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Report on the

Risk Assessment Framework for Cumulative Effects (RAFCE)

December 2023

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Acknowledgments

The Risk Assessment Framework for Cumulative Effects (RAFCE) is the culmination of work by a multidisciplinary team of researchers. It meets the commitment of Natural Resources Canada (NRCan) to develop national-level science-based decision-making tools for cumulative effects research and management.

This report outlines a risk management framework for regional-scale assessments of the cumulative effects of natural resource development in Canada. It also contributes to regional assessments led by the Impact Assessment Agency of Canada of Environment and Climate Change Canada.

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- the Wildlife Conservation Society Canada
- the University of Ghana and its School of Engineering

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- Matthew Wheatley, Director, Ecosystem Health Science Program, Northern Forestry Centre
- Angela Majic, Senior Policy Advisor, Great Lakes Forestry Centre.

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Please address any questions or comments to Effah Antwi and/or Evisa Abolina.

Table of contents

Acknowledgments **5**

Executive Summary **9**

1. Introduction **10**

1.1. Cumulative effects and natural resource management in Canada 11

1.2. Impact assessment 11

1.3. Regional Assessments as per the Impact Assessment Act 11

2. Scope of the RAFCE **13**

3. Framework development – integrated risk and scenario-based analysis **14**

3.1. Risk analysis using the Bowtie Risk Analysis Tool (BRAT) 15

4. RAFCE application **17**

4.1. Methodological approach 18

4.1.1. Data collection and analysis 18

4.1.2. Defining/choosing potential VECs, sub-VECs and indicators 18

4.1.3. Strategic engagement toward developing the BRAT risk diagrams 22

5. Bowtie risk analysis outcomes **23**

5.1. Valuation, estimation and prioritization of impacts 24

6. Implications for Regional Assessments - lessons learned **25**

6.1. Improved transparency in communication and decision making 25

6.2. Indigenous engagement and knowledge co-creation 26

6.3. Improved science-policy interactions 26

6.4. Enhanced visualization and understanding of risk management process 26

6.5. Quantitative and qualitative risk assessment 26

6.6. Identification of VECs and issues or areas of regional concern 26

6.7. Planning, Mitigation, Monitoring and Follow-up 27

6.8. Public access 27

6.9. Assessing implemented RAs 27

7. Limitations and next steps **28**

Appendix A: Bowtie risk analysis diagrams resulting from expert workshops and consultations **29**

Appendix B: Legislation listed in Bowtie risk analysis diagrams **43**

Appendix C: Criteria for scoring and valuation of impact **44**

Appendix D: Summary of model impact categories, score and ranking **46**

Appendix E: Model calculation **52**

References **53**

Executive Summary

The assessment of cumulative effects (CEs) in the context of a regional assessment (RA), is a complex scientific and management activity. It requires interdisciplinary knowledge, purposefully designed and integrative science-policy interactions as well as effective planning guided by structured decision making. Currently, there are no commonly agreed upon frameworks or methods to guide how to conduct a RA. For instance, identifying and prioritizing potential risks and issues for the effective management of decisions about CEs is challenging and not well known.

This report is the outcome of work predominantly led by scientists from the Canadian Forest Service, Natural Resources Canada. It provides specialist information and expert knowledge needed to effectively address and manage the CEs of natural resource development to guide future RAs. It summarizes the work carried out to develop the Risk Assessment Framework for Cumulative Effects (RAFCE), a risk and impacts-based cumulative effects assessment (CEA) framework. The RAFCE helps with scoping and prioritizing regional risk and CEs issues in the context of a RA. This report also provides information on how the RAFCE was tested using Northern Ontario's Ring of Fire (RoF) region as a case study. It concludes with lessons learned and implications for conducting future regional-scale assessments.

1. Introduction

The Canadian Forest Service (CFS), Natural Resources Canada (NRCan) leads the Government of Canada's efforts to address cumulative effects from natural resource activities on forested landscapes. In 2019, the CFS published Addressing Cumulative Effects of Natural Resources Development in Canada's Forests, a national-scale research agenda (NRA) that presents a coordinated vision to performing research on the cumulative effects (CEs) of natural resource development in Canada's forests.

The NRA

- focuses on developing science-based decision-making tools that help resource managers and decision makers prepare for and respond to different challenges;
- acknowledges the importance of including Indigenous Knowledge and values;
- recognizes the need to proactively develop science-based methods and tools to effectively manage increasingly complex and changing landscapes;
- proposes a set of research priorities, subject to revisions based on new needs, challenges and evidence that could emerge, until 2029.

The NRA also reinforces the need for a CEs risk assessment framework to assist governments with consistent, transparent and fair impact assessments. Such a framework would support national, sustainable resource management.

This report provides a summary of the work carried out to develop a Risk Assessment Framework for Cumulative Effects (RAFCE). The RAFCE combines bowtie risk analysis with scenario analysis to address regional CE issues by supporting:

- the identification of the drivers and impacts of CEs, including potential preventive and mitigative measures, e.g., procedure(s), legislation and practices for CE management;
- the identification and prioritization of major impact categories and components to support effective impact management;
- the quantification and ranking of impacts that are cross-cutting, multi-sector driven, synergistic and relevant to a regional context;
- scenario planning to guide present and future RAs

This report also describes the outcomes of the application of the RAFCE (Antwi et al., 2023) to a case study in the Ring of Fire (RoF) region. It demonstrates how regional CE issues can be addressed in response to disturbance resulting from the development of natural resources.

The framework:

- contributes a clearer understanding of the complexity of CEs problems;
- enables the outcomes of the RA to drive CEs management decisions;
- supports further scenario analysis through modelling.

Future application of the RAFCE can facilitate decision making by:

- presenting a clear visual and quantitative synthesis of risks;
- effectively translating our knowledge of risk to stakeholders;
- facilitating effective science-policy interactions;
- providing guidance for successful engagement and knowledge co-creation with the public, stakeholders and rights-holders involved in environmental decision-making.

1.1. Cumulative effects and natural resource management in Canada

Cumulative effects (CEs) are defined as "the changes to economic, environmental, social and cultural values caused by the combined effects of past, present and potential future actions or events, both natural and anthropogenic" (NRCan, 2019, p. 8). CEs can emanate from a broad range of activities, which may consist of direct, indirect, significant or insignificant impacts occurring over small or large geographic areas at a certain point in time or over several years or decades (Sonntag et al, 1987). CEs present a continuous challenge for the natural resources sector due to their complex nature (NRCan, 2019). For instance, the activities associated with forestry, energy and mining can impose CEs on ecosystems and communities that are difficult to predict, manage and recover from, especially under a changing climate (NRCan, 2019).

Improved knowledge and understanding of the risks and impacts of CEs from multiple stressors on forest ecosystems is a research priority identified in the NRA. This priority aims to improve spatial and temporal baseline data, as well as identify indicators and thresholds to better recognize the risks.

1.2. Impact assessment

Impact assessment (IA) is a planning and decision-making approach for proposed resource development projects. It measures the positive and negative environmental, economic, health and social effects including impacts on the livelihoods and rights of Indigenous Peoples. Until 2017, the Federal Environmental Assessment and Review Process, 1974, and the *Canadian Environmental Assessment Act*, 1992 and 2012, were the drivers of federal environmental assessment across Canada. These documents provided the legislative basis for the environmental assessment of projects within federal jurisdiction with potential adverse environmental effects. However, they were severally criticized for significant drawbacks including a lack of transparency, a limited understanding of what qualified as significant projects or public interest project and jurisdictional overlaps (Rees, 1980; Gibson, 1983; Wallace, 1986).

In 2019, *the Impact Assessment Act* (IAA) marked a significant shift in how major projects carried out on federal lands are assessed. The IAA revised the process by:

- providing greater transparency on critical environmental decisions
- providing prompt and early consideration of issues that might cause litigation
- clearly defining the criteria by which public interest determinations are made.

