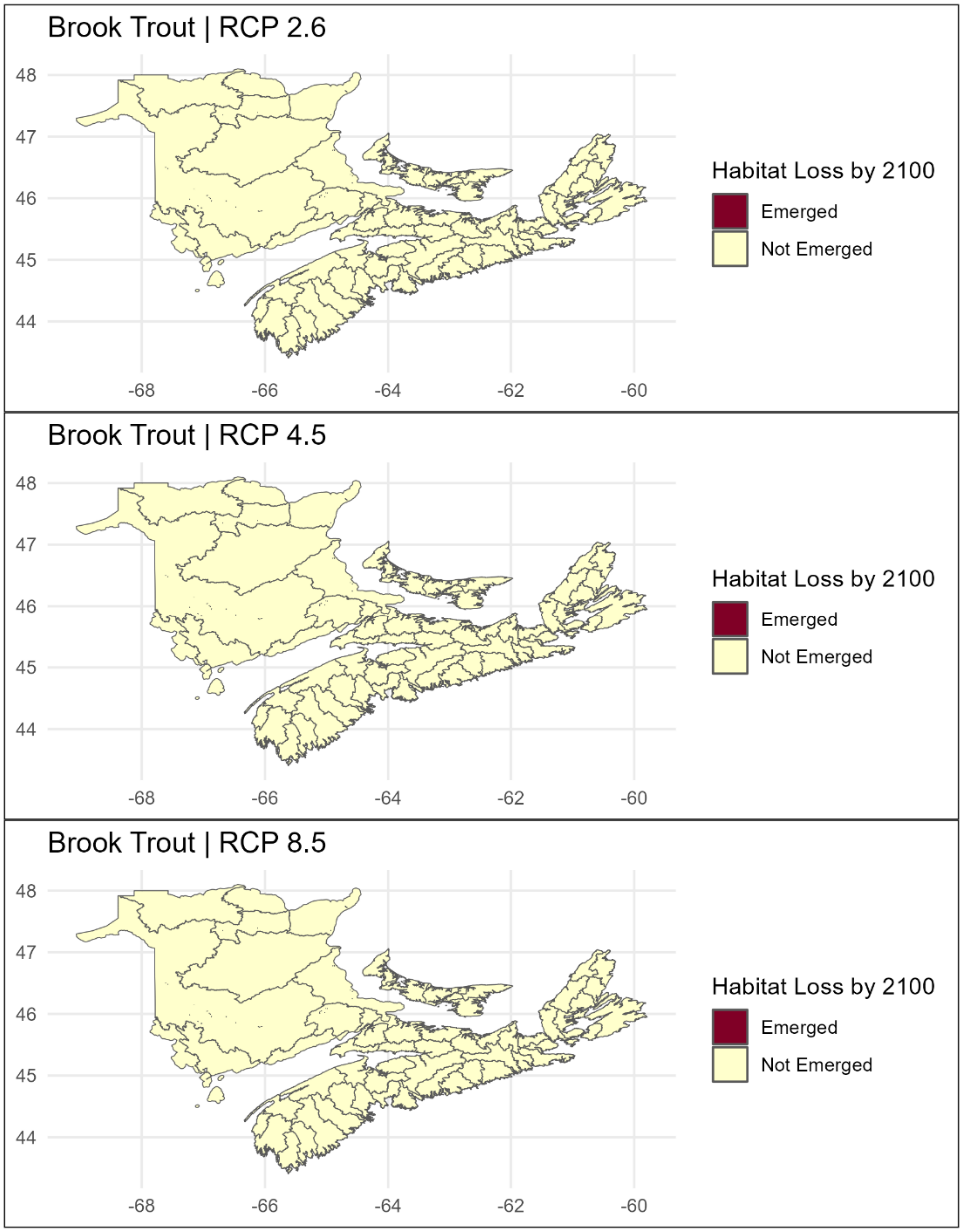
Appendix 83 Map of study area coloured by alewife time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



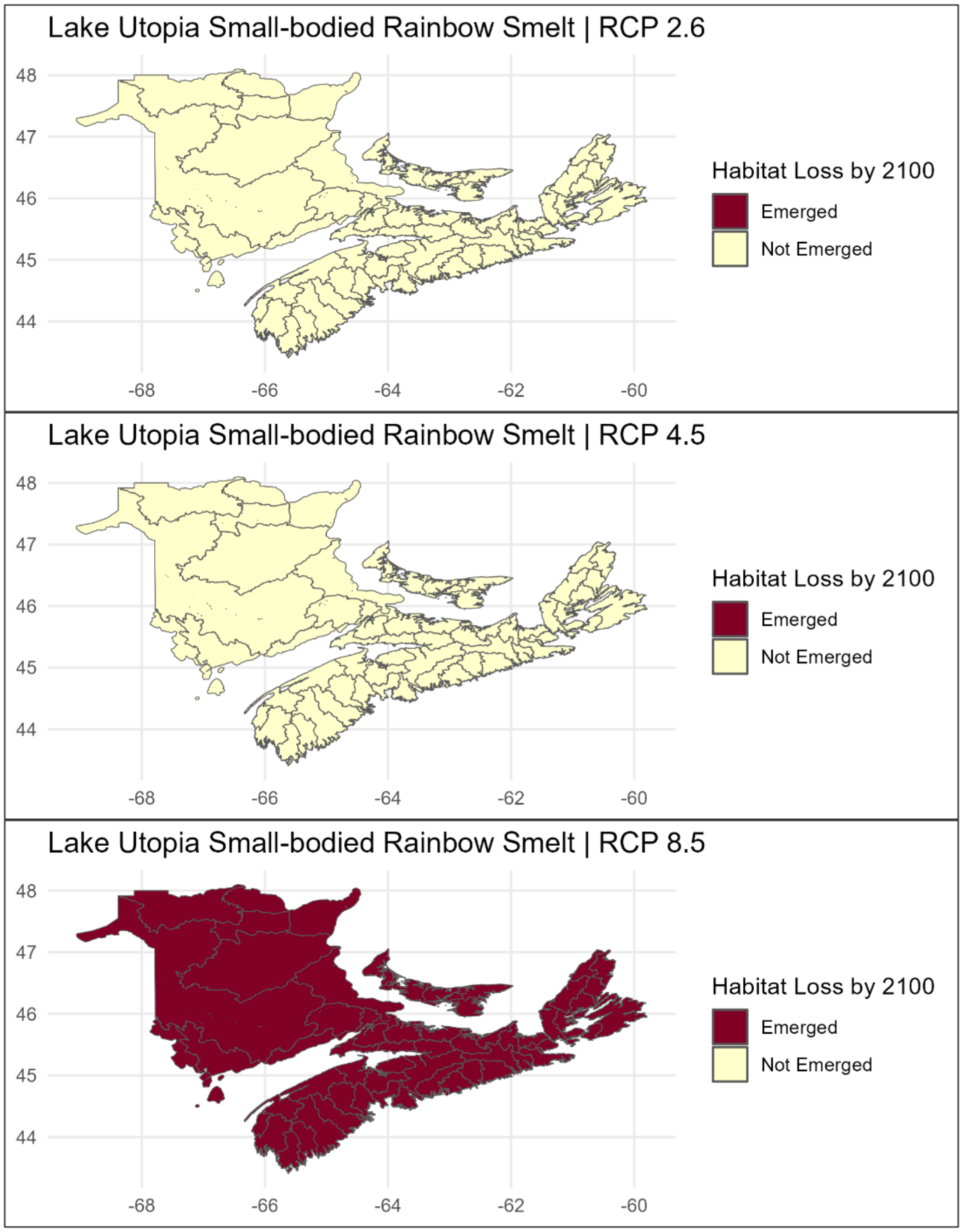
Appendix 84 Map of study area coloured by Atlantic whitefish time of emergence index scores in years, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



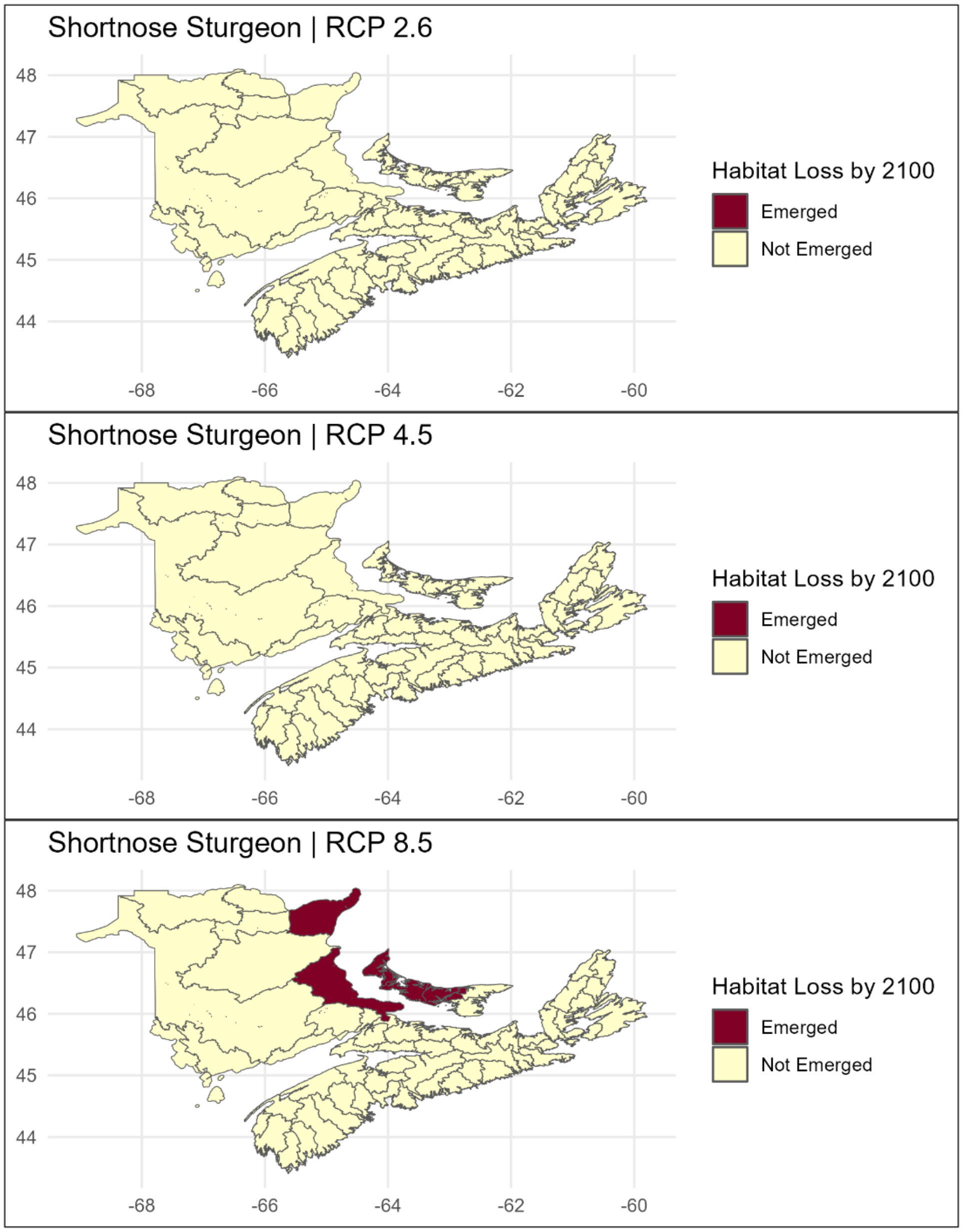
Appendix 85 Map of study area coloured by Atlantic whitefish time of emergence index risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



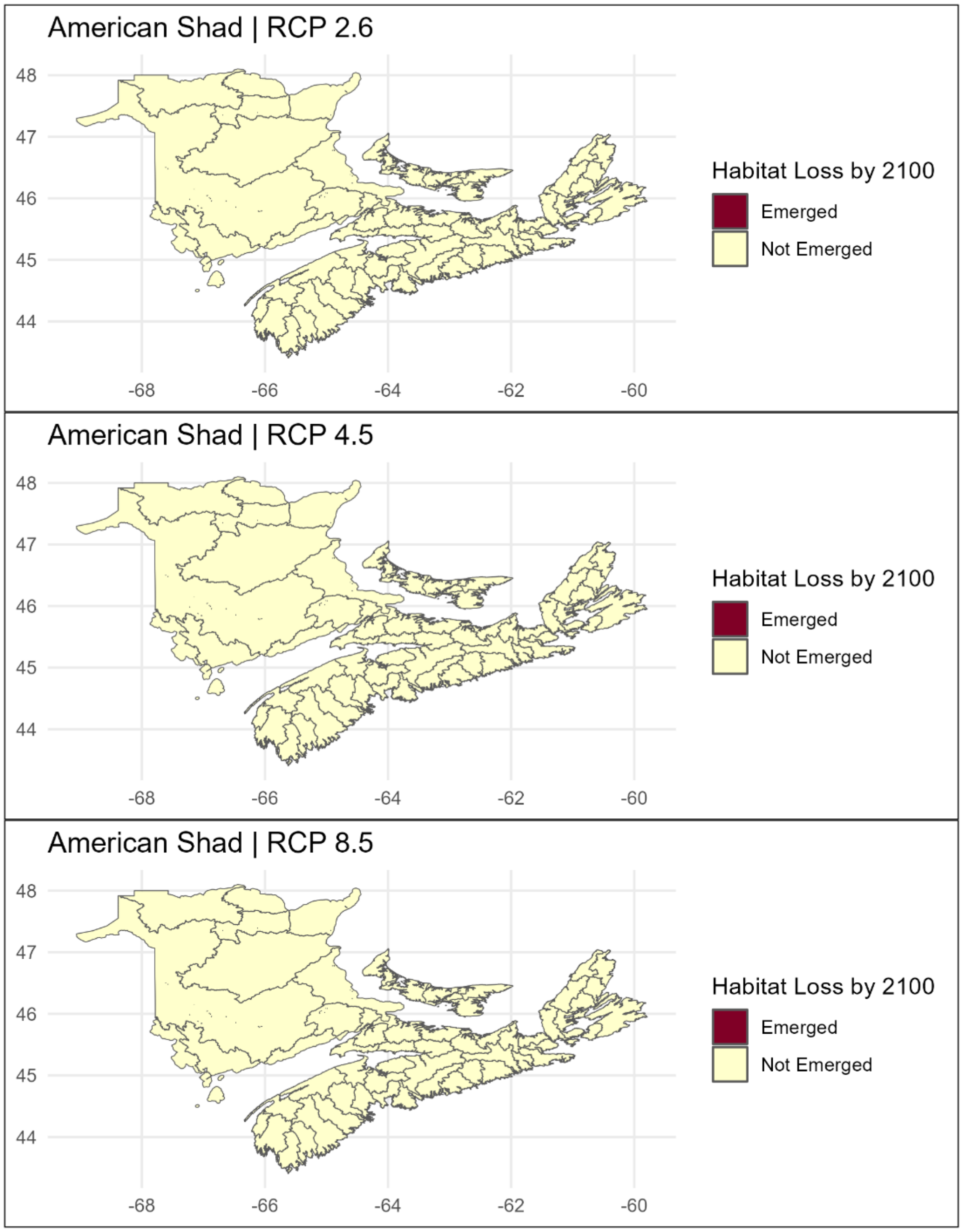
Appendix 86 Map of study area coloured by brook trout habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



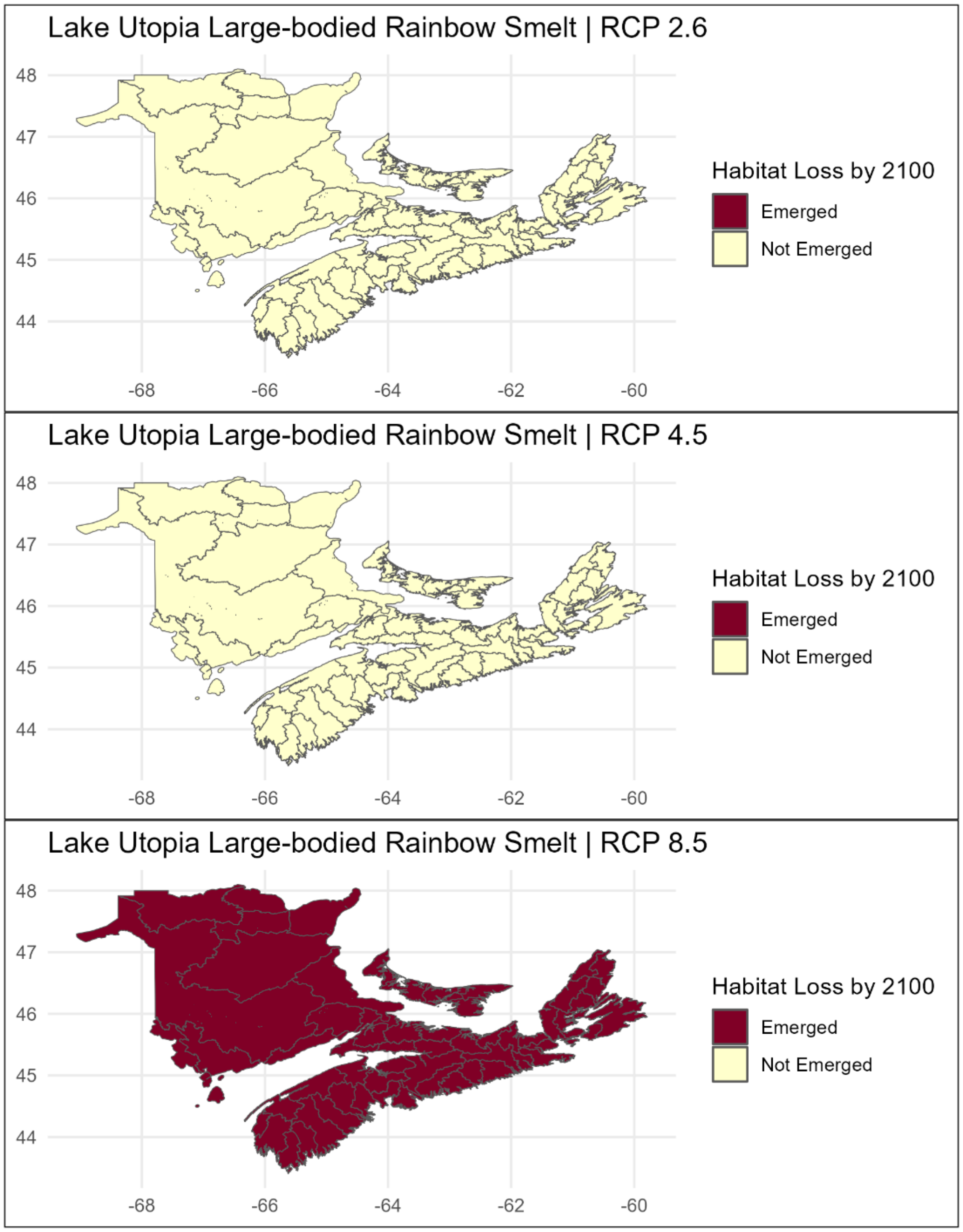
Appendix 87 Map of study area coloured by Lake Utopia small-bodied rainbow smelt habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



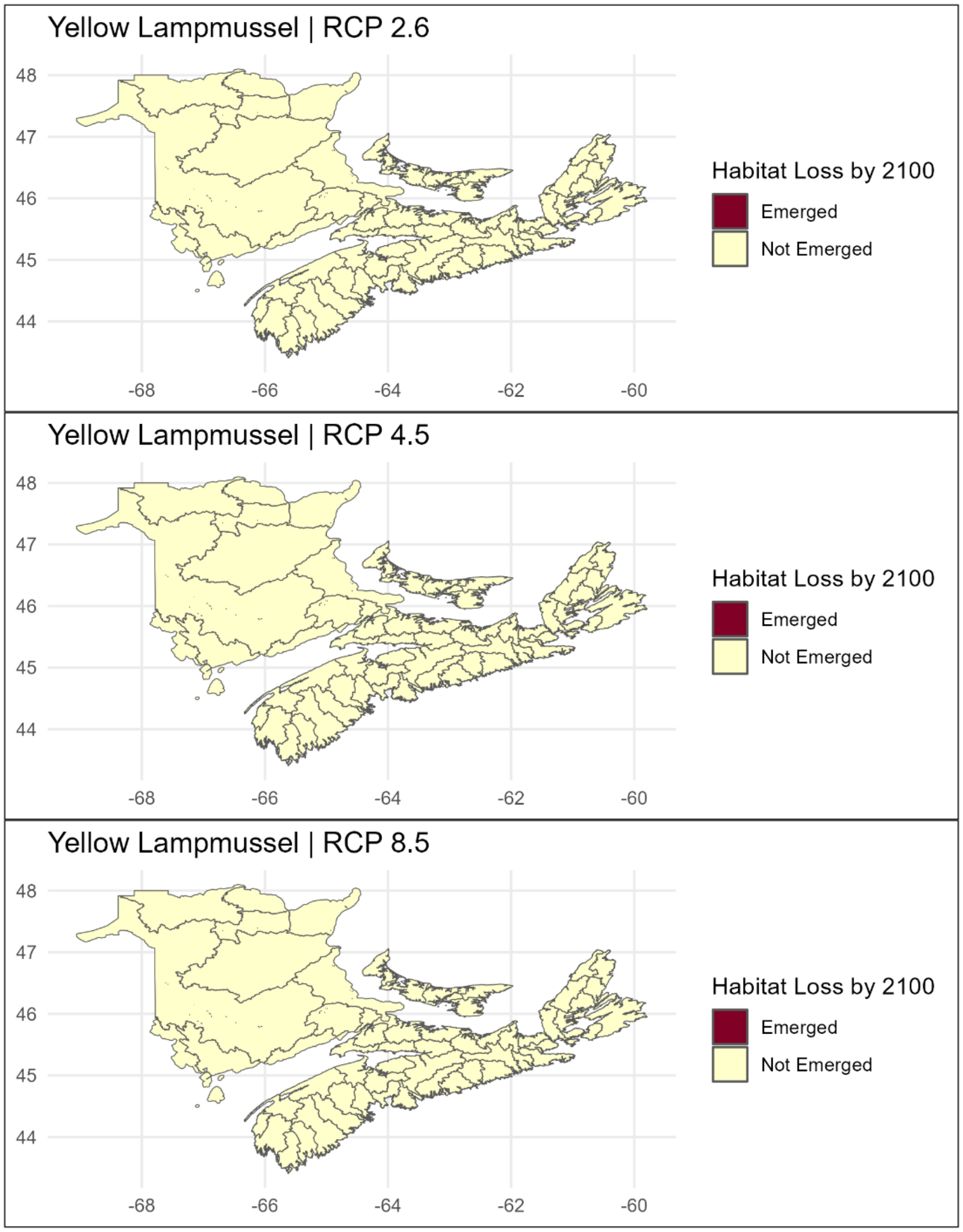
Appendix 88 Map of study area coloured by shortnose sturgeon habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



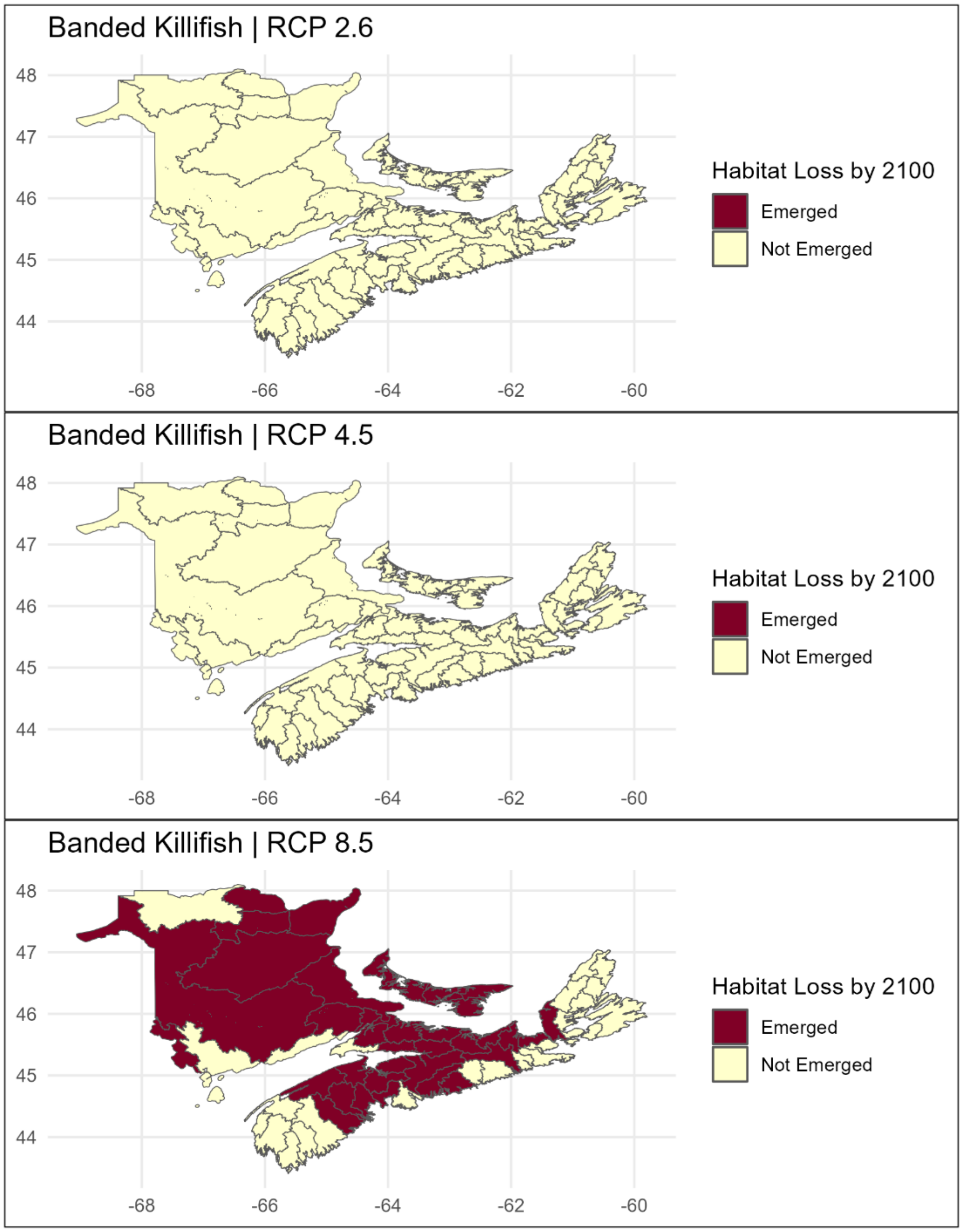
Appendix 89 Map of study area coloured by American shad habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



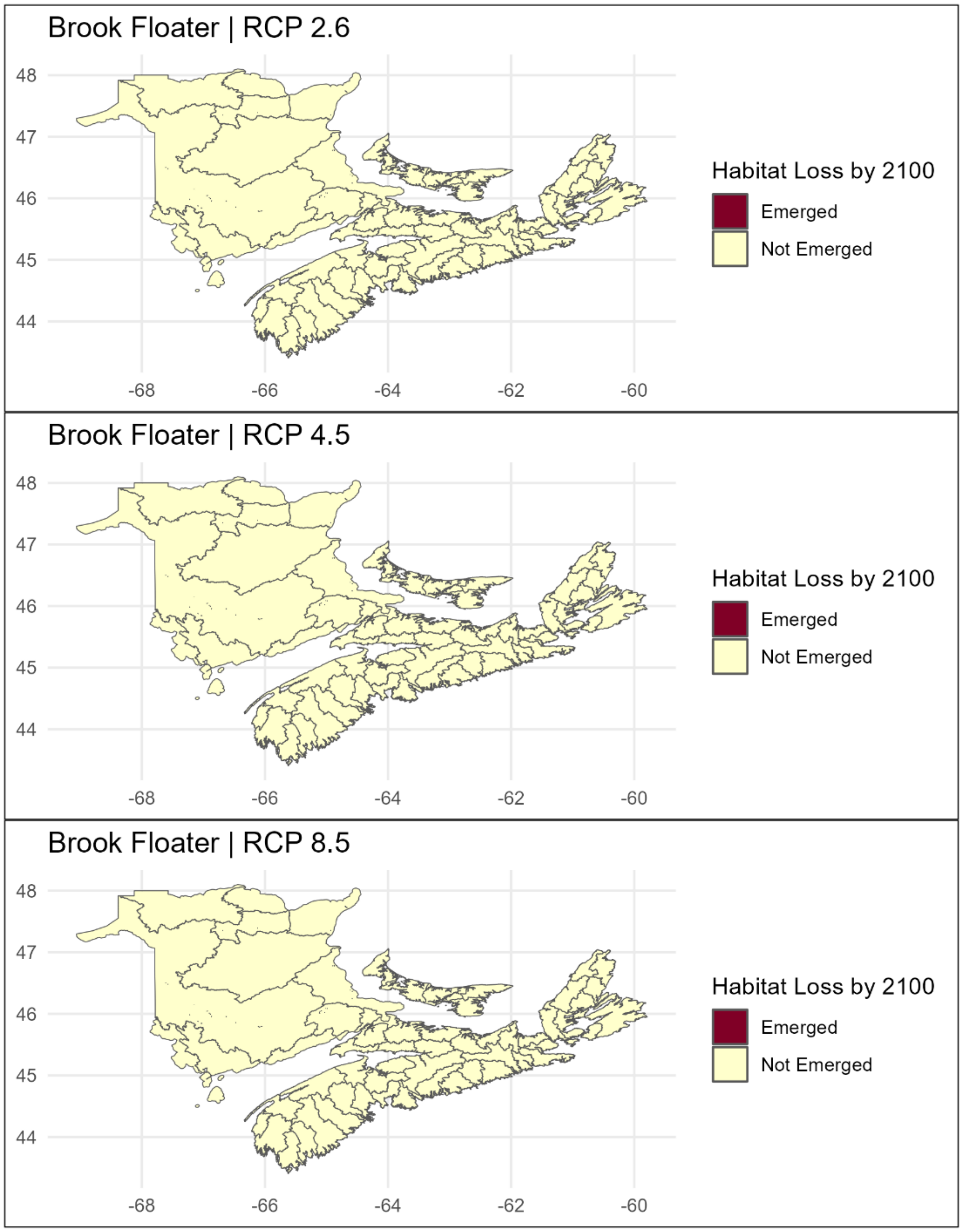
Appendix 90 Map of study area coloured by Lake Utopia large-bodied rainbow smelt habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



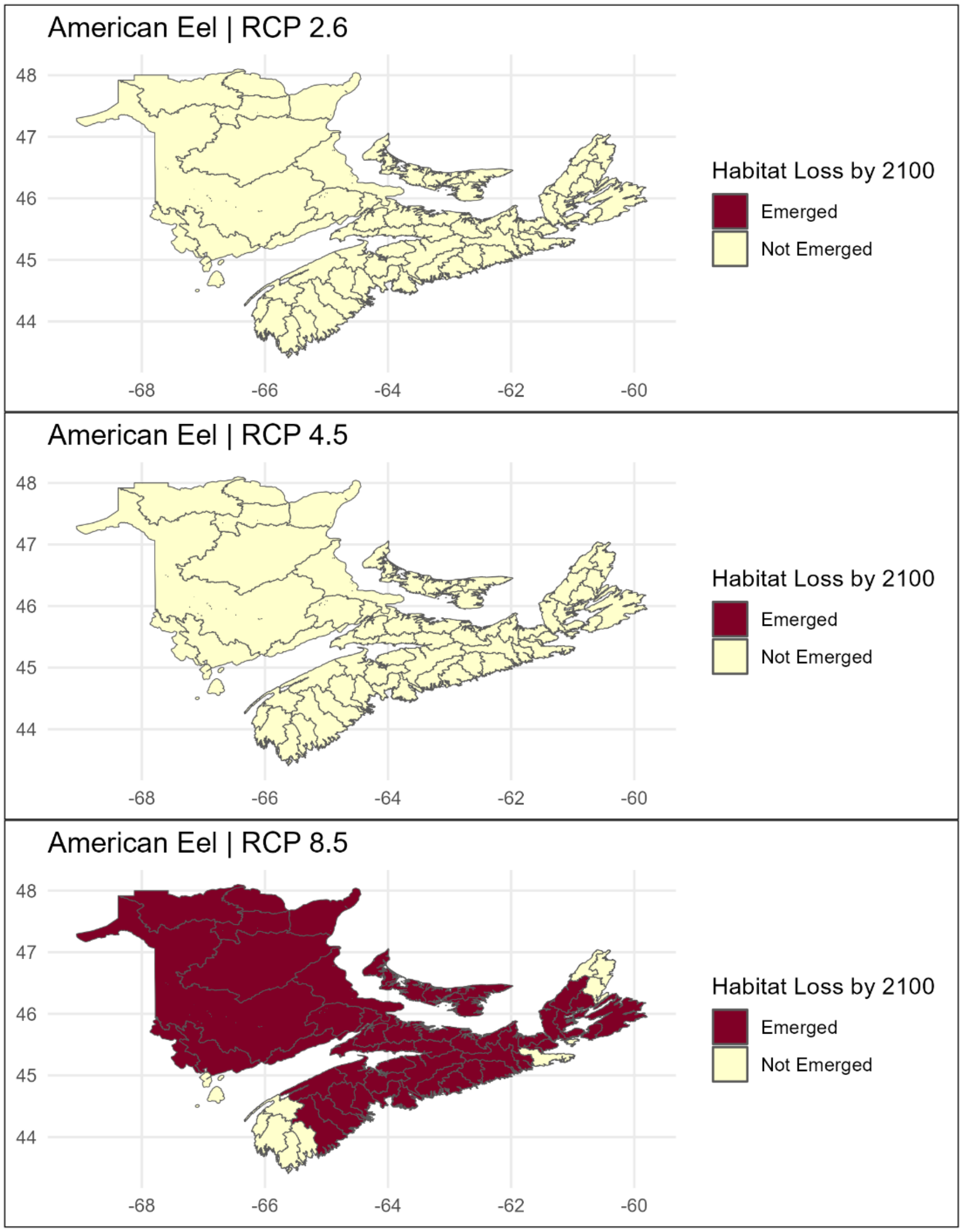
Appendix 91 Map of study area coloured by yellow lampmussel habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