The IAA changed from a sole focus on bio-physical valued ecosystem components (VECs) to a more socially, economically and environmentally inclusive impact assessment (IA) process. The IAA also broadened the scope of consultations with stakeholders to include Indigenous representatives. The IAA process mandates the consideration of Indigenous Knowledge and values, as well as the effects projects may pose on Indigenous rights and culture. In summary, the IAA provides simplicity, efficiency and predictability in the assessment process while ensuring substantive protection of the environment (Kruger, 2009).

1.3. Regional Assessments as per the *Impact Assessment Act*

Another significant process introduced in the IAA was regional assessments (RAs). According to Environment and Climate Change Canada's (ECCC) Impact Assessment Agency of Canada (IAAC), RAs "go beyond project-focused impact assessments to understand the regional context and provide more comprehensive analyses to help inform future impact assessment decisions" (IAAC, 2022). RAs are "conducted in areas of existing or anticipated resource development projects to inform planning and management of cumulative effects and project impact assessments" (IAAC, 2022). They can be used to inform and identify:

- a baseline against which to assess the incremental impact of a discrete project;
- thresholds to support future project decisions;
- standard mitigation measures for future projects;
- potential impacts on rights and interests of Indigenous peoples;
- guidance for land- or marine-use planning and other initiatives for managing cumulative effects that may be undertaken by various jurisdictions" (IAAC, 2022).

Achieving any or all of a RA's objectives requires a purposefully designed and integrative science-policy framework to provide the information, knowledge and data needed for informing current and future IAs. Such a framework must also build and establish new partnerships with provincial, territorial and Indigenous jurisdictions, which can provide an understanding of regional interests and concerns. Particularly, the engagement of Indigenous Peoples as rights holders is critical to ensure meaningful participation. As is the inclusion of Indigenous Knowledge to inform the direction of a RA.

Federal departments, including NRCan, are obligated to provide on request specialist or expert information or knowledge for RA(s) (GoC, 2019). Federal science departments can be asked to provide advice, data, knowledge and the tools needed to effectively address and manage the CE of natural resource development. While RAs are methodologically complex, few frameworks exist to guide how a RA is conducted. How to identify and prioritize potential risks and issues for effective management of CE decisions at a regional scale is challenging and not readily known.

2. Scope of the RAFCE

The Risk Assessment Framework for Cumulative Effects (RAFCE) addresses CE issues in the context of a RA by supporting:

- the identification of the drivers and impacts of CEs, including potential preventive and mitigative measures, e.g., procedure(s), legislation and practices for effective CEs management;
- the identification of major impact categories and components to support effective impact management;
- the quantification and ranking of impacts that are cross-cutting, multi-sector driven, synergistic and relevant to a regional context;
- scenario planning to guide future RAs.

The RAFCE was developed and tested using Northern Ontario's Ring of Fire (RoF) region as a case study.

3. Framework development – integrated risk and scenario-based analysis

Cumulative effects assessment in the context of a RA is a complex scientific and management activity that requires effective planning guided by structured decision making (SDM). SDM is the organized analysis of problems to address defined objectives (Martin et al., 2009) through the integration of science, efficient decision-making and transparent communication of options. SDM regards decision making as consisting of a core set of elements, e.g., management objectives, decision options and predictions of decision outcomes, that should be analyzed separately through a comprehensive decision-making framework. Since RAs require science, management and policy integration, SDM is particularly suitable for guiding the process.

SDM involves a series of steps that proceed from defining the problem to decision-making. These steps are typically repetitious instead of linear. The SDM process can facilitate RAs through three simple stages:

- inclusive definition of the management problem, objectives and alternatives
- comprehensive assessment of impacts and trade-offs
- adaptive implementation of management action (Robin et al., 2012).

Guided by the SDM process, the RAFCE combines traditional bowtie risk analysis with scenario analysis (see Figure 1). Both tools provide an effective approach to achieve the requirements of SDM. The RAFCE enables the outcomes of a bowtie risk analysis to drive cumulative effect management decisions, as well as advance scenario analysis through modelling.

Although not discussed in this report, the scenario component builds upon the results from the bowtie risk analysis. Thus, it considers the use of the drivers of CE, the impact of top event (policy objectives at risk) and the effectiveness of management strategies that can; (i) reduce the negative impacts, (ii) model the negative impacts to understand trade-offs, and (iii) guide the prioritization of impacts and the adaptive implementation of management action.

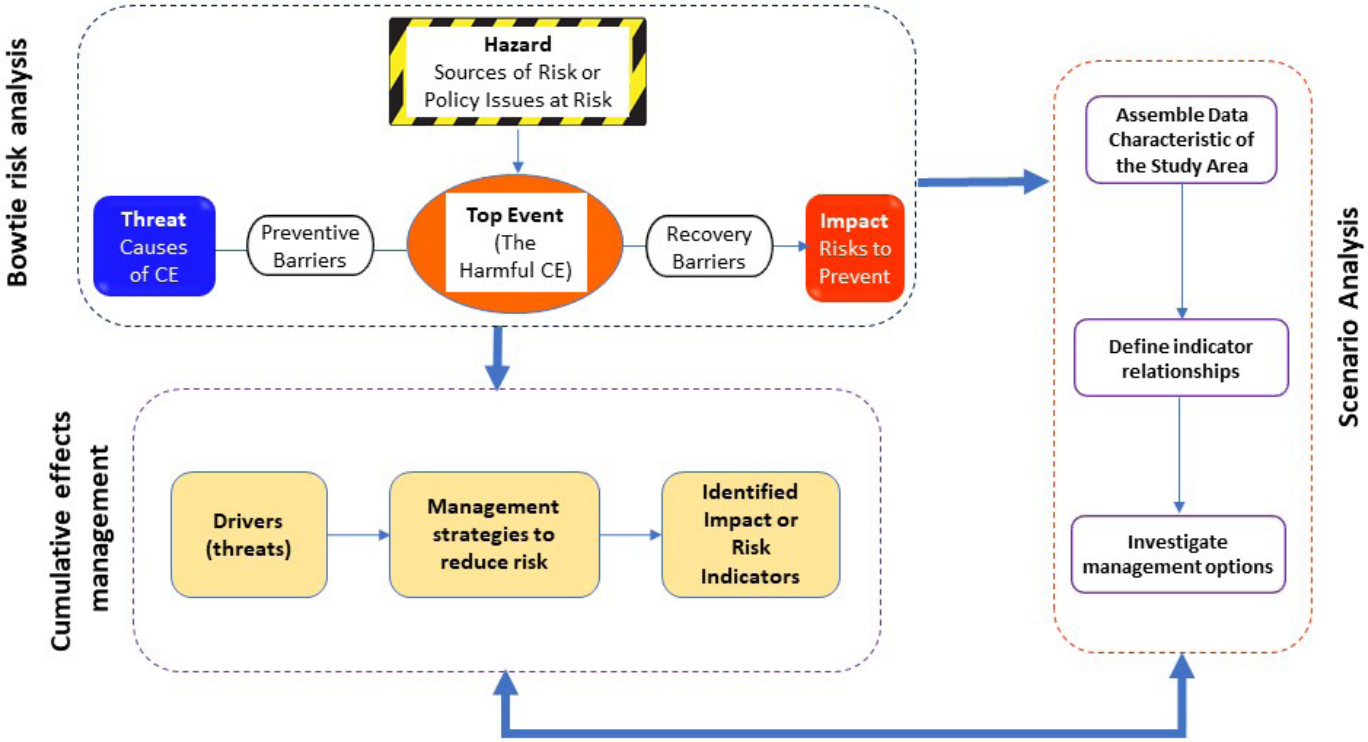


Figure 1. Integrated Risk and Scenario Based Framework for Regional-Scale Cumulative Effects Assessment. Adapted and modified from Antwi et al., 2023.