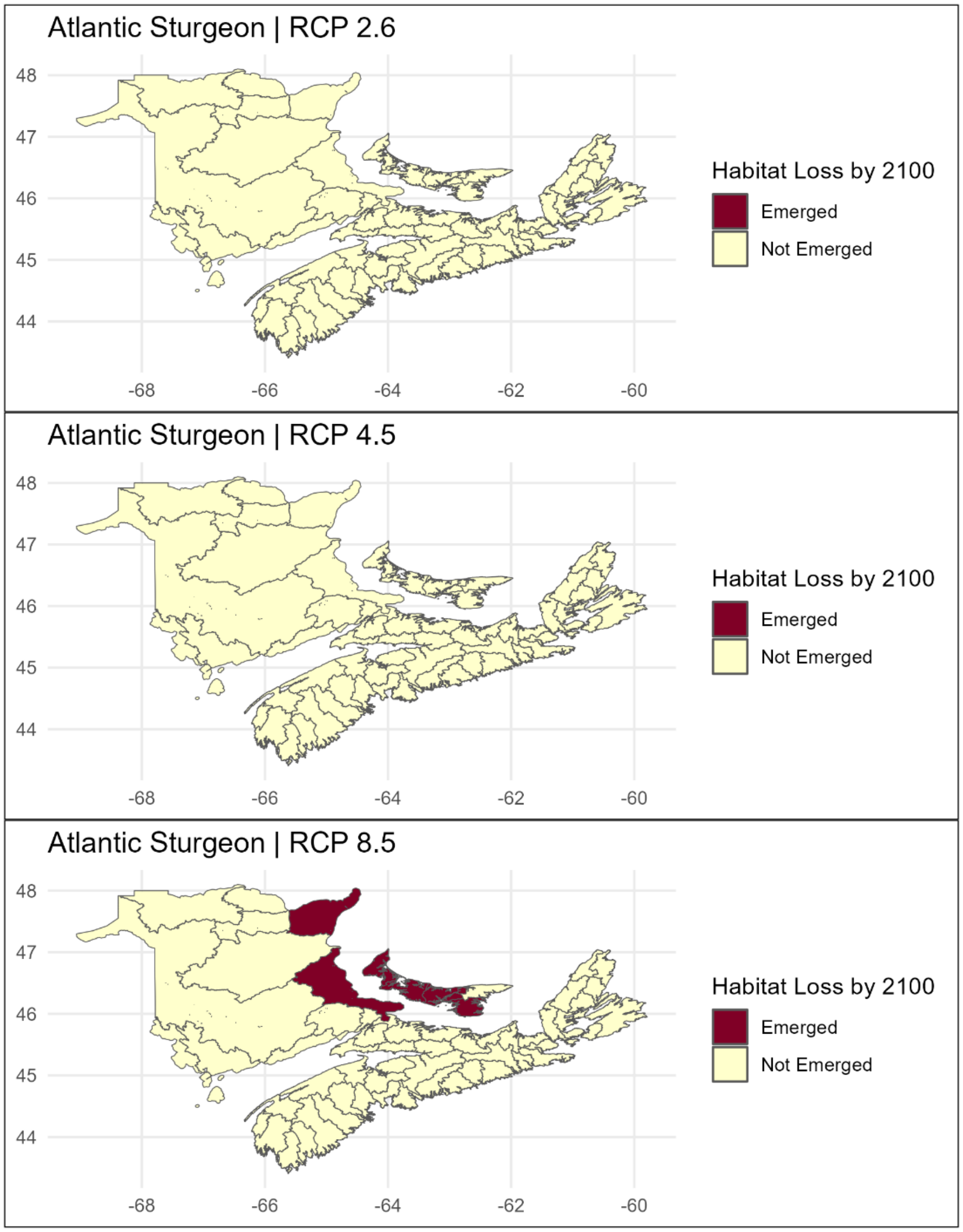
Appendix 92 Map of study area coloured by banded killifish habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



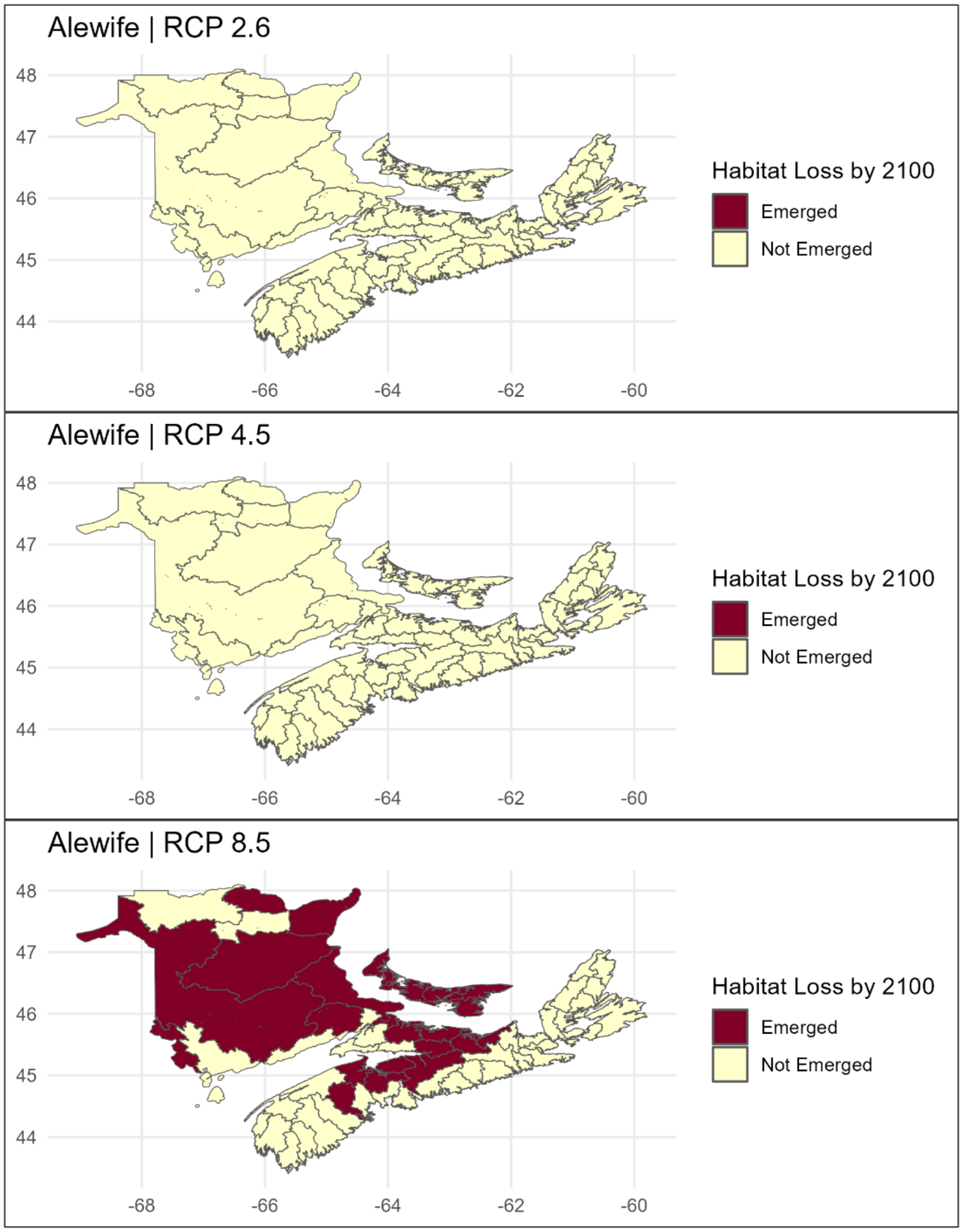
Appendix 93 Map of study area coloured by brook floater habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



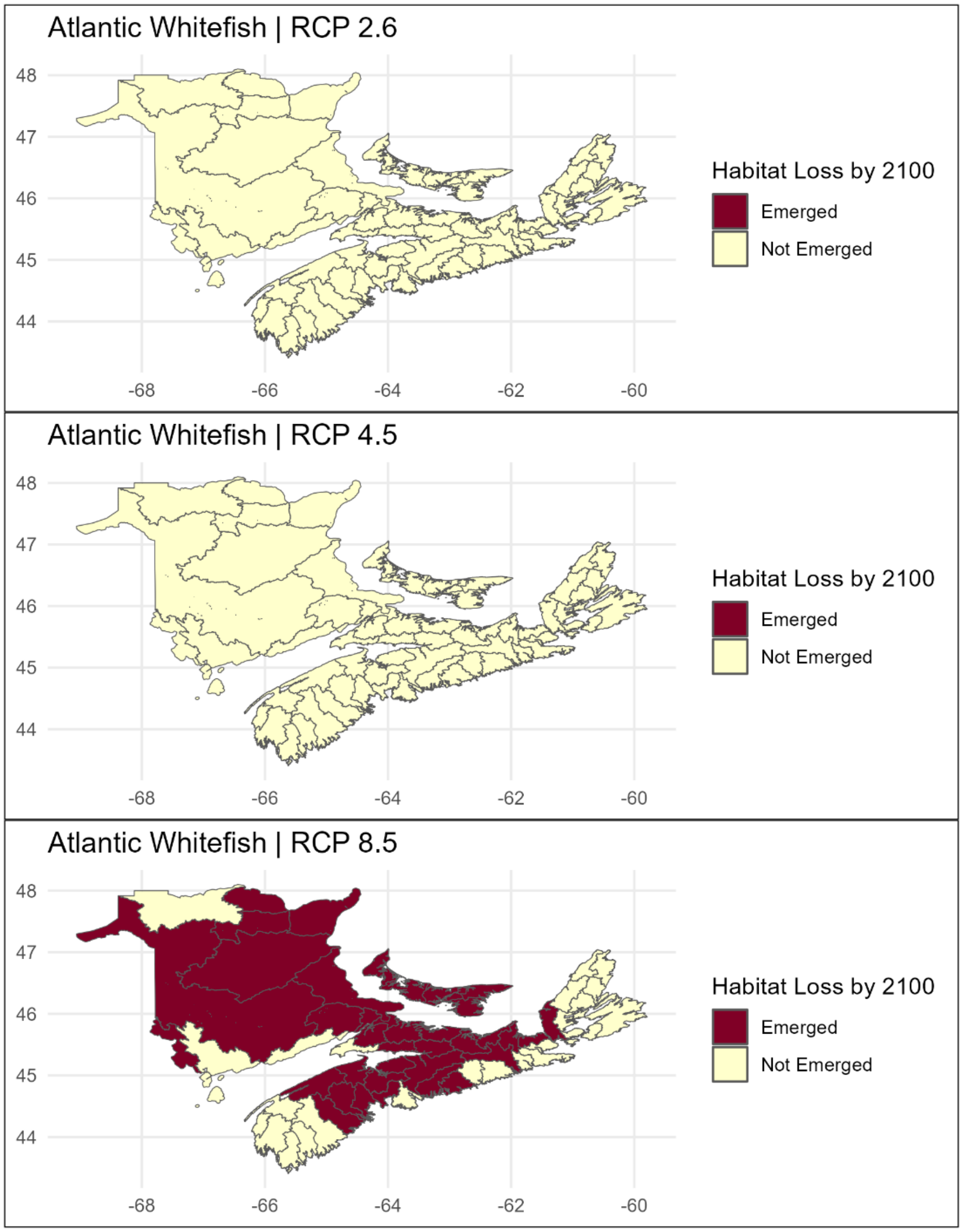
Appendix 94 Map of study area coloured by American eel habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



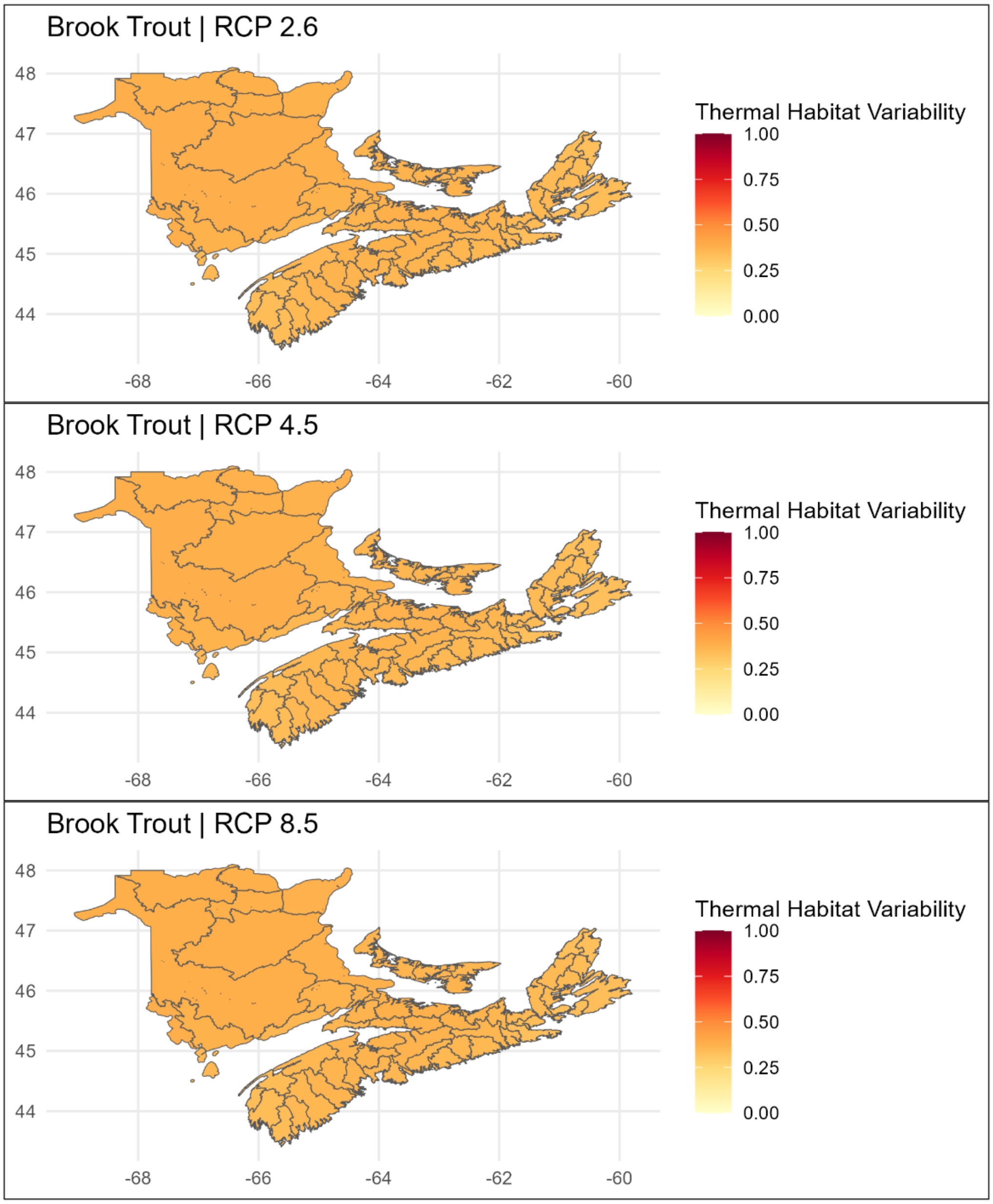
Appendix 95 Map of study area coloured by Atlantic sturgeon habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



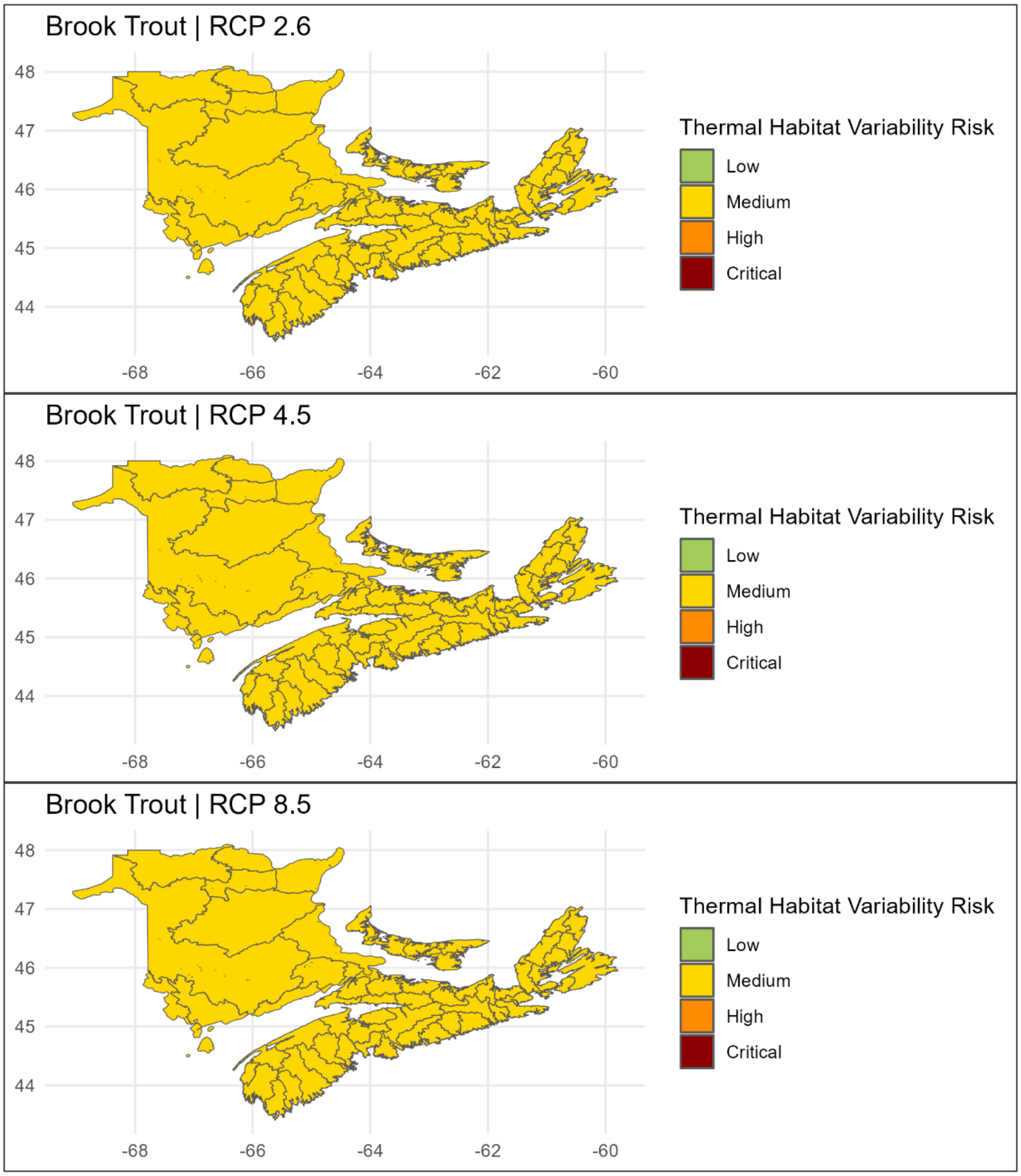
Appendix 96 Map of study area coloured by alewife habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



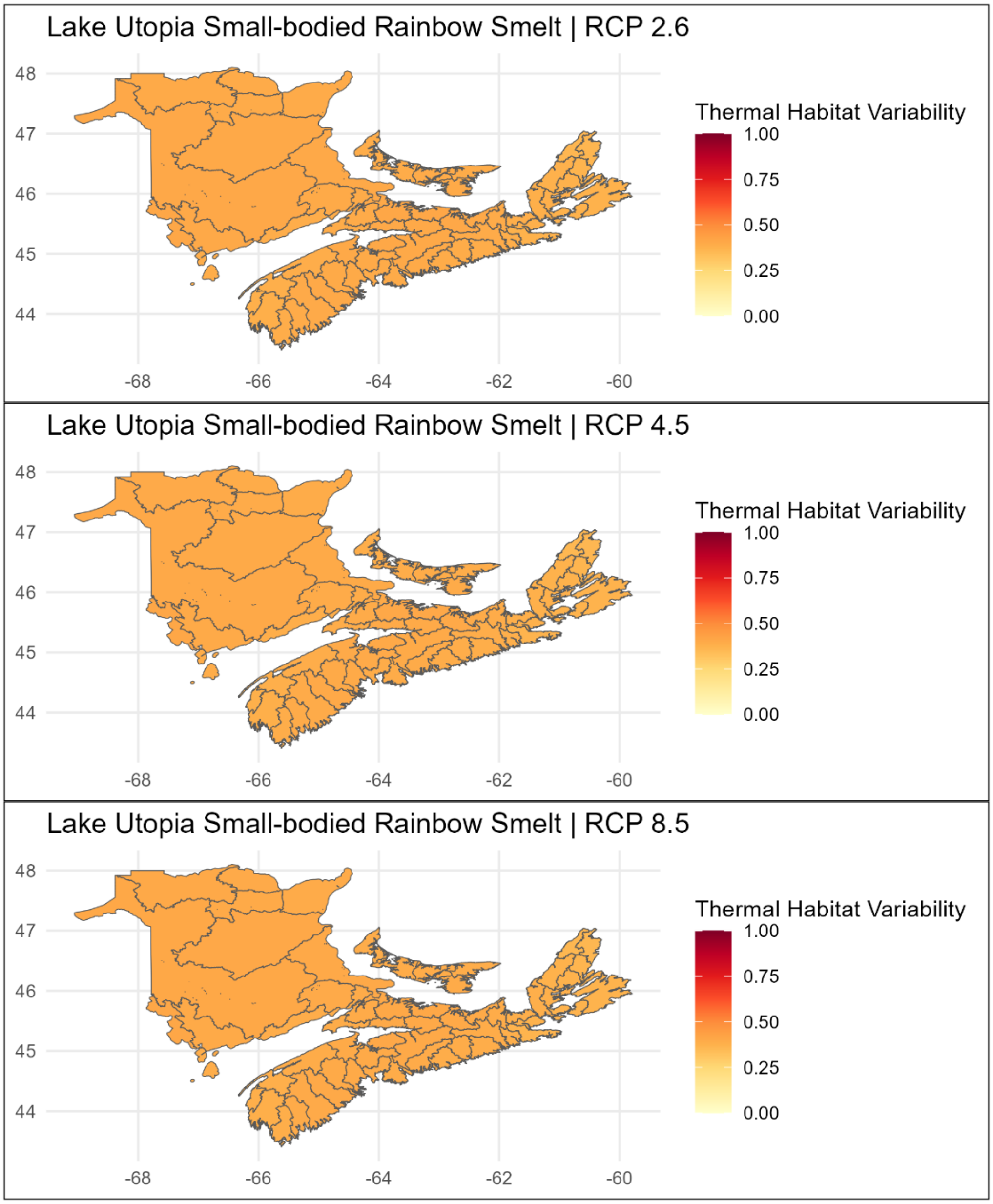
Appendix 97 Map of study area coloured by Atlantic whitefish habitat loss by 2100 index scores, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



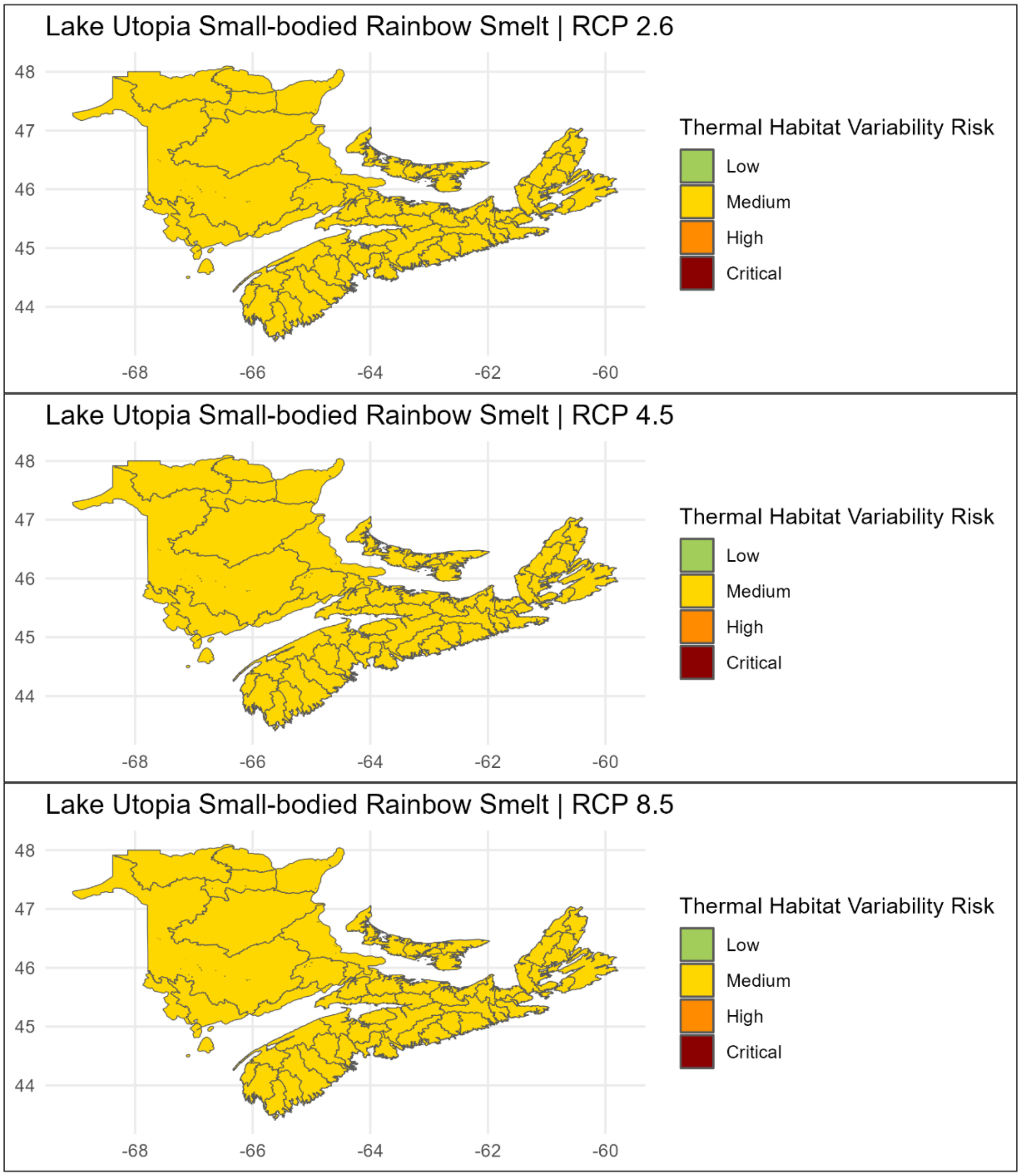
Appendix 98 Map of study area coloured by brook trout thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



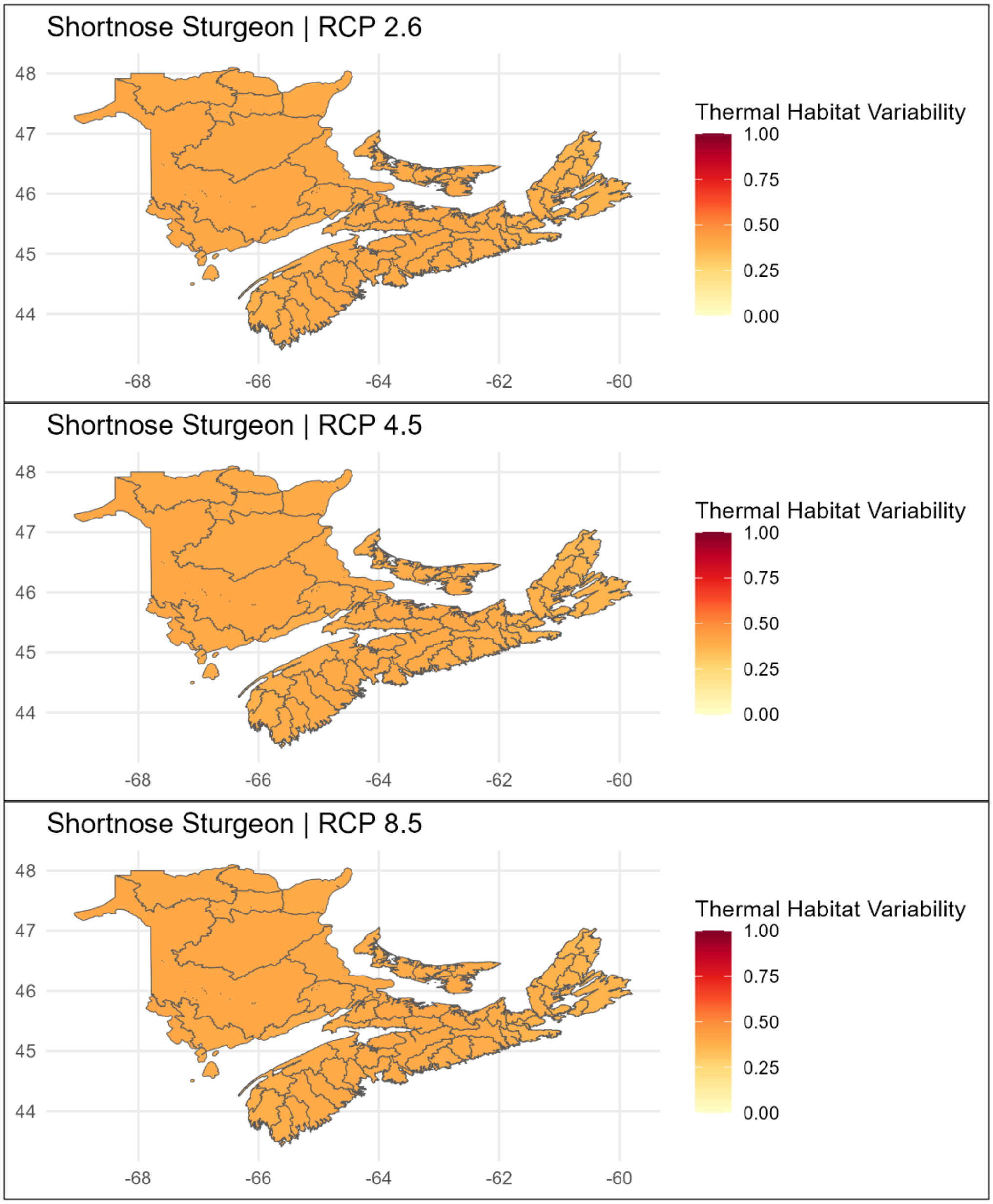
Appendix 99 Map of study area coloured by brook trout thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



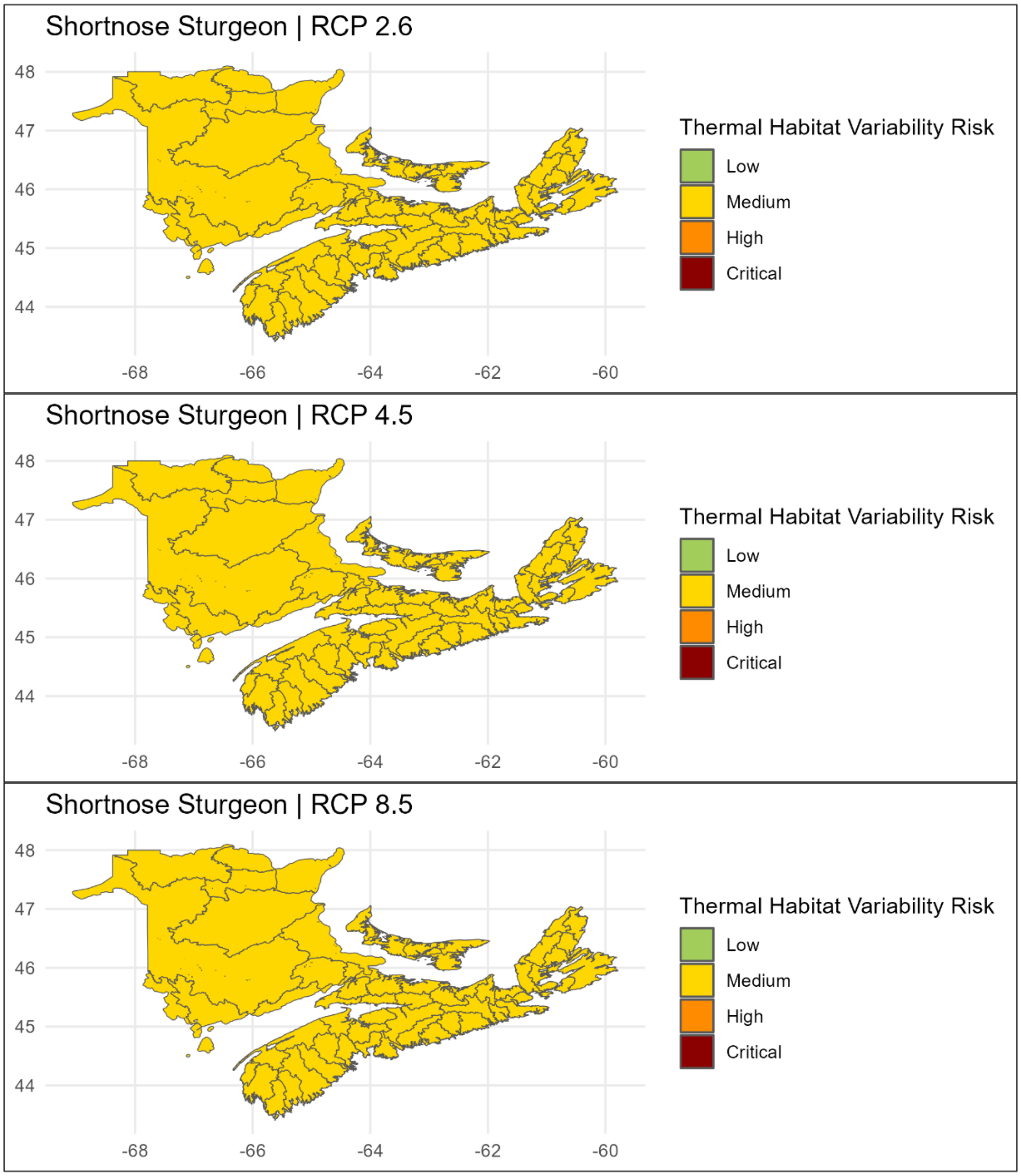
Appendix 100 Map of study area coloured by Lake Utopia small-bodied rainbow smelt thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