3.1. Risk analysis using the Bowtie Risk Analysis Tool (BRAT)

The Bowtie Risk Analysis Tool (BRAT) is a risk assessment technique as per the International Organization for Standardization (ISO) 31000 risk management standard (ISO, 2018), which is well-suited for environmental assessment (EA) (Cormier et al., 2019). BRAT maps out how threats (i.e., drivers or causes of CEs) can trigger a risk event, (i.e., an ecological tipping point), that violates management objectives and thereby leads to negative impacts. Additionally, the BRAT helps identify management strategies that can act as barriers to risk. This is done through preventing CE drivers from triggering the risk event or mitigating the negative impacts after a risk event. Collectively, BRAT diagram components enable a detailed understanding of policy objectives to be obtained, quantify the effectiveness of risk barriers and analyze deficiencies in management systems. The BRAT achieves this by providing a concise representation of key components of the risks by identifying drivers [threats], indicators [impacts] and management scenarios [barriers].

Figure 2 shows the components of a BRAT diagram, which include:

- the policy objective at risk [the hazard];
- the risk event that violates the management objective;
- the threat that causes of the risk event [the source of the cumulative effects];
- the impacts of the risk event;
- the preventative barriers that impede the drivers of the cumulative effects from triggering the risk event;
- the mitigative barriers that reduce the negative impacts of the risk event.

The BRAT also identifies management strategies that act as barriers preventing the causes of CEs from triggering the risk or mitigating the negative impacts after a risk event. The BRAT works very well when risk management decisions require engagement of diverse interests, knowledge and rights holders. It facilitates decision-making through clear visuals and quantitative synthesis that helps to translate knowledge of risk to stakeholders (Winder et al., 2020). In summary, the BRAT helps balance complexity and the need to understand at the landscape level with the interactive effects of multiple stressors/disturbances (Winder et al., 2020). It contributes to a clearer understanding of complex CE problems at the regional scale.

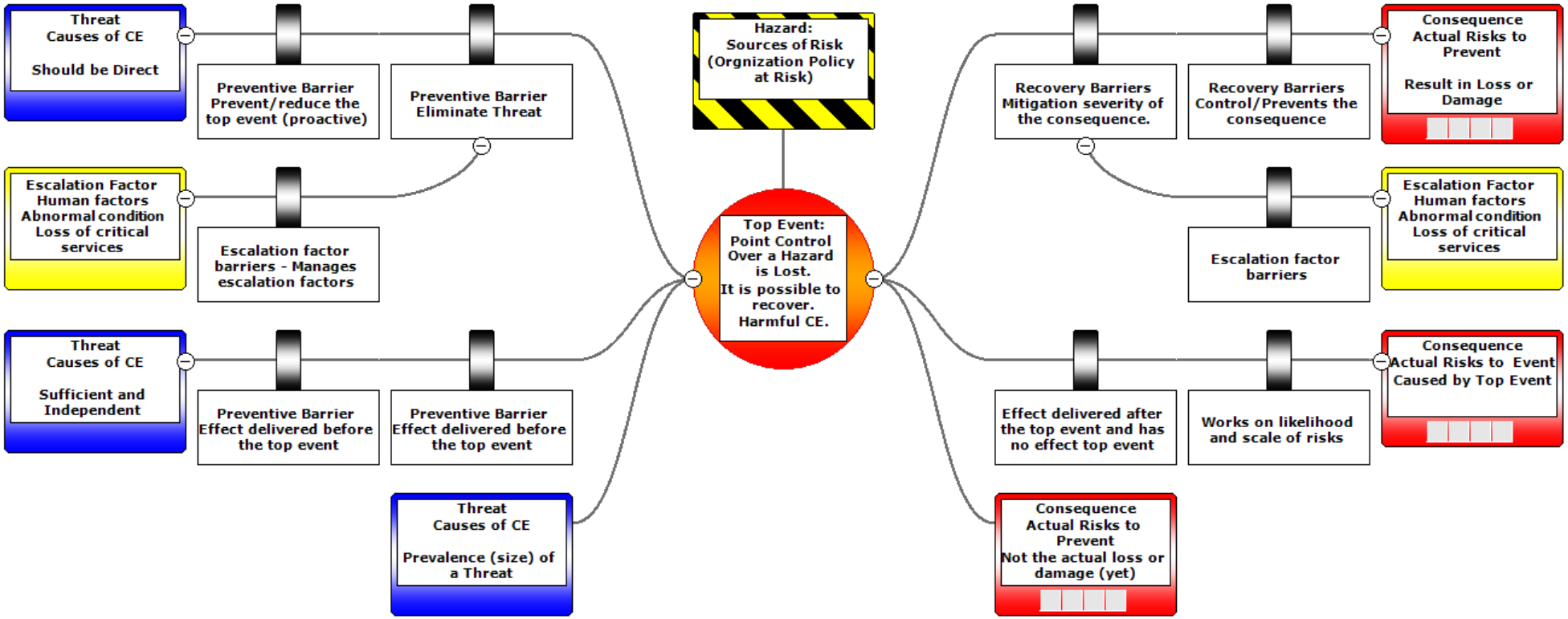


Figure 2. Components of a bowtie diagram. Source: Antwi et al., 2023.

4. RAFCE application

To apply and demonstrate the effectiveness of the RAFCE, Ontario's Ring of Fire (RoF) region was selected as a case study. The RoF is a vast mineral-rich area 500 kilometers northeast of Thunder Bay. The proposed mining for critical minerals and associated development are considered as a major concern to the region's ecological and social systems. This region was selected, based on the following considerations.

1. Policy

On February 11, 2020, the Honourable Jonathan Wilkinson, former Minister of Environment and Climate Change Canada, approved the request for a RA in Ontario's RoF. The CFS considered the proposed location a helpful focal point for developing CEs research and contributing scientific data, knowledge and expertise. CFS researchers were encouraged to propose projects that could contribute to the RA for this area.

2. Resource development

The RoF region possesses tremendous mineral wealth due to deposits of copper, zinc, nickel, gold, chromite, platinum, palladium and titanium. It will likely experience a broad-spectrum of CEs drivers and impacts from proposed natural resource developments. A thorough regional assessment will be required (Chetkiewicz and Lintner, 2014). Expected development includes multiple open-pit and underground mines with associated onsite infrastructure. Also anticipated is the development of infrastructure connections including rail, all-season roads, hydro transmission lines and broadband networks to remote First Nation communities.

3. Ecological importance

The RoF is located in the ecologically sensitive James Bay Lowlands, which is a subset of the Hudson Bay Lowlands. The Hudson Bay Lowlands is part of the world's second-largest, contiguous peatland complex (Packalen et al, 2014), and is one of the world's largest storehouses of carbon. It supports a wide variety of flora and fauna including at least 816 native and 98 non-native plant species; approximately 300 bird species that are predominantly migratory; more than 50 species of terrestrial and marine mammals; and at least 35 species of fish (Abraham and Keddy, 2005).

Notably, the region includes several species at risk including polar bear (*Ursus maritimus*), woodland caribou (*Rangifer tarandus caribou*), wolverine (*Gulo gulo*), lake sturgeon (*Acipenser fulvescens*), and numerous bird species including Canada Warbler (*Cardellina canadensis*) and Common Nighthawk (*Chordeiles minor*).

One of the key priorities for CEs management in forested landscapes is addressing species at risk, particularly Caribou. The RoF region overlaps with multiple caribou ranges. The region's large extent also makes it possible to consider the implications of climate change on wildlife habitats.

4. Indigenous considerations

The RoF region is part of Treaty No. 9, commonly known as the James Bay Treaty. Local First Nation communities include Webequie, Nibinamik, Neskantaga, Marten Falls and Eabametoong. There are several other First Nations communities, some of which are geographically distant, that consider the land encompassed by the RoF as Traditional Territory. Multiple Indigenous communities have expressed concern over the proposed developments. While some communities are leading the development of roads, others are opposed.

The involvement of all First Nation communities in the RA is of utmost importance. This helps to address emerging concerns that can affect development in the region, safeguard Traditional lifestyles and achieve reconciliation efforts. Meaningful inclusion of Indigenous Knowledge and values is key to successfully addressing cultural and ecological CE that may occur due to resource development and ecosystem alterations.

4.1. Methodological approach

4.1.1. Data collection and analysis

Guided by the need to identify and prioritize regional impacts, several approaches (see Figure 3) were used to gather information and data for the application of the RAFCE in a stepwise direction. These approaches included:

- a literature review;
- interdepartmental BRAT workshops with subject matter experts;
- interviews with subject matter experts;
- quantitative prioritization of impact through modelling.

4.1.2. Defining/choosing potential VECs, sub-VECs and indicators

The first step in the application of the RAFCE was a literature review to broadly identify the impacts of mining on ecosystems and people in the RoF region. This review enabled the identification of valued ecosystem components (VECs) of importance in the context of mining disturbance. VECs are environmental attributes associated with a proposed project development that have been identified to be of concern by directly affected stakeholders/rights holders, governments or the professional community. VECs may be both biophysical [ecosystem] and socioeconomic attributes. Biophysical VECs were mainly focused on for this report.

To identify VECs of importance, the literature review concentrated on the impacts of mining in Indigenous, rural and remote communities of Canada. Recognizing the differences between the RoF and other regions in Canada, information from studies where mining was either ongoing or ceased were used as proxy indicators. Using the effects of mining from other similar contexts was helpful to understand what could happen in the RoF region. A qualitative content analysis using NVivo 12 Pro was undertaken to analyze data from the review. Coding and theme identification were performed for each of the identified sources, focusing on identifying specific VECs. A deductive coding approach, based on the CEA questionnaire developed by Canter and Kamath (1995) was used.

To achieve systematic analysis, data were sorted according to key regional issues of concern and specific VECs. These criteria ensured that the coding exercise supported the scoping of regional issues of interest to different stakeholders. VECs and sub-VECs were categorized (see Table 1) according to six major components:

- organism
- biodiversity
- land
- climate change
- fish/wildlife habitat
- water

To facilitate quantitative or qualitative measurement of potential project effects and CEs, measurable parameters, defined here as sub-VECS, were selected for each VEC where possible and appropriate. Measurable parameters provide a means to determine the level or amount of change in a VEC.

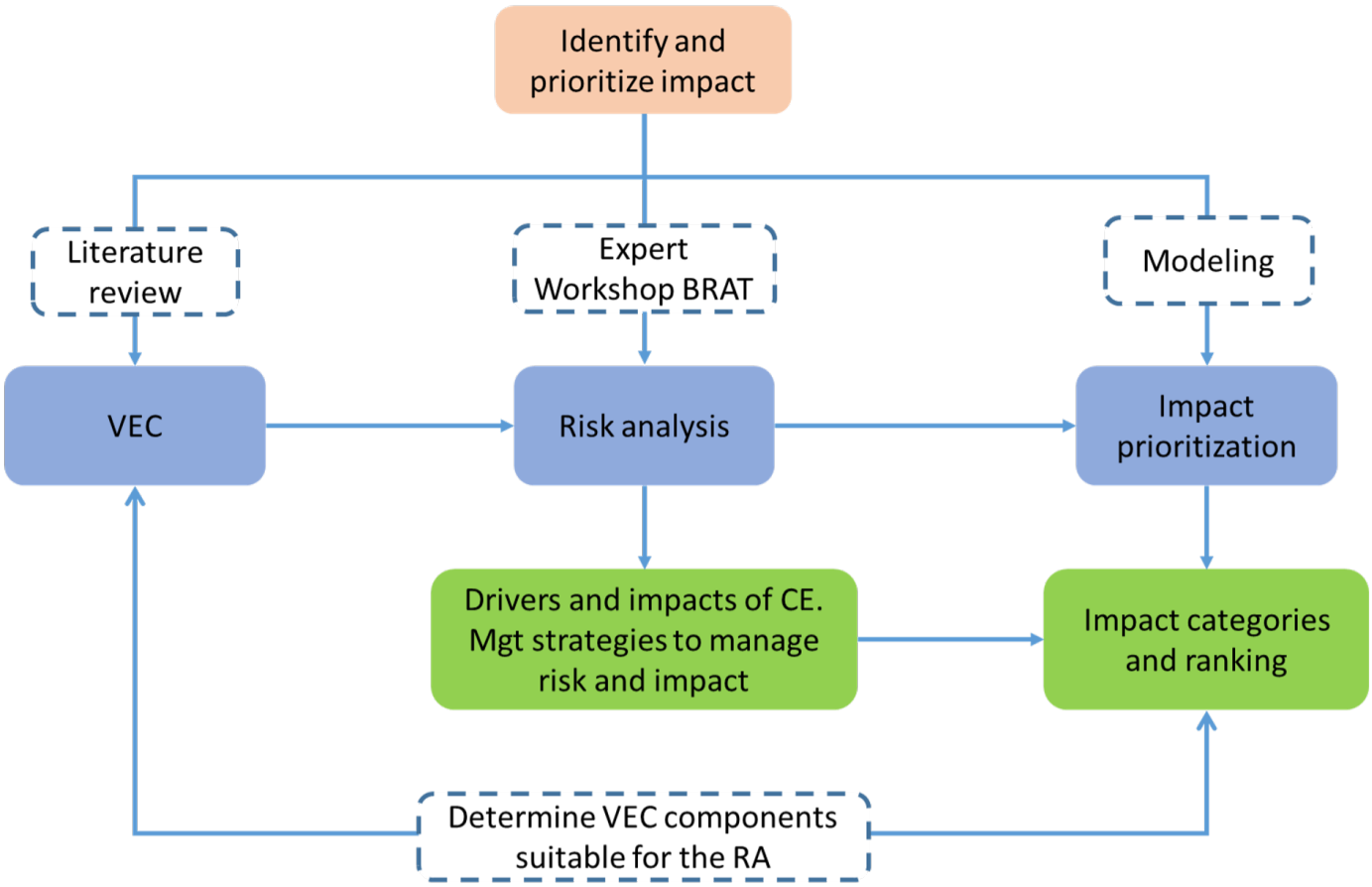
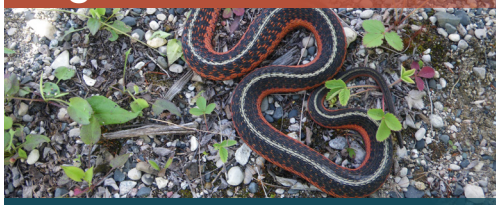
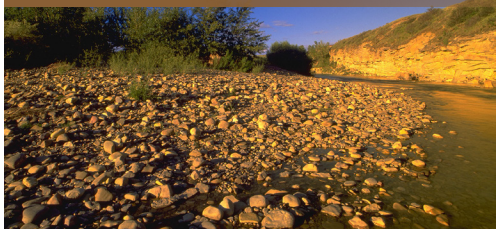


Figure 3. Steps involved in the application of the RAFCE to the RoF case study. Adapted from Antwi et al., 2023.

Table 1. Summary of VECs and sub-VECs

Valued ecosystem component	Valued ecosystem component Sub-component
Organism  Photo credit: Philip Wiebe (CFS)	Vegetation (composition & connectivity) Mammals/Wildlife Migratory birds Fish (health) Herpetofauna
Biodiversity 	Species biodiversity (species richness/diversity, species at risks) Landscape biodiversity Community biodiversity Aquatic biodiversity
Land 	Wetland (morphology & hydrology) Soil (quality & stability) Topography/Terrain Land use/Landcover Geology/Geohazard Sediment quality
Climate change 	Atmospheric/Meteorological conditions GHG emissions Carbon sink and storage Air quality (dust and other forms of emissions)
Fish/Wildlife Habitat Photo credit: Philip Wiebe (CFS)	Wildlife habitat Caribou habitat Migratory bird habitat Fish habitat Habitat connectivity
Water Photo credit: Evisa Abolina (CFS)	Surface water quality (flow, quantity, quality, & discharge) Groundwater (flow, quantity, quality, & discharge) Potable water

Adapted from Antwi et al., 2022.