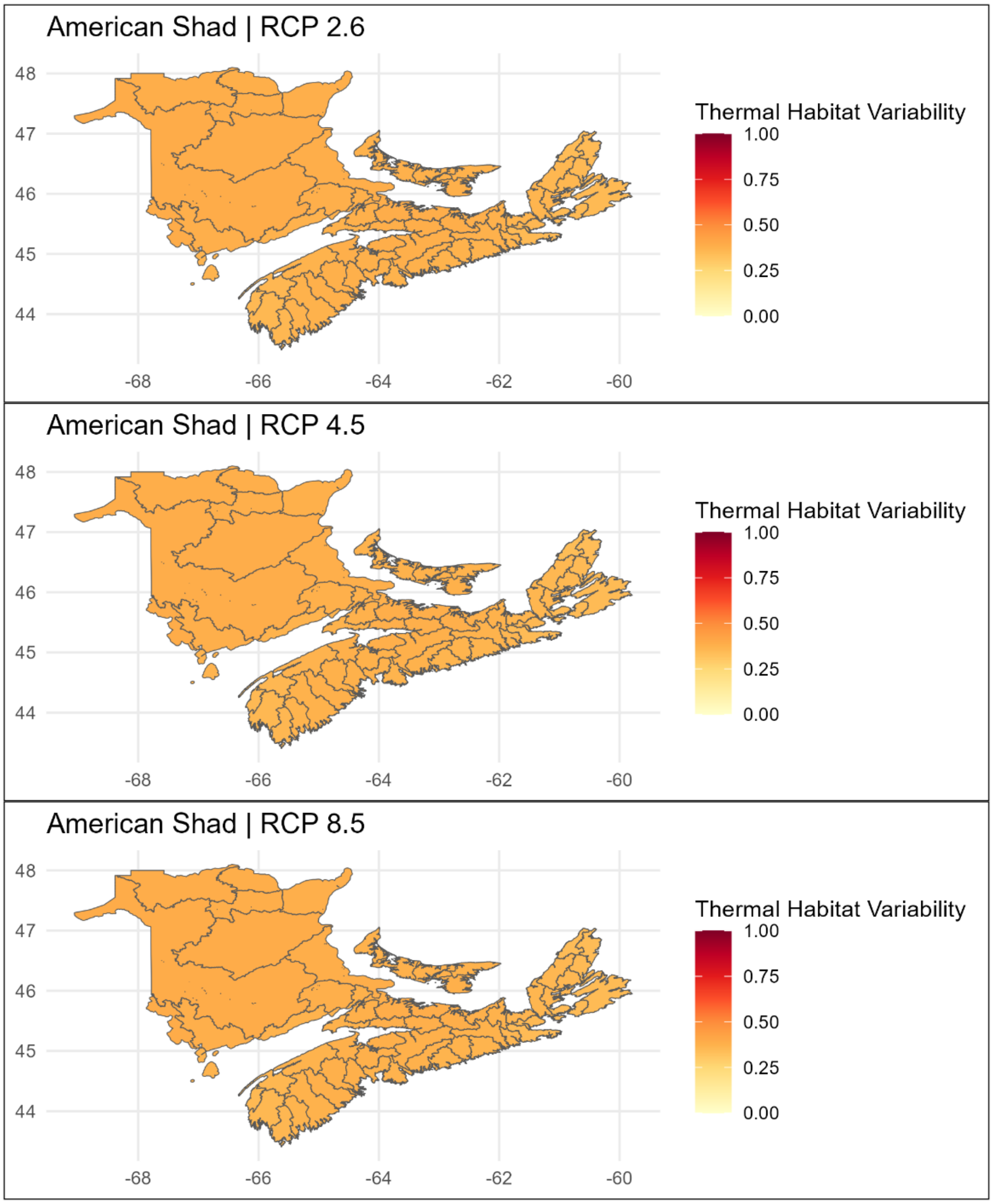
Appendix 101 Map of study area coloured by Lake Utopia small-bodied rainbow smelt thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



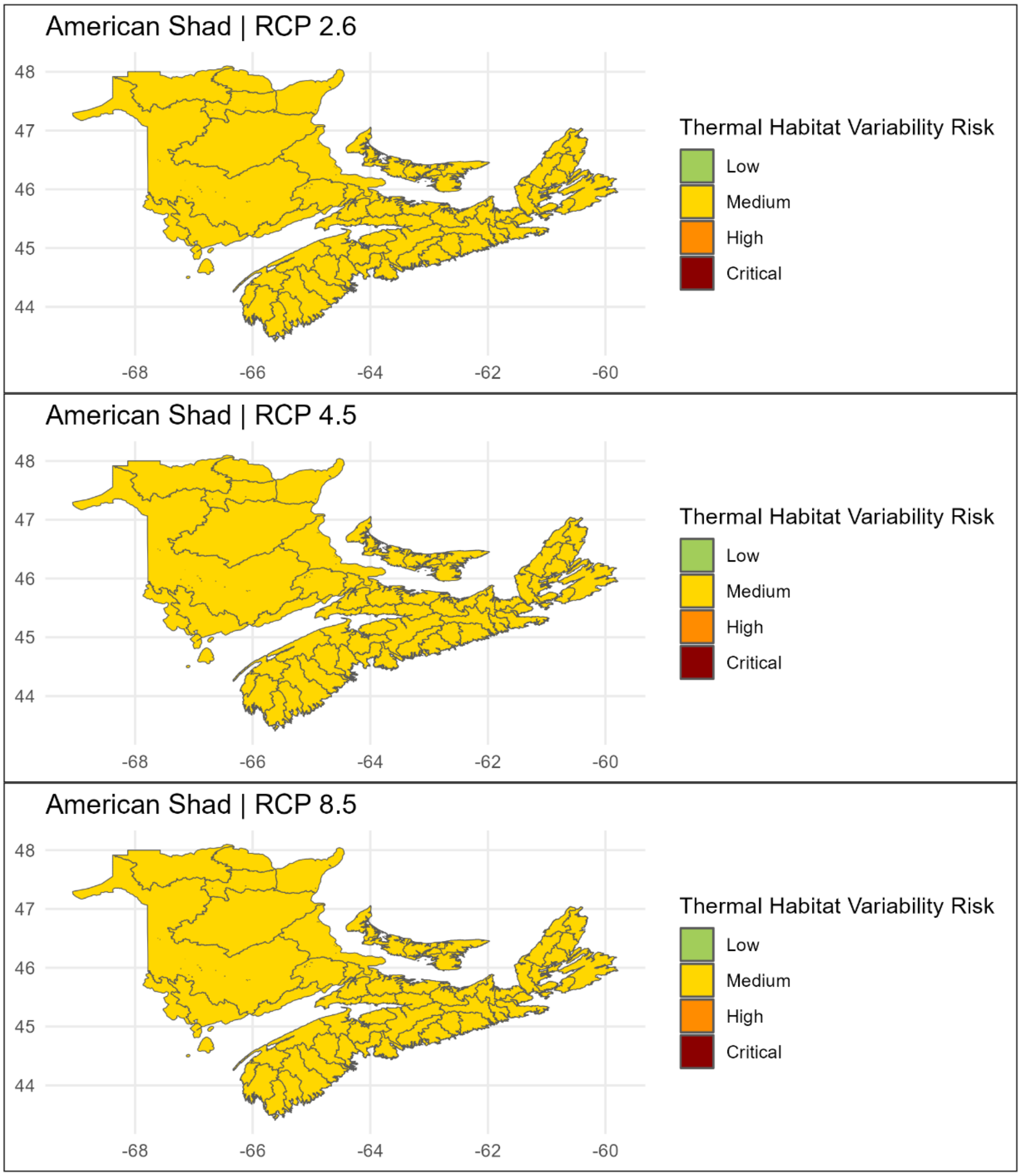
Appendix 102 Map of study area coloured by shortnose sturgeon habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



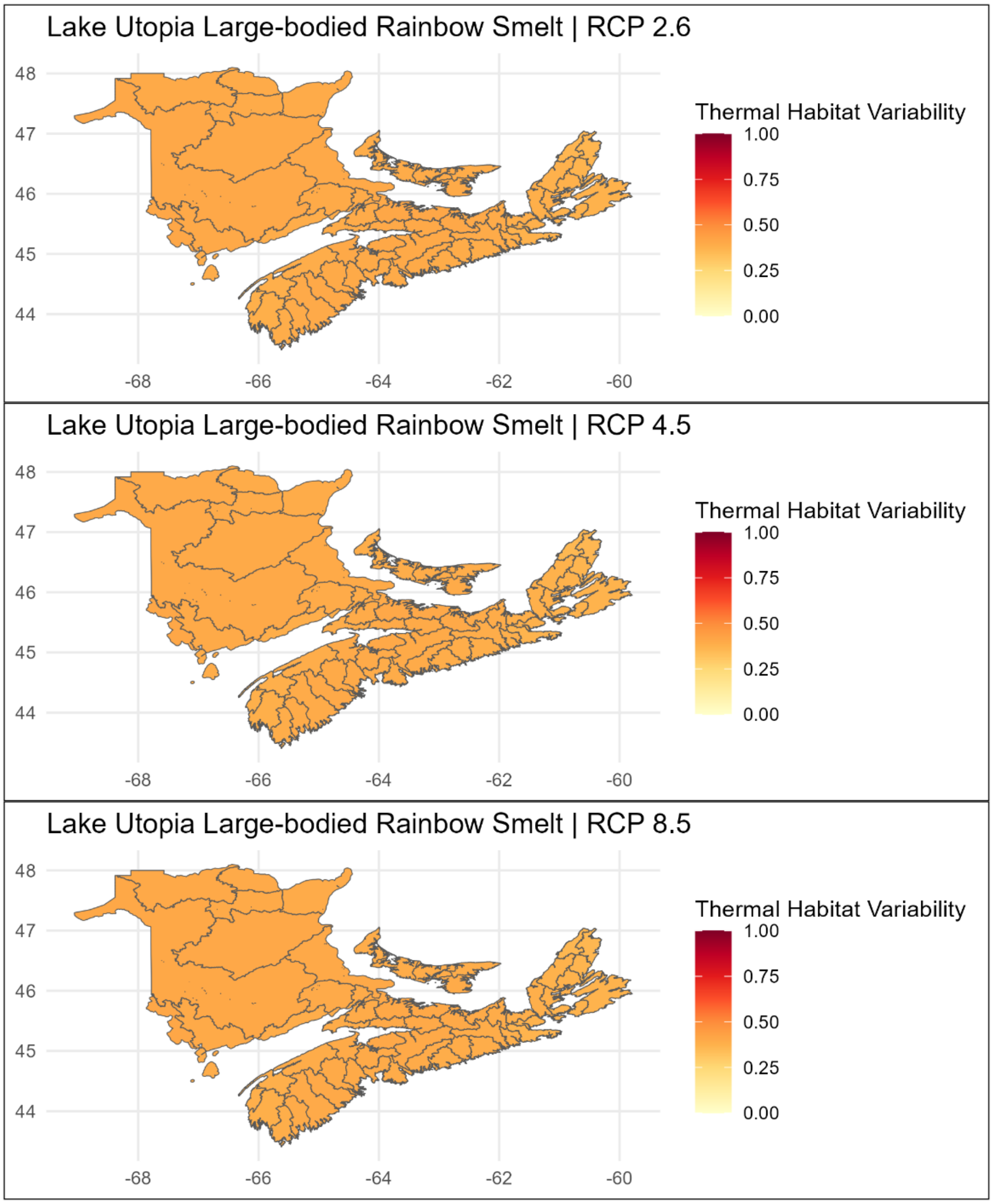
Appendix 103 Map of study area coloured by shortnose sturgeon thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



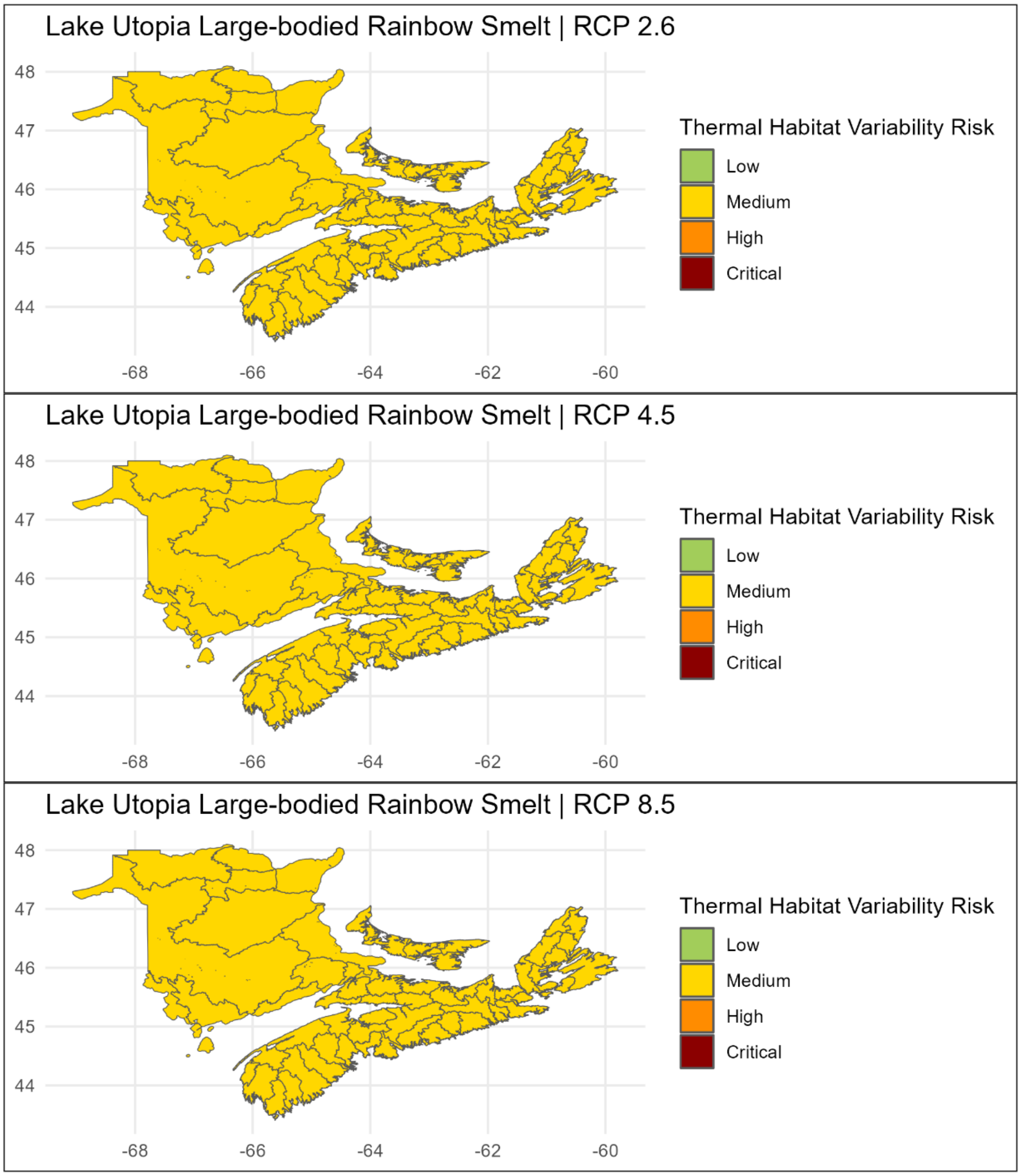
Appendix 104 Map of study area coloured by American shad thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



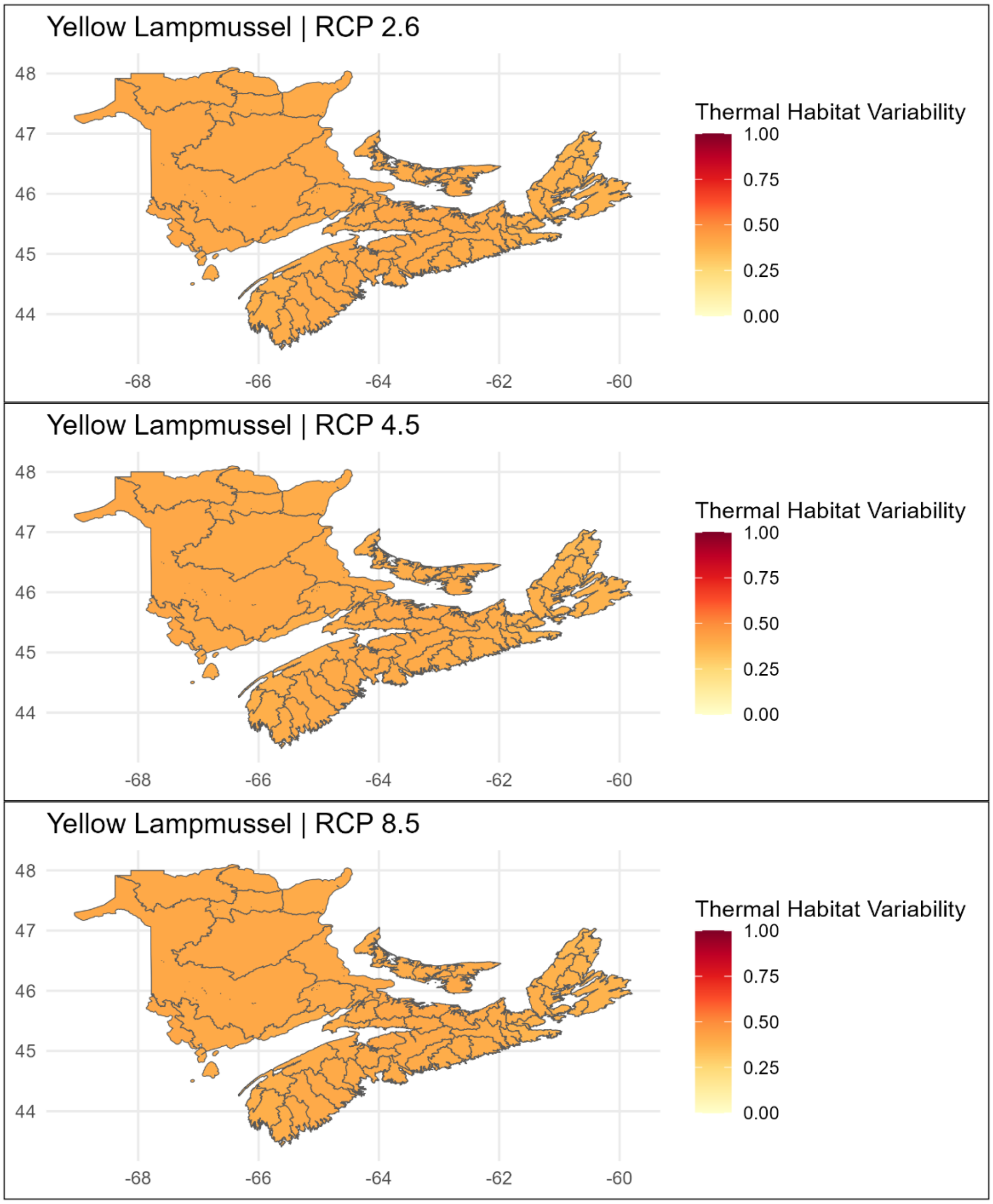
Appendix 105 Map of study area coloured by American shad thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



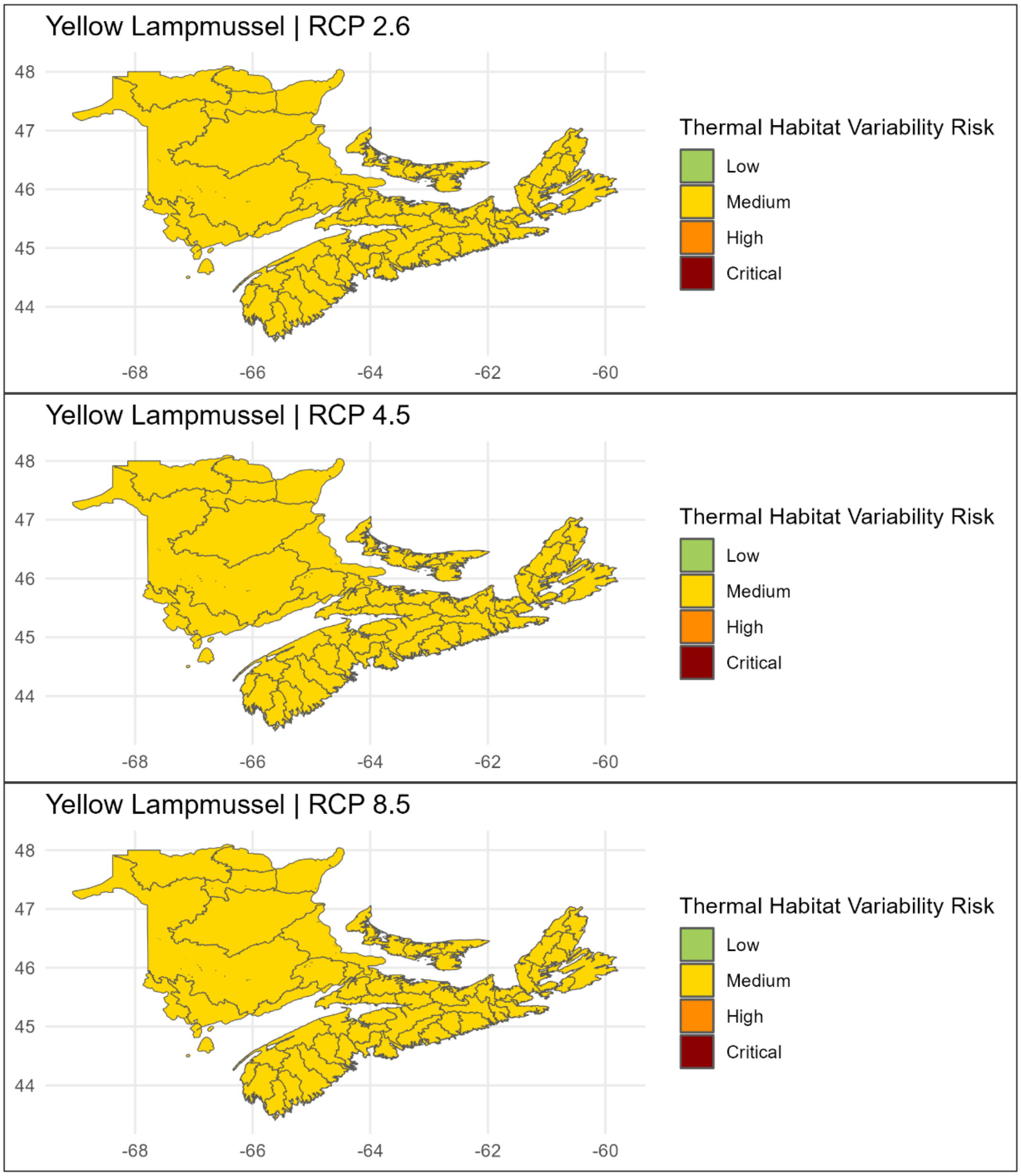
Appendix 106 Map of study area coloured by Lake Utopia large-bodied rainbow smelt thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



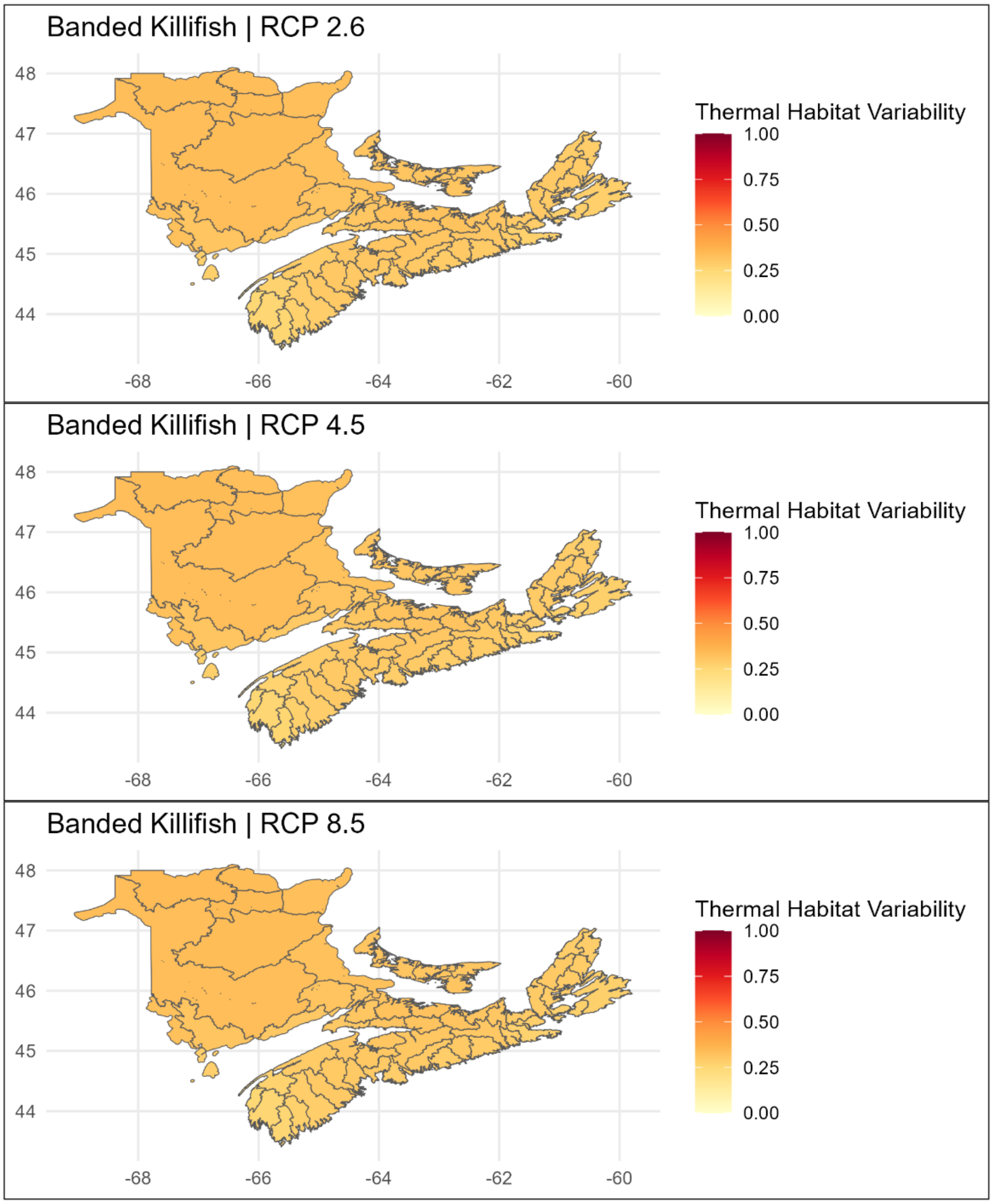
Appendix 107 Map of study area coloured by Lake Utopia large-bodied rainbow smelt thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



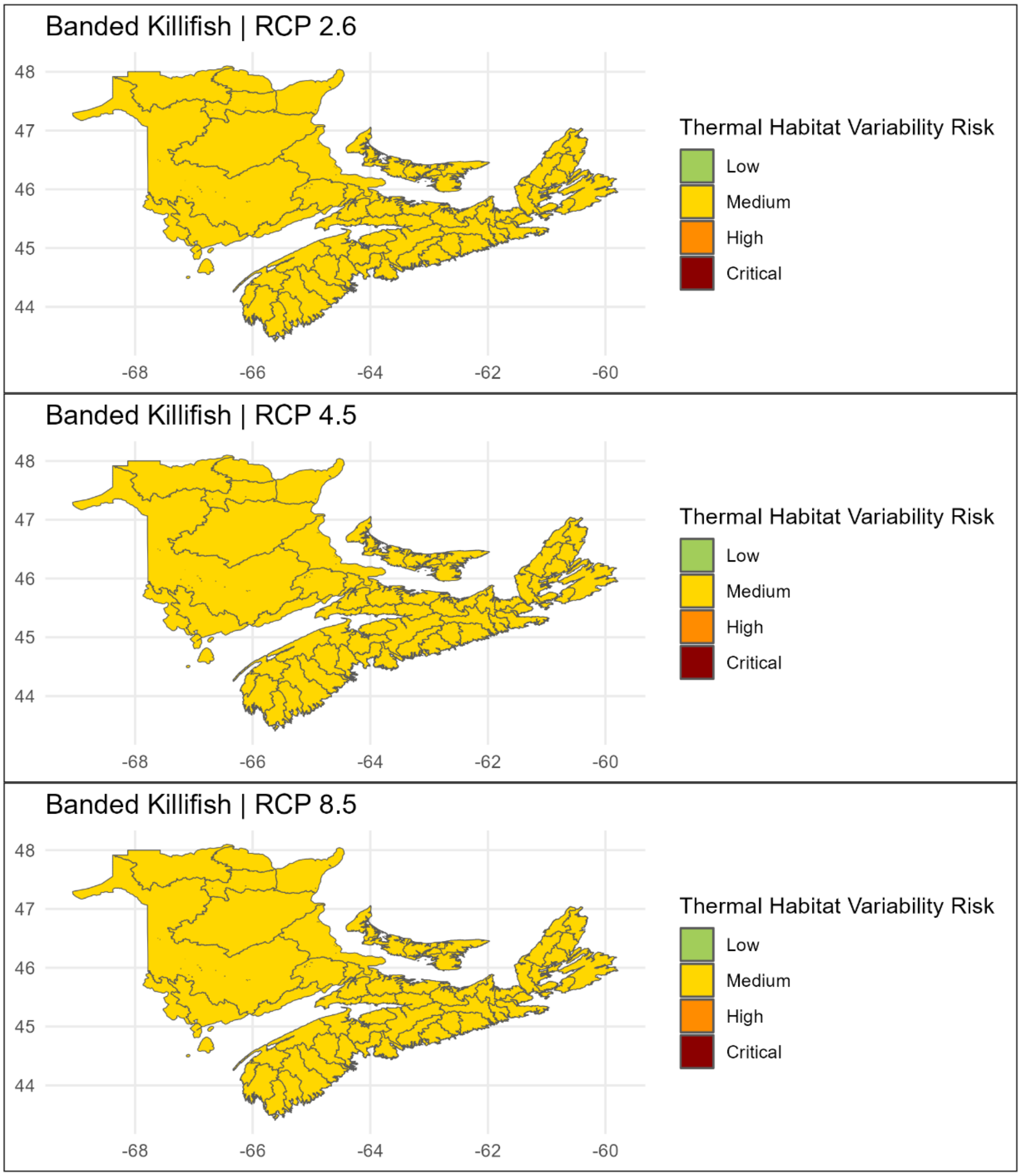
Appendix 108 Map of study area coloured by yellow lampmussel thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



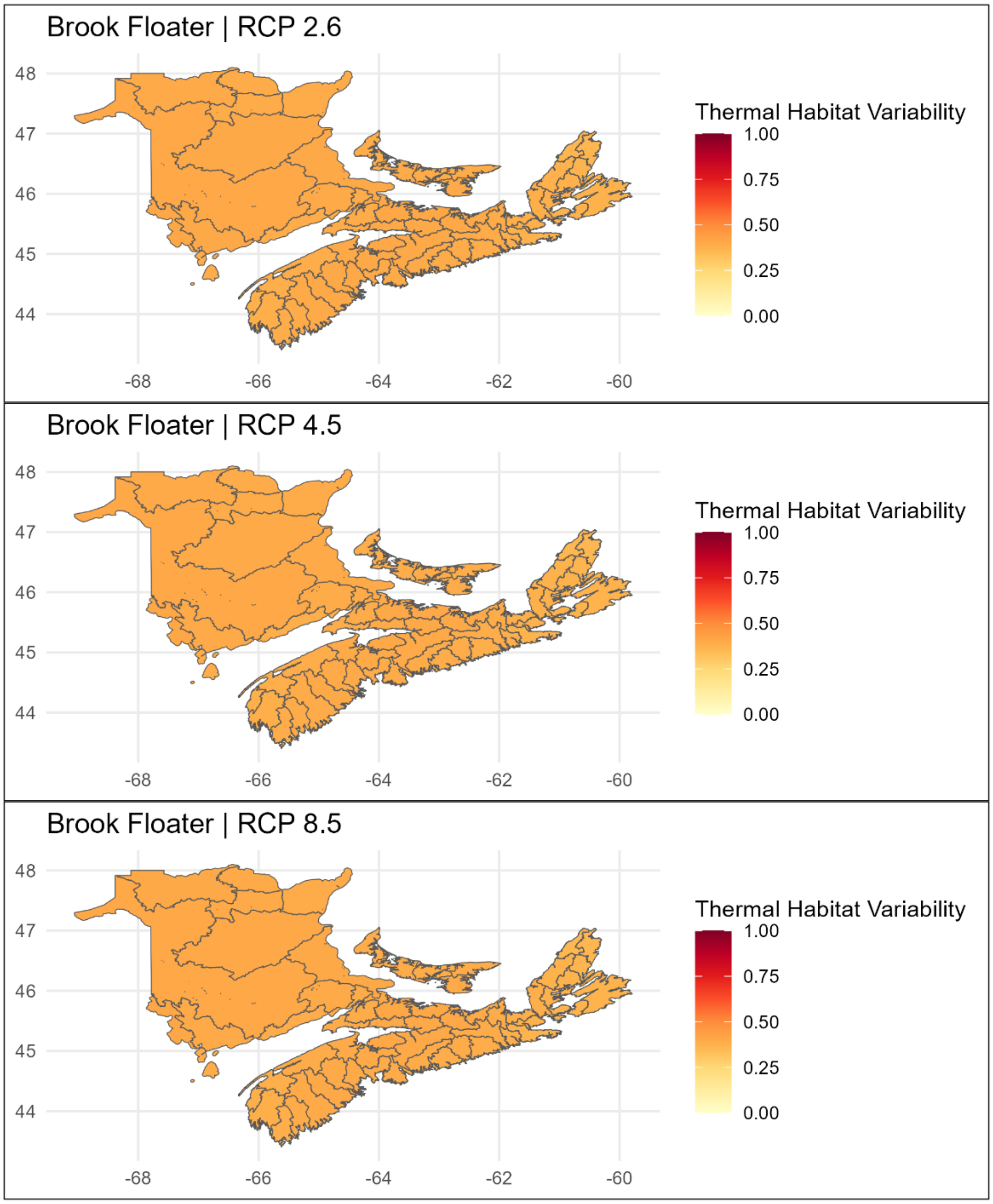
Appendix 109 Map of study area coloured by yellow lampmussel thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