Following the identification of the VECs and sub-VECs, a risk mapping exercise using the BRAT occurred. For this, specific sub-VECs were chosen and further explored through a bowtie risk analysis (see Table 2). The selection of specific sub-VECs was determined through consultation with experts. Selection was also guided by policy objectives at risk [top events] in the context of the proposed mining in the RoF region along with the expertise of workshop participants.

Table 2. VECs, sub-VECs and relationship to specific policy objectives

Valued ecosystem component	Valued ecosystem component Sub-component	Policy objective / Top event
Organism	Vegetation (composition & connectivity)	Increase in fire severity and frequency
	Mammals/Wildlife	Unsustainable wildlife population Alteration of baseline noise-causing disturbance to wildlife
	Migratory birds	Failure to protect migratory birds and their habitat
Biodiversity	Species biodiversity (species richness/diversity, species at risks)	Successful colonization of non-native species Failure to protect species at risk
Land	Soil (quality & stability)	Soil contamination
	Topography/Terrain	
Climate change	Air quality (dust and other forms of emissions)	Decline in air quality
Fish/Wildlife Habitat	Caribou habitat	Maintaining critical caribou habitat
	Migratory bird habitat	Failure to protect migratory birds and their habitat
	Habitat connectivity	Disruption of habitat connectivity below critical thresholds
Water	Surface water quality (flow, quantity, quality, & discharge)	Declining surface water quality
	Groundwater (flow, quantity, quality, & discharge)	Disrupted flow regimes
	Potable water	Lowering of drinking water quality

Adapted and modified from Antwi et al., 2022.

4.1.3. Strategic engagement toward developing the BRAT risk diagrams

Under the BRAT, outcomes of policy objectives are determined by assessing the most significant cumulative effects arrived at through expert consensus rather than adapting threat [driver] data to account for every possible interaction (Winder et al., 2020). The development of the BRAT diagrams (see Appendix A) involved continuous engagement with experts to solicit information through workshops and individual consultations. Fourteen top events or policy objectives in the BRAT workshops were focused on. See Appendix B for a listing of federal and provincial legislation listed in the diagrams.

The first workshop happened in November 2020, and involved researchers from different teams within the CFS. Guided by the outcomes of the literature review, this workshop helped to identify the top events and discuss key regional risks, sources, impacts and mitigation measures (see Table 2). Additional follow-up consultations and/or interviews with subject matter experts developed and refined the Bowtie diagrams for the selected VECs.

The second workshop occurred on July 14, 2022, at which the BRAT diagrams were reviewed and finalized. The workshops and the expert consultations helped to complete the BRAT diagrams for each of the 14 top events. These diagrams involved descriptions of each category of impact along with the source of the impact, plus the prevention and mitigation measures identified to avert or reduce the magnitude of the impacts.

5. Bowtie risk analysis outcomes

Having completed the BRAT diagrams/analysis for the 14 top events [policy objectives] relevant in the RoF region, an analysis focused on the impacts occurred. In total, 66 unique impacts (see Appendix D) were identified from the 14 top events [policy objectives at risk]. Impacts were further categorized under five broad impact themes as shown in Table 3.

Table 3. impacts were identified from the 14 top events and their groupings under the Bowtie risk analysis outcomes

Impact theme	Description
Hydrological related disturbances	• flow regimes • surface water declines • lowering of drinking water quality
Fish and wildlife related disturbances	• migratory bird habitat loss • unsustainable fish population • unsustainable wildlife population • alteration of baseline noise-causing disturbance to wildlife
Habitat and biodiversity related forms of destruction	• disruption of habitat connectivity below critical thresholds • successful colonization of non-native species • negative population growth for species at risk
Soil, air and fire disturbances	• soil contamination • decline in air quality • increase in fire severity and frequency
Maintaining critical caribou habitat.	

The next stage of the analysis focused on how to quantify and prioritize impacts of regional concern to support CEs management.

5.1. Valuation, estimation and prioritization of impacts

An impact prioritization model was developed and applied to help identify, quantify and prioritize impacts of regional concern to support CEs management. Two stages were involved with developing the model.

1. Scoring and Valuation of Impacts

Each individual impact was scored according to nine criteria (see Appendix C). The criteria were selected based on the RA framework developed by the GoBC (2013), and Antwi et al., (2014, 2017). The criteria broadly enabled impacts that were convergent, multi-sector driven and synergistic to be identified. Impacts of most relevance to the region for effective management and policy intervention were then prioritized.

Using the criteria, scores of high (1), moderate (0.66), or low (0.33) were assigned to each individual impact (see Appendix D). Some impacts were scored as either present (1) or absent (0) (see Appendix C). Each impact was scored through consensus by the research team, which was often guided by key subject experts and literature references.

2. Calculations to estimate and rank the impacts

The following equation (see Appendix E for a detailed description) was used to consider which impacts should be given priority during decision making.

$$IT_i = S_i + U_i + C_i + \sum_{1}^{J} F_j.$$

The model enabled numerical values to be computed for the individual impacts, rank the impact and determine components of major impact categories. The total score for each impact was ranked (see Appendix D). In addition, impacts were ranked individually and in various impact categories.

6. Implications for Regional Assessments - lessons learned

Several lessons were learned from the application of the RAFCE to the RoF region, with potential implications for conducting a RA. Generally, one tool often used within a CEs framework is spatial analysis. This type of analysis shows the location and spatial extent of each impact as well as areas of overlapping concern (Winder et al., 2020; GoBC, 2014). For example, the Regional Assessment of Offshore Oil and Gas Exploratory Drilling East of Newfoundland and Labrador (C-NLOPB, 2022) used a Geographic information systems (GIS) decision making tool. Spatial analysis is well recognized for its efficient presentation of geospatial information and data that offers resource managers the means to identify and analyze the multitude of factors at play in diverse environments, including terrestrial and aquatic. However, it has some limitations in providing a comprehensive regional cumulative effects assessment and evaluation when compared to the BRAT. For instance, a GIS based approach enables the analysis of proposed projects and impacts with respect to the range of a threatened species. However, it fails to show:

- how decisions are determined;
- which risks and impacts to prioritize;
- the extent to which effects may interact in the context of specific risks;
- how risks could be managed (Winder et al., 2020).

Below is a summary of lessons learned along with examples of potentially broader applications and comparison with other models of RA application.

6.1. Improved transparency in communication and decision making

Large scale projects that involve multiple departments, jurisdictions and stakeholders have an inherent risk that the information, and especially decisions, are passed or posted without adequate notice and/or consultations. This lack of engagement has created recurring concerns over the effectiveness of communication, which should be dealt with in future RAs. There is a need for better ways to involve and inform Indigenous Peoples and other stakeholders about the decisions that may affect them. In this study, the BRAT served as a platform for communicating and collaborating about the risk management process between federal, provincial and territorial governments and agencies. The BRAT enabled early engagement through multiple working sessions to discuss policy objectives. Additionally, risk events, sources and impacts were identified along with possible management strategies to mitigate the risks associated with disturbances. The outcome of these working sessions facilitated better inclusion of diverse values and concerns in the identification of significant cumulative events, sources and impacts. Their associated indicators and management strategies, based on expert scientific and regulatory opinions, supports further research at NRCan. The transparency over the final decisions made, which may not be apparent when using GIS based tools, was increased.