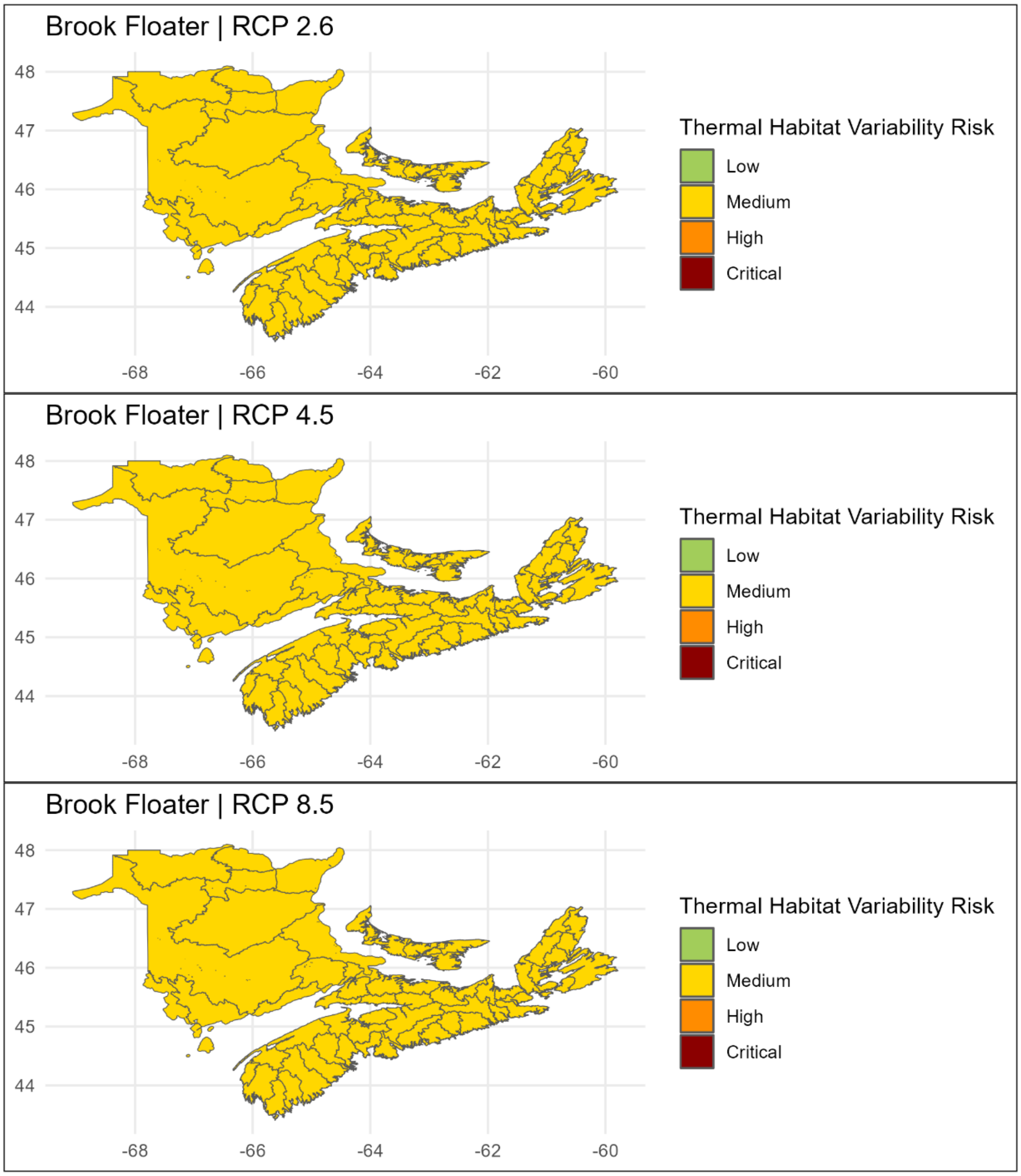
Appendix 110 Map of study area coloured by banded killifish thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



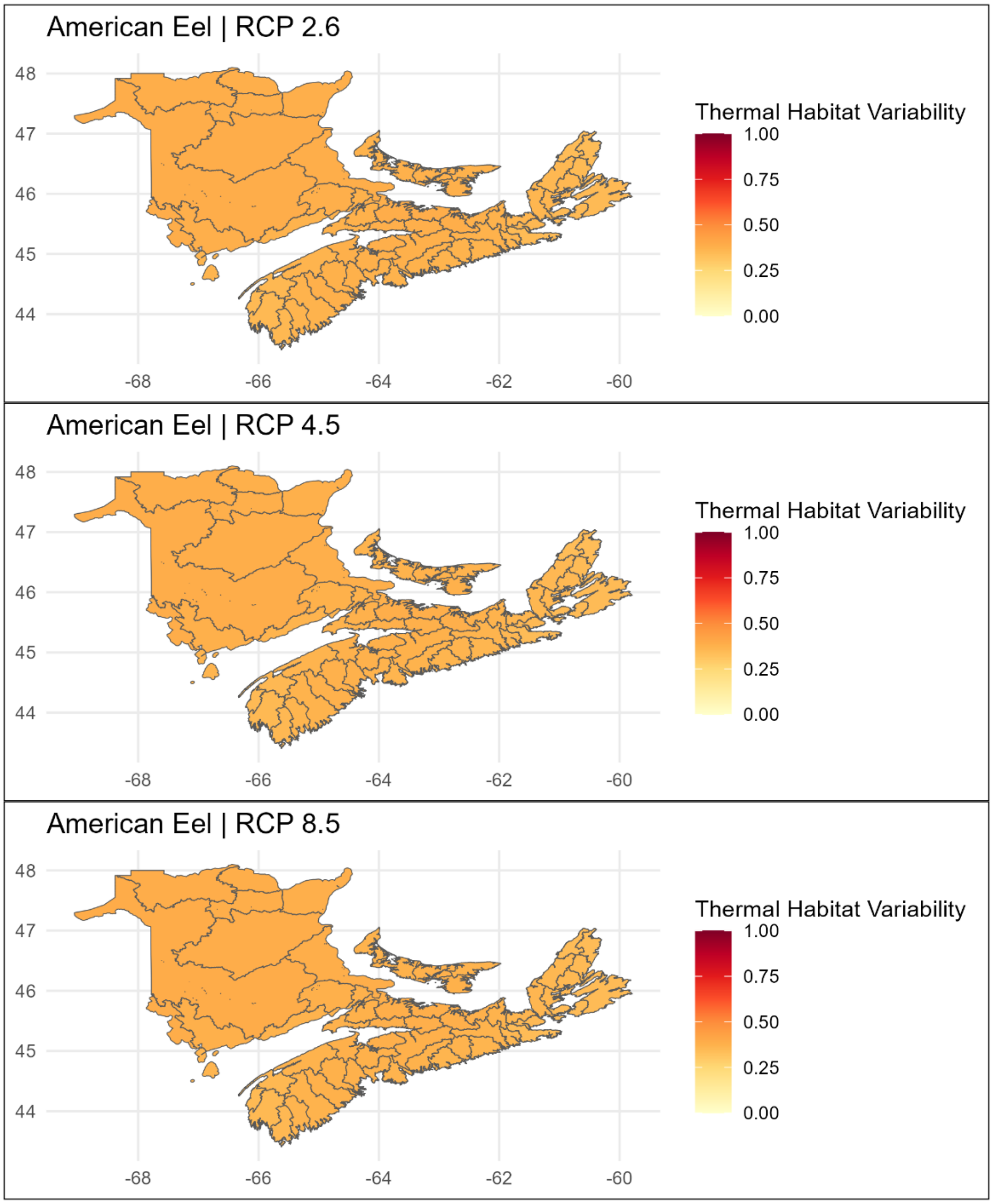
Appendix 111 Map of study area coloured by banded killifish thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



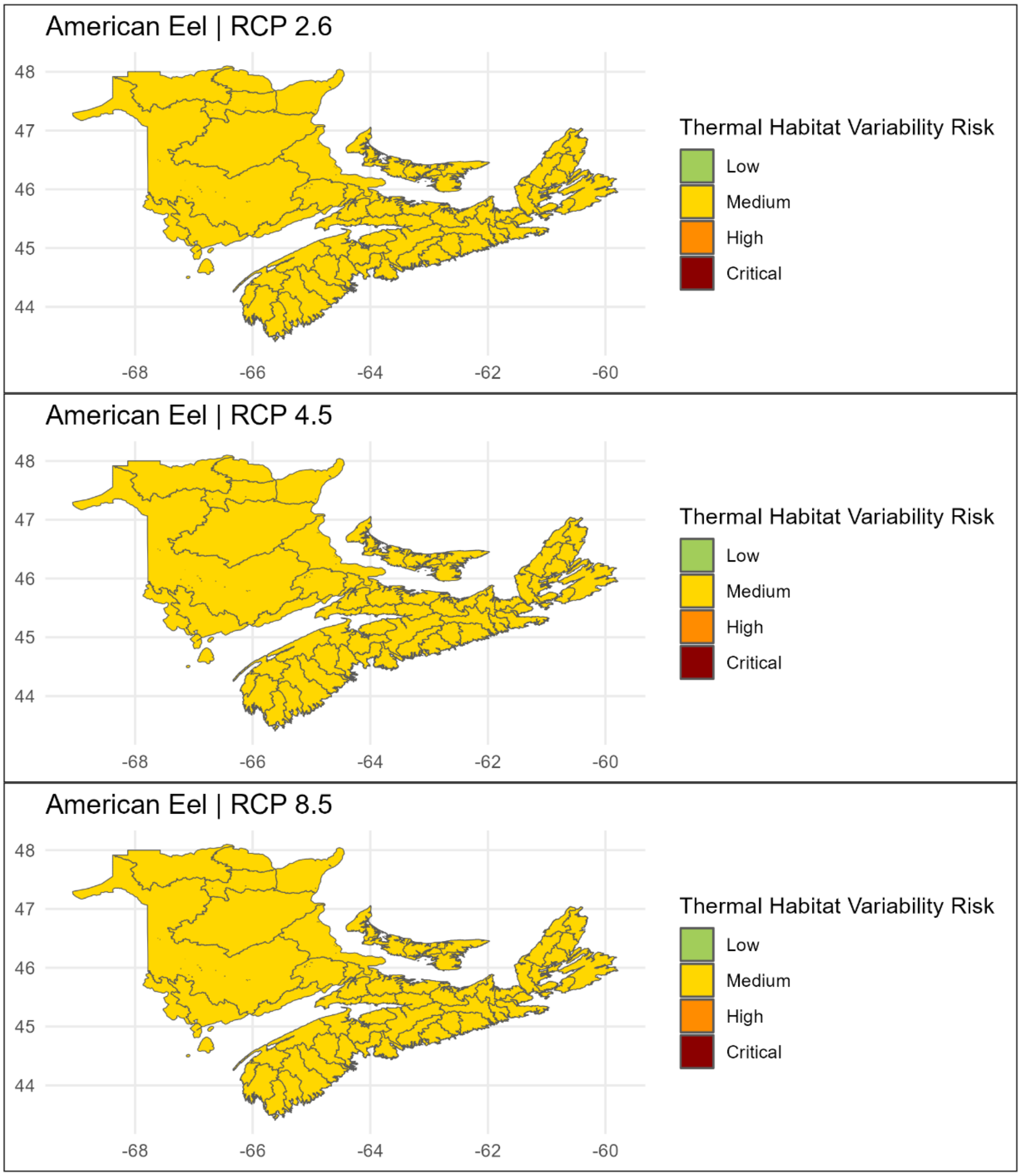
Appendix 112 Map of study area coloured by brook floater thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



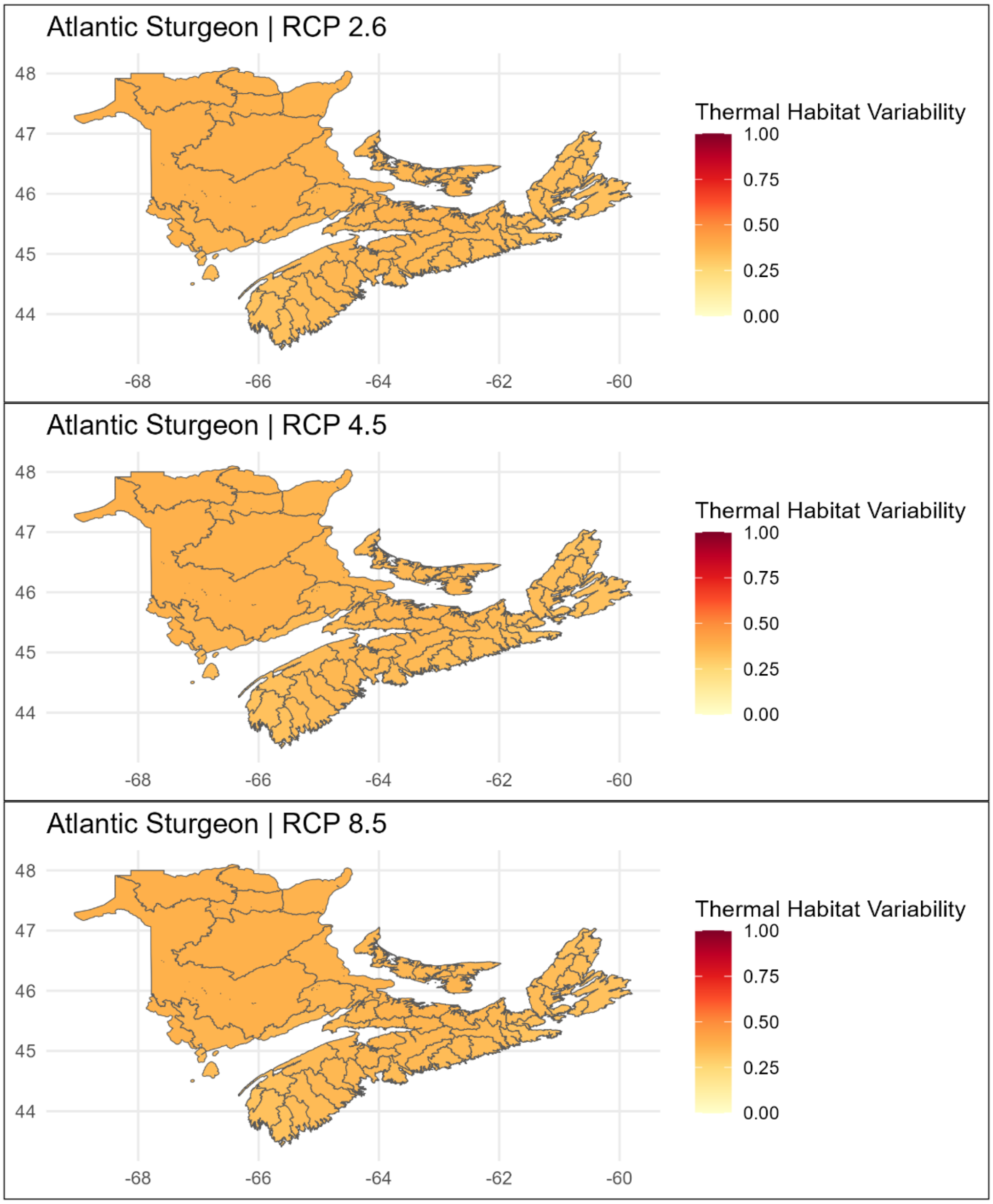
Appendix 113 Map of study area coloured by brook floater thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



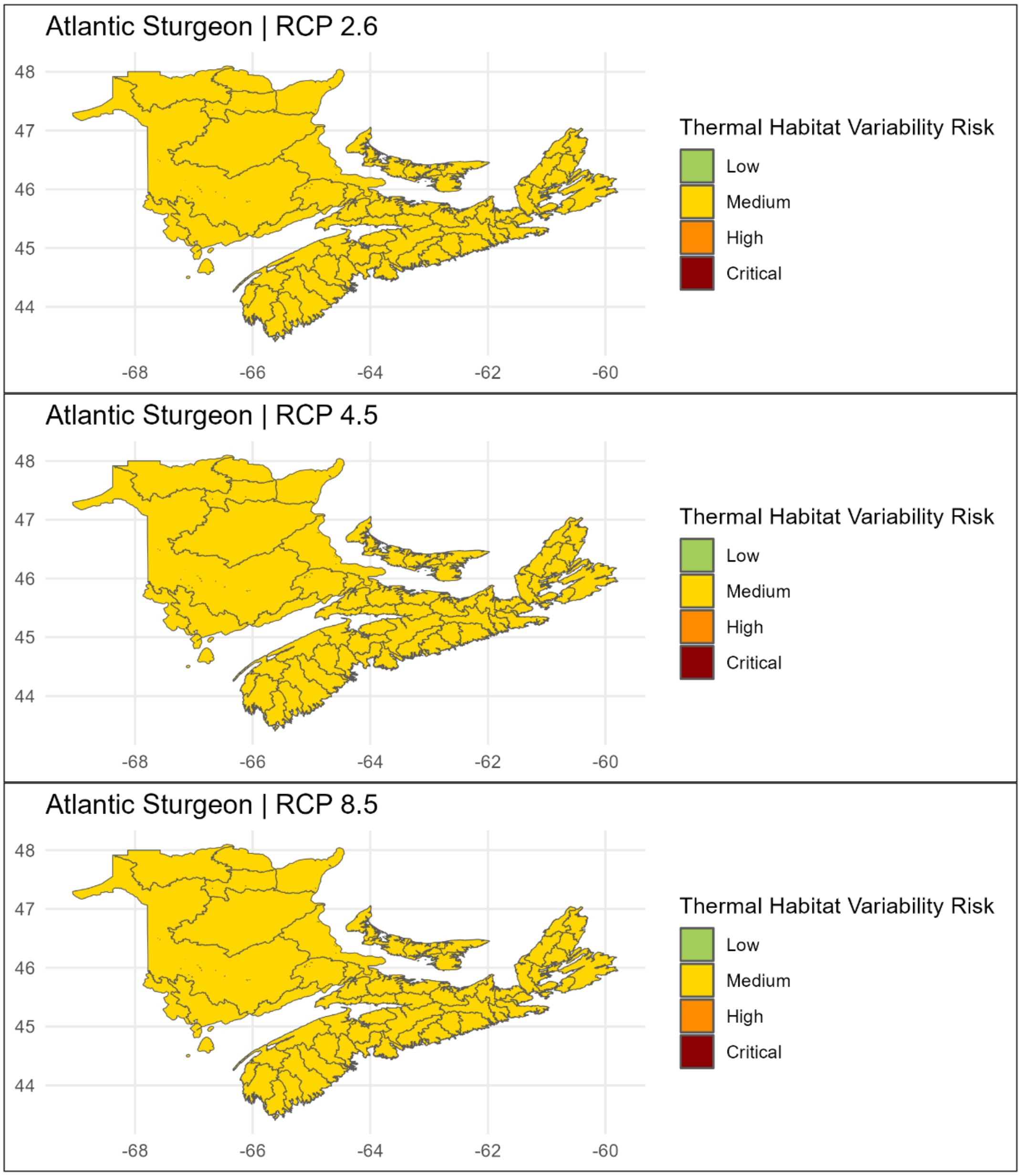
Appendix 114 Map of study area coloured by American eel thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