6.2. Indigenous engagement and knowledge co-creation

One of the shortcomings of the Regional Assessment of Offshore Oil and Gas Exploratory Drilling East of Newfoundland and Labrador was the inability to meaningfully engage Indigenous communities. In its final report, some persons stated that their knowledge and worldviews were not well recognized; calling for "a more sustained effort to reflect on these views together with western science" (ECCC, 2020 p.ix). As mine development and management encompass multiple and diverse human activities that cause pressures, policy and management responses that address traditional, cultural, social, ecological, technical and economic policy objectives are required. The RAFCE can be an effective tool for engagement with Indigenous Peoples and knowledge co-creation. Indigenous leaders could identify risks, impacts, mitigation and prevention options from an Indigenous perspective. The visual approach offered by the BRAT and the prioritization of impacts provides an opportunity for experts with diverse values to engage in dialogue on environmental decision-making. Thus, the RAFCE provides opportunities to engage, collaborate and establish partnerships with multiple stakeholders. As a result, the objectives and outcomes of the process are more aligned with the interests of key stakeholders and rights holders. This result is consistent with the goals of RAs as defined by the IAA, which calls for tools to understand and help manage issues that have the potential to impact Indigenous Peoples and their rights.

6.3. Improved science-policy interactions

The RAFCE can support effective science-policy interactions due to the consideration of management and policy issues in the context of risk management and mitigation. The Regional Assessment of Offshore Oil and Gas Exploratory Drilling East of Newfoundland and Labrador called for cooperative frameworks between scientists and industry to improve our understanding of how resource development may impact wildlife, such as migratory bird species, including appropriate measures for mitigation and monitoring (ECCC, 2020). The BRAT is ideal for inclusive and interdisciplinary risks management process. For each risk source or consequence identified, the BRAT enables management or policy options that can be used to prevent the risk or mitigate the impacts to be identified. By integrating legislation, regulations, policies, standards, procedures and guidelines from multi-sector operations, the RAFCE goes beyond the pressure-state-impact risk assessment pathway. It considers approaches that collectively contribute to preventing or mitigating risks. In this context, scientists can use the BRAT to translate research to policy makers to produce on-the-ground change.

Given that mine development involves multi-sectoral, cross-boundary and multi-stakeholder considerations, the RAFCE can be adapted to inform vertical policy integration, e.g., from local/municipal to federal levels, required to ensure coherence and equivalency of operational controls implemented in multiple situations (Cormier et al., 2019).

6.4. Enhanced visualization and understanding of risk management process

Applying the RAFCE to the RoF region showed that the BRAT enhanced the visualization and understanding of the risk management process. The BRAT provided a graphic interface that facilitated understanding of the various aspects of risk including CEs drivers, impacts, prevention and mitigation. This is useful for engaging subject matter experts and non-experts who may not be directly involved in evaluating the risk, alike. The visual and qualitative synthesis of the risk assessment process can facilitate dialogue and effectively translate risk knowledge to stakeholders. It also highlights the risks that are better safeguarded by legislation or management practices, as well as those that are more challenging to address.

6.5. Quantitative and qualitative risk assessment

GIS based analysis has traditionally been applied as an expert and objective led quantitative data analysis tool. In the context of risk management, this type of analysis can serve as an effective approach to quantify risks at large spatial and temporal scales. However, in the context of risk management, both quantitative and qualitative evaluation and analysis of risks are needed. The BRAT mapping process provides a clearer understanding of risks and contributes to reducing the complexity of cumulative effect issues. The integration of scenario analysis and modelling through the impact prioritization model moved qualitative analysis of risks to quantitative. Thus, the BRAT enables seamless integration of qualitative and quantitative analysis of risks.

6.6. Identification of VECs and issues or areas of regional concern

One of the common challenges in any RA is determining geographic areas of protection that require additional or enhanced mitigative measures (ECCC, 2020). Similar to the Regional Assessment of Offshore Oil and Gas Exploratory Drilling East of Newfoundland and Labrador, the BRAT exercise on proposed mining in the RoF region showed that the impacts of the proposed development on ecological VECs are multiple, complex and possibly overwhelming from a management perspective. To ensure effective, efficient policy and management response, the impact prioritization model provides an objective

quantitative approach to rank the most relevant impacts. By prioritizing the impacts with significant regional attention, decisions can be made with high confidence. The comprehensiveness of the model provides enough confidence to drive management and policy actions toward addressing impacts with the highest priority in regional CEAs.

6.7. Planning, Mitigation, Monitoring and Follow-up

In most instances, the complexity of RAs requires a planning rather than a predictive modelling approach as it is more useful if potential adverse effects in the region are to be avoided. Both scientific and stakeholder approaches to monitoring CEs may be involved to provide information around potential effects. The BRAT is very responsive and can support long term planning for risk management including monitoring; especially when new information or data is available or conditions change. For instance, stakeholders can revise the BRAT diagrams to reflect changing dynamics when new risk sources, impacts or consequences are discovered.

6.8. Public access

Two of the main challenges of IAs and RAs is how to engage the public in the process and how meaningful that engagement is. This is because there is the tendency for the process to be controlled by science expertise. The extent to which such experts are responsive to feedback is questionable. This was the case with the Regional Assessment of Offshore Oil and Gas Exploratory Drilling East of Newfoundland and Labrador where scientists from the federal government were not available or accessible (ECCC, 2020).

Having the BRAT as a tool available to researchers within federal departments can support more proactive engagement in future RAs because it helps to simplify the risk assessment process. It also can be an effective tool to solicit public feedback. The use of BRAT diagrams helps simplify the complex risk management processes and can be effective in public communication and engagement.

6.9. Assessing implemented RAs

The RAFCE is useful for past, present and future RAs. It can be applied to the identification of gaps in implemented RAs. It can be used to identify the relationship among impacts, for effective resource allocation and the examination of whether significant impacts are prioritized. To do such requires conscious, unbiased brainstorming sessions, particularly with experts who have knowledge of the implemented RA.

7. Limitations and next steps

Three key caveats have been identified to guide the understanding and the evaluation of our methods and framework analysis.

1. **The use of the BRAT was limited only to the identification of impacts.**

Although direct and indirect impacts were considered, a typical bowtie risk assessment only considers direct impacts. Thus, the BRAT was used in a limited, but purposively driven manner. In general, the use of the BRAT to assess cumulative effects does not consider secondary interactions among components (Winder et al., 2020). The use of the impact prioritization model helped to address this limitation. However, a detailed quantitative and detailed risk assessment through the conversion of the BRAT outcomes to Bayesian belief network can help overcome this (Periera et al., 2015). Future analyses need to detail the relationships among threats [drivers] and impacts, ecological thresholds, natural barriers, as well as specific rules and regulations mitigating the drivers/causes of cumulative effects (GoBC, 2014; Winder et al., 2020).

2. **The identification of issues in the BRAT analysis, model scoring and calculations relied extensively on expert opinion.**

Future research can engage other stakeholders, including Indigenous communities and resource managers. A BRAT workshop can identify regional cumulative effects issues of concern or of interest to stakeholders beyond the scientific community. To encourage transdisciplinary thinking and knowledge co-creation, experts and community stakeholders can work together to identify regional risk issues. Such collaboration can enrich workshop outcomes as the potential identification of multiple values and diverse regional issues of concern is high.

3. **Mining can have positive impacts, at least for some segments of the surrounding, local communities, such as the provision of employment of local Indigenous community members.**

Our assessment approach was simplified to reflect only negative impacts of mining, which is often the case when the focus is on ecological VECs compared with social systems or both. Notwithstanding, the RAFCE can be easily adapted to differentiate negative and positive impacts, such as when social and ecological VECS are considered, or where trade-offs are more balanced.

The development of the impact prioritization model and analysis involved several methodological steps that emphasized subjective decisions.

The use of expert judgment and qualitative information to score impacts and the absence of sensitivity analysis reduced the robustness of our results. To limit such methodological shortcomings, future analysis can use actual data, complimented with undertaking principal component analysis, factor analysis, or distance to target normalization (Singh et al. 2012). The use of a SDM approach to ground the framework, a literature review to select VECs, the transparent process adopted during the development of the BRAT and the involvement of wide diversity of experts enhanced the effectiveness of our approach. With this, the RAFCE can be adapted for assessing the regional sustainability and risk of resource development in other contexts. Future use and adaptation of our approach can improve its effectiveness by considering these limitations and involving other stakeholders such as communities and resource managers.

Appendix A: Bowtie risk analysis diagrams resulting from expert workshops and consultations

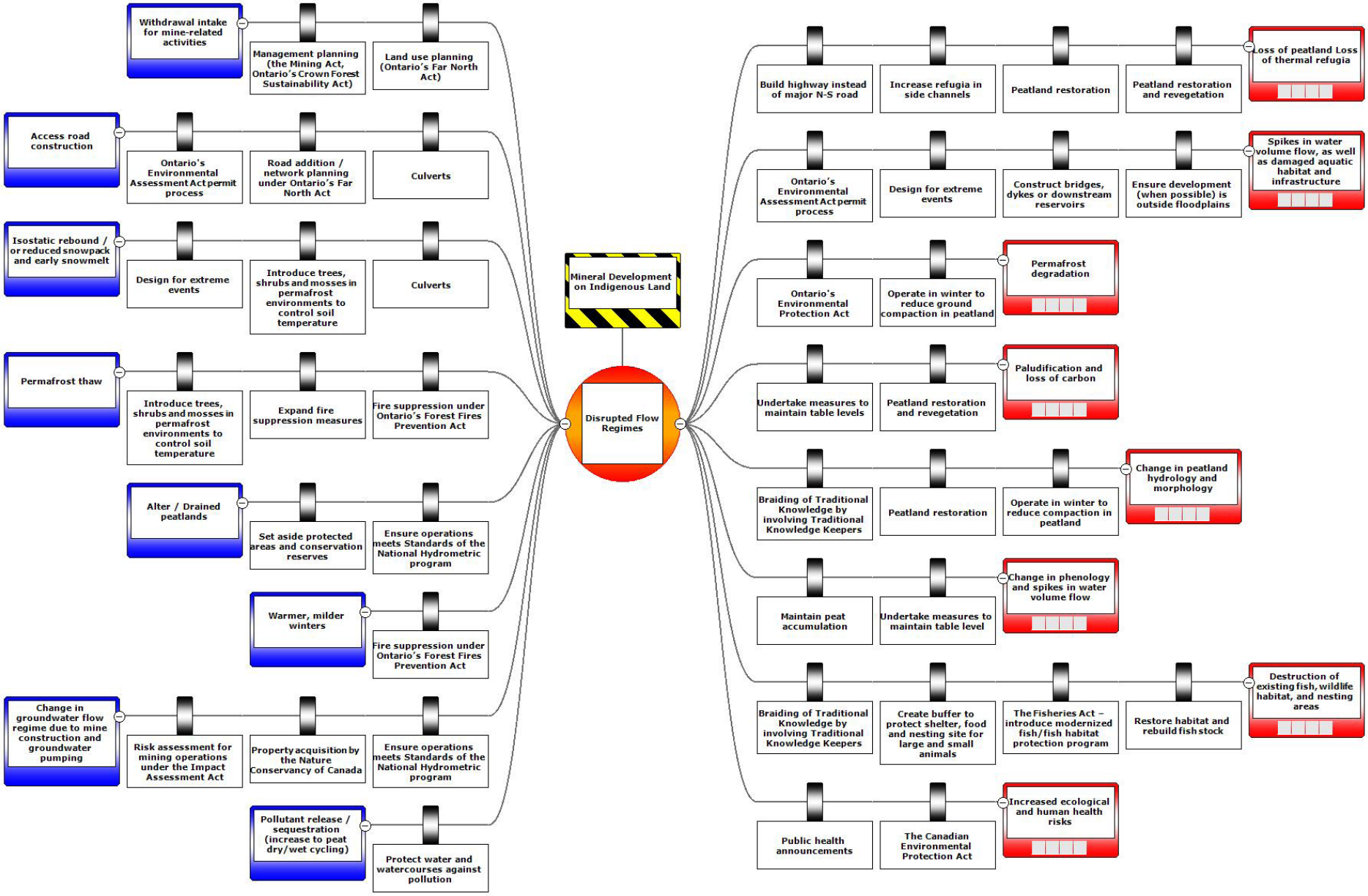


Figure A-1a. Risk Analysis Related to Hydrological-related Disturbances in the Ring of Fire Area: Disrupted Flow Regimes.

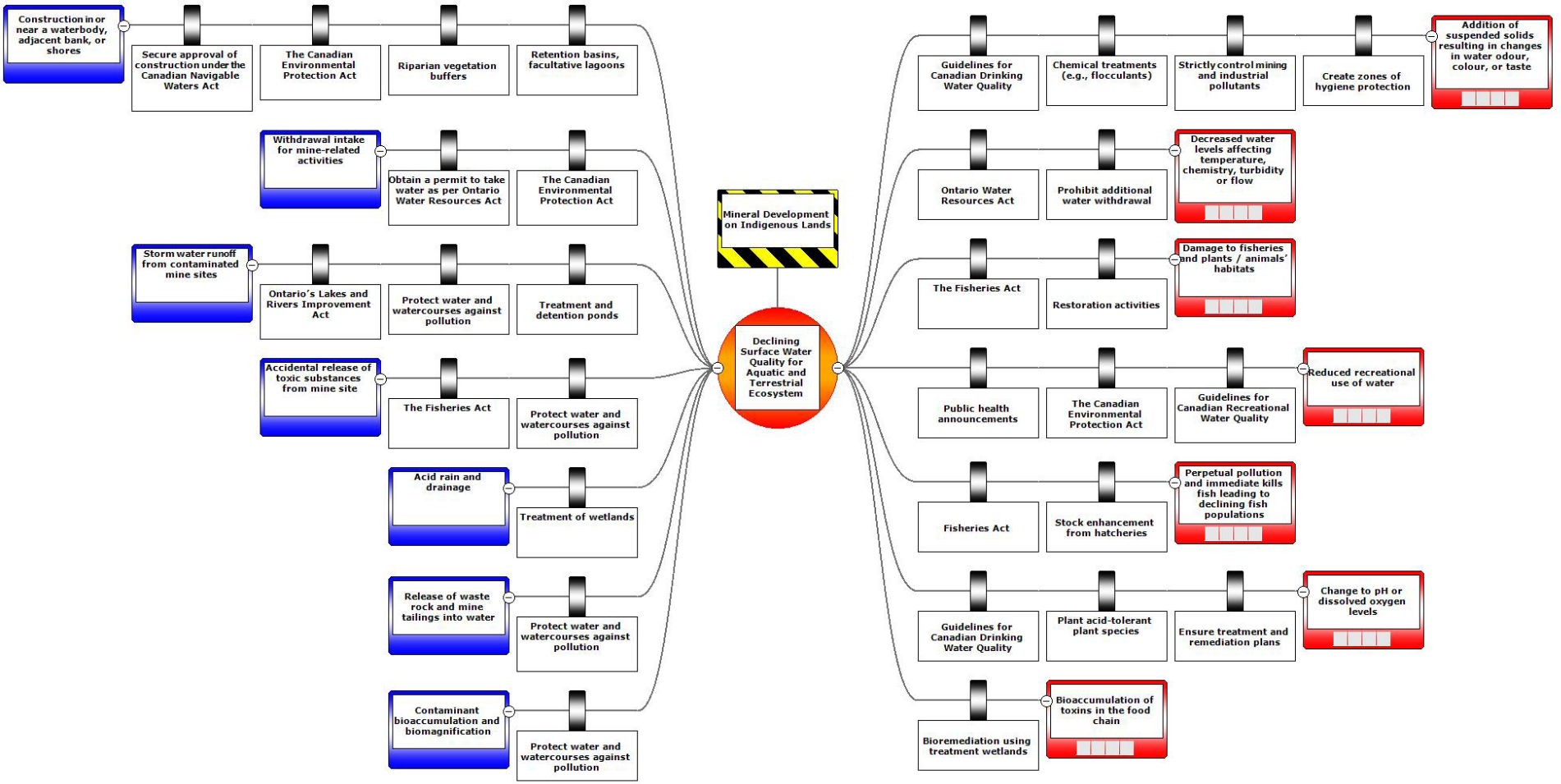


Figure A-1b. Risk Analysis Related to Hydrological-related Disturbances in the Ring of Fire Area: Surface Water Declines.