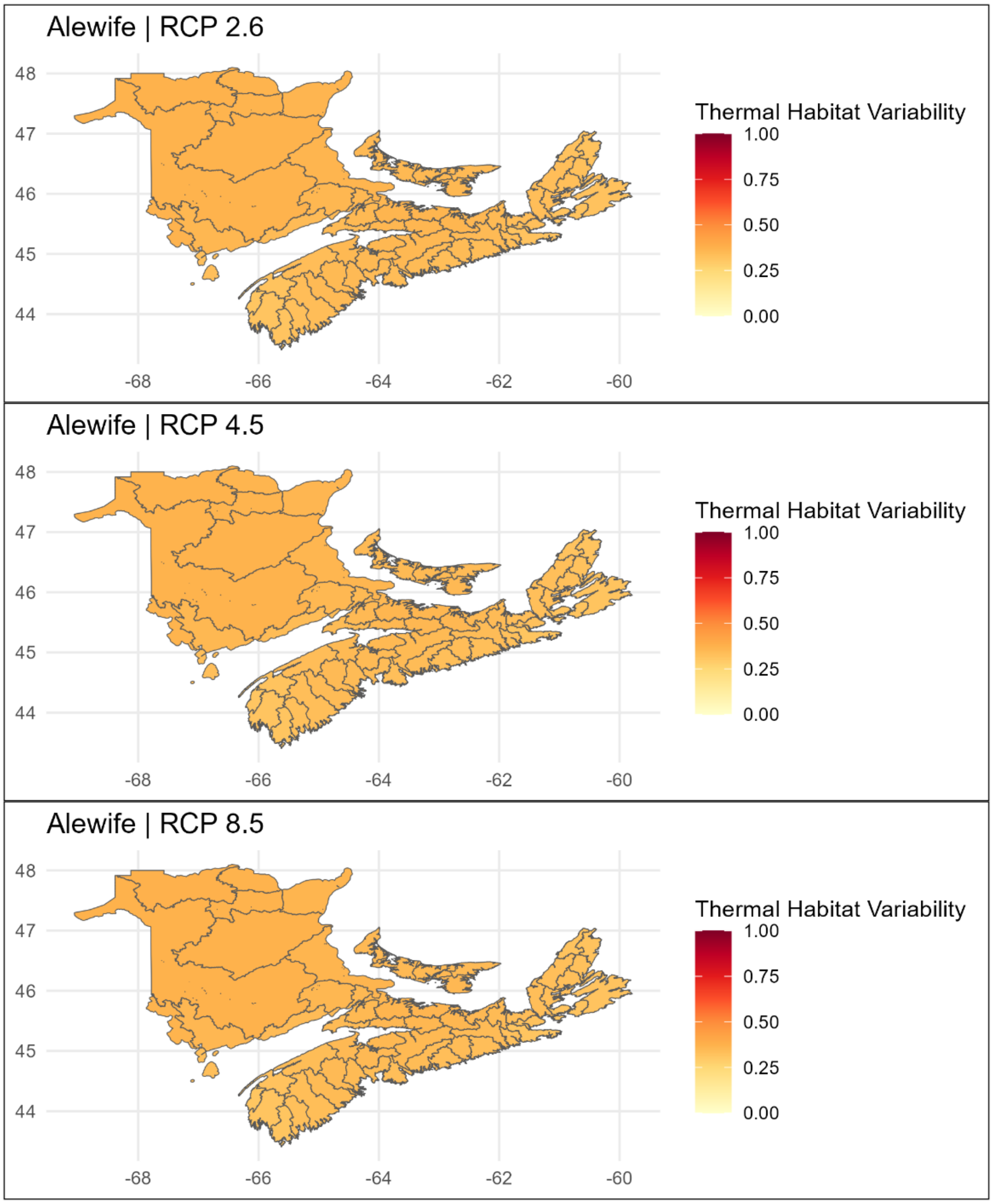
Appendix 115 Map of study area coloured by American eel thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



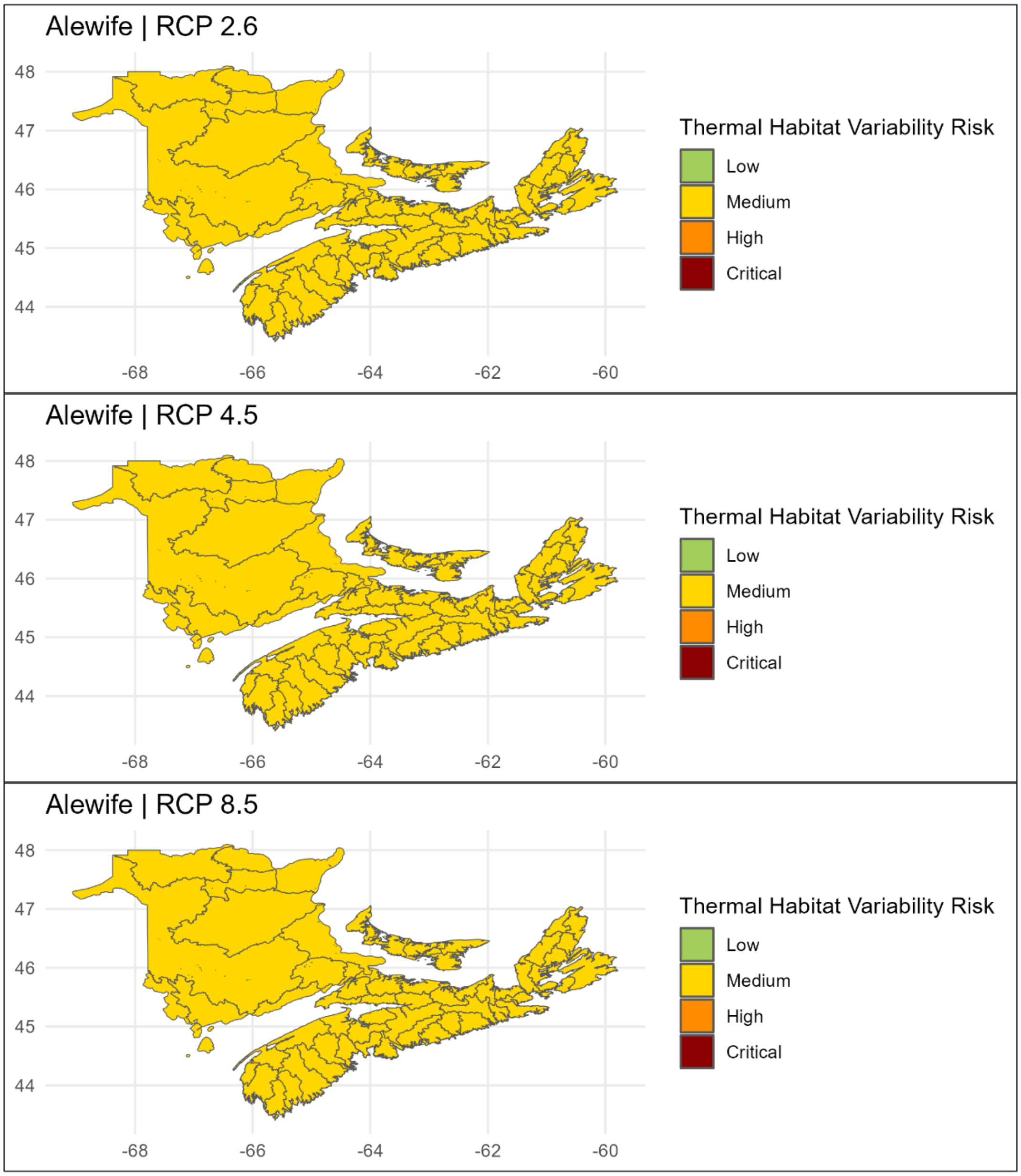
Appendix 116 Map of study area coloured by Atlantic sturgeon thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



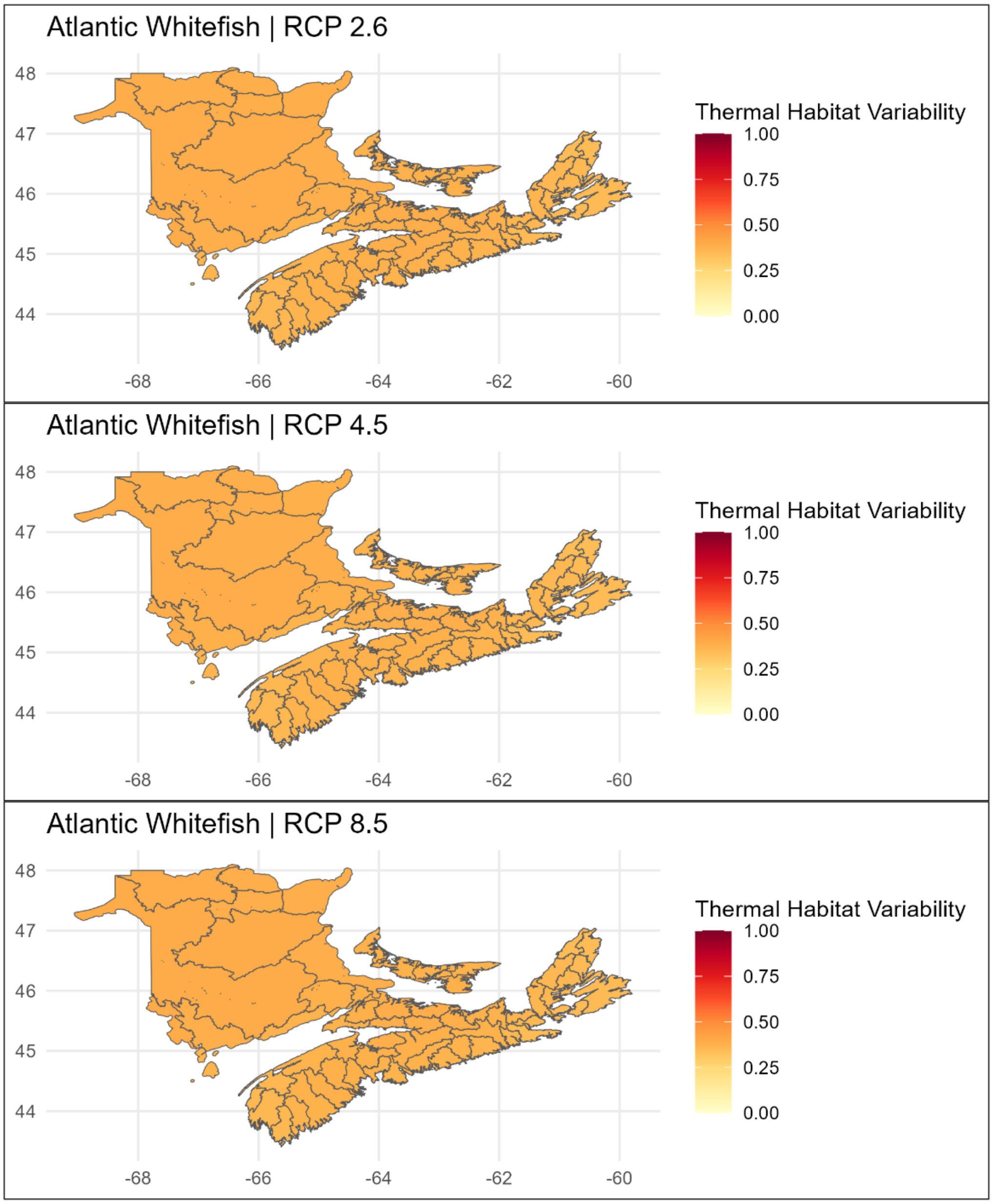
Appendix 117 Map of study area coloured by Atlantic sturgeon thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



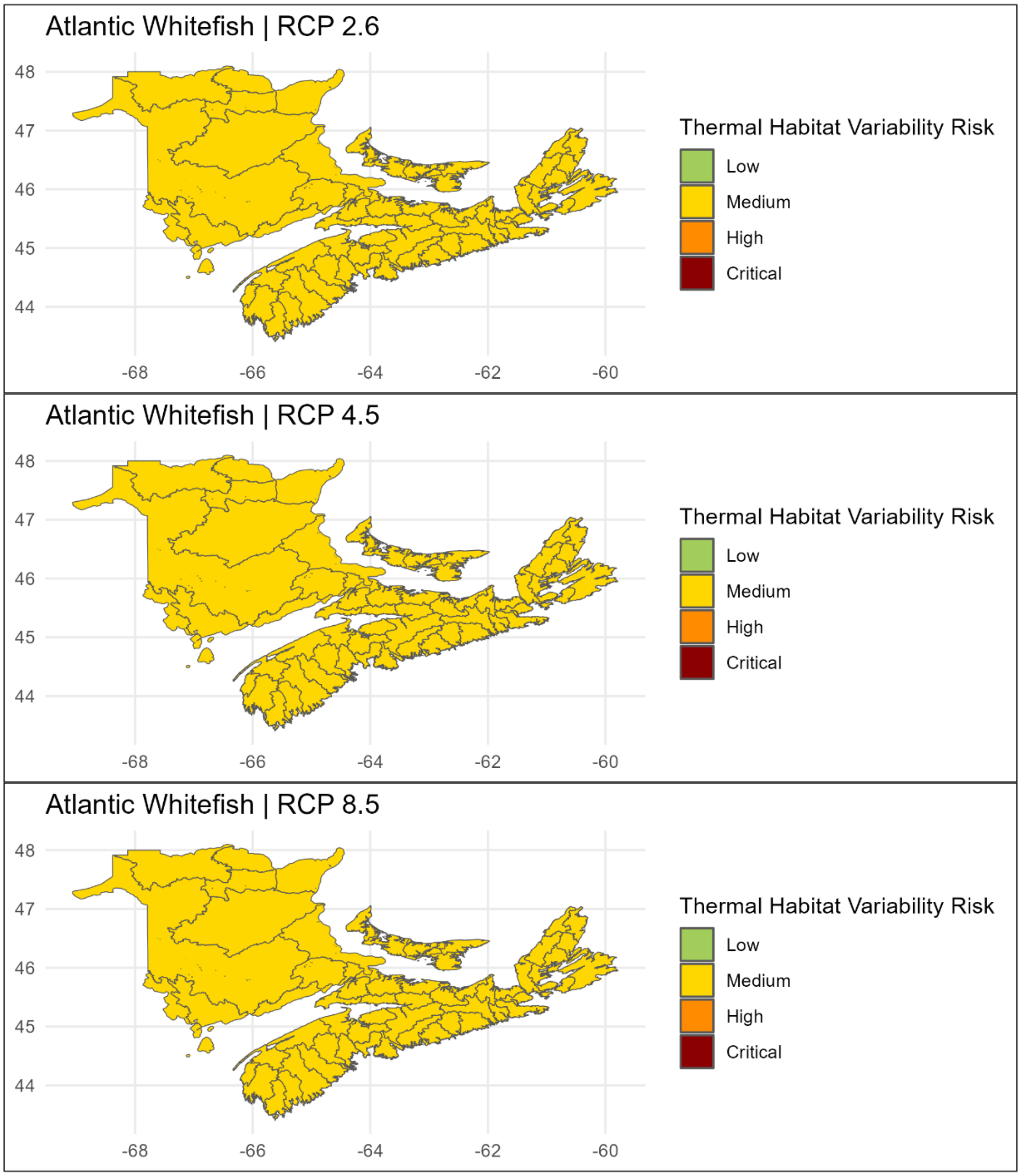
Appendix 118 Map of study area coloured by alewife thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



Appendix 119 Map of study area coloured by alewife thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



Appendix 120 Map of study area coloured by Atlantic whitefish thermal habitat variability index scores from 0-1, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.



Appendix 121 Map of study area coloured by Atlantic whitefish thermal habitat variability risk levels, for each RCP (2.6, 4.5, and 8.5); Nova Scotia, New Brunswick, and Prince Edward Island, delineated at the primary watershed level.