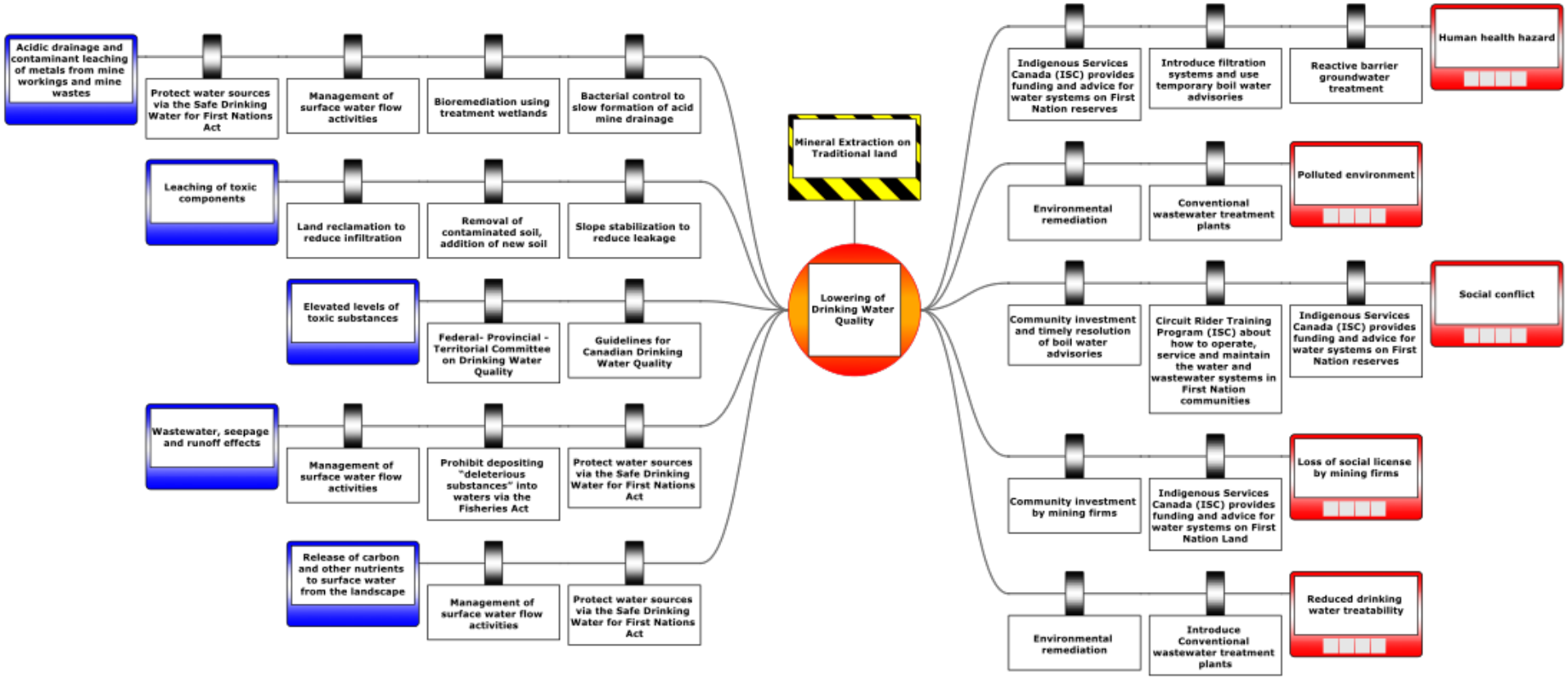


Figure A-1c. Risk Analysis Related to Hydrological-related Disturbances in the Ring of Fire Area: Lowering of Drinking Water Quality.

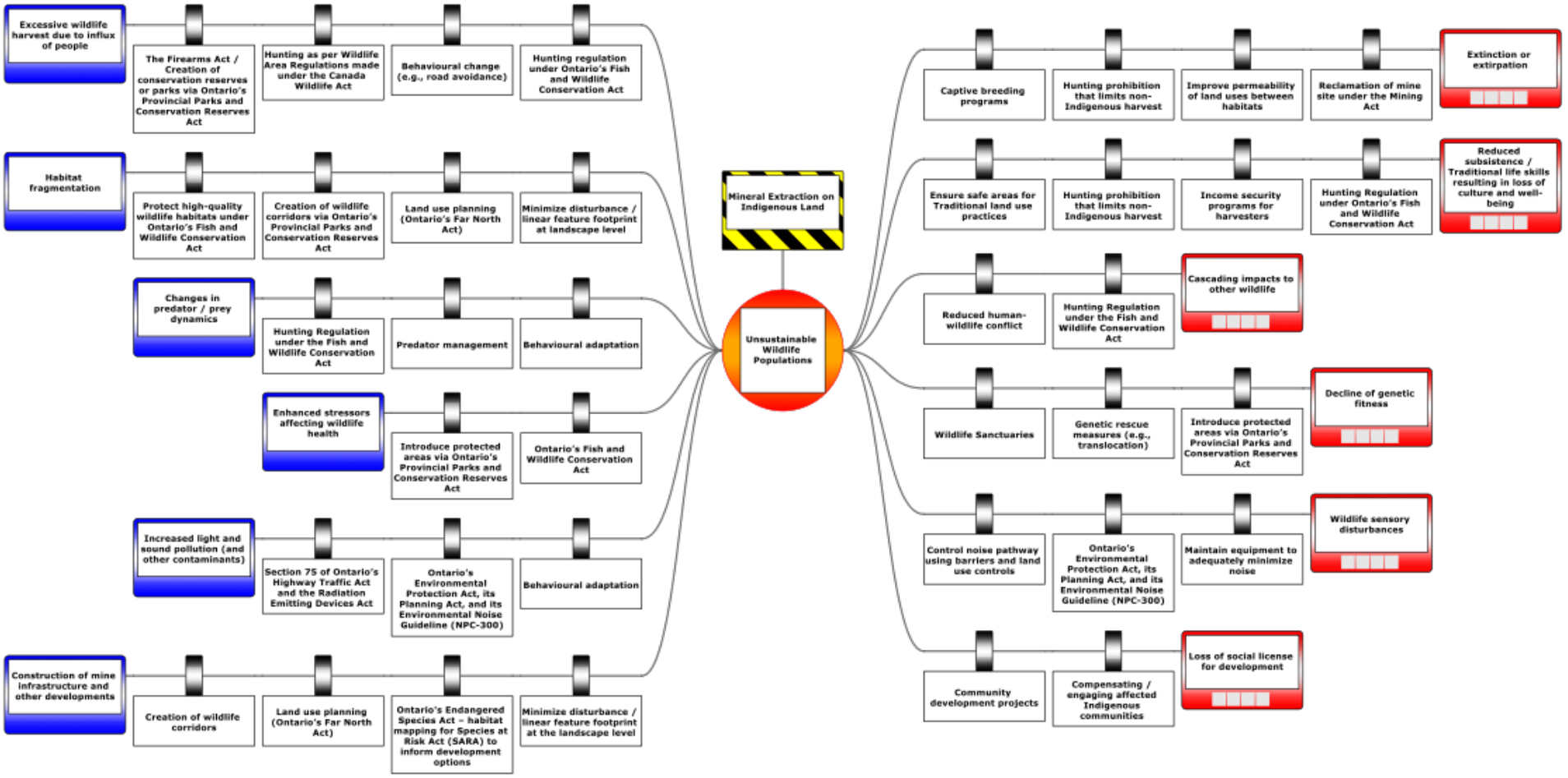


Figure A-2a. Risk Analysis Related to Fish and Wildlife Disturbances: Unsustainable Wildlife Population.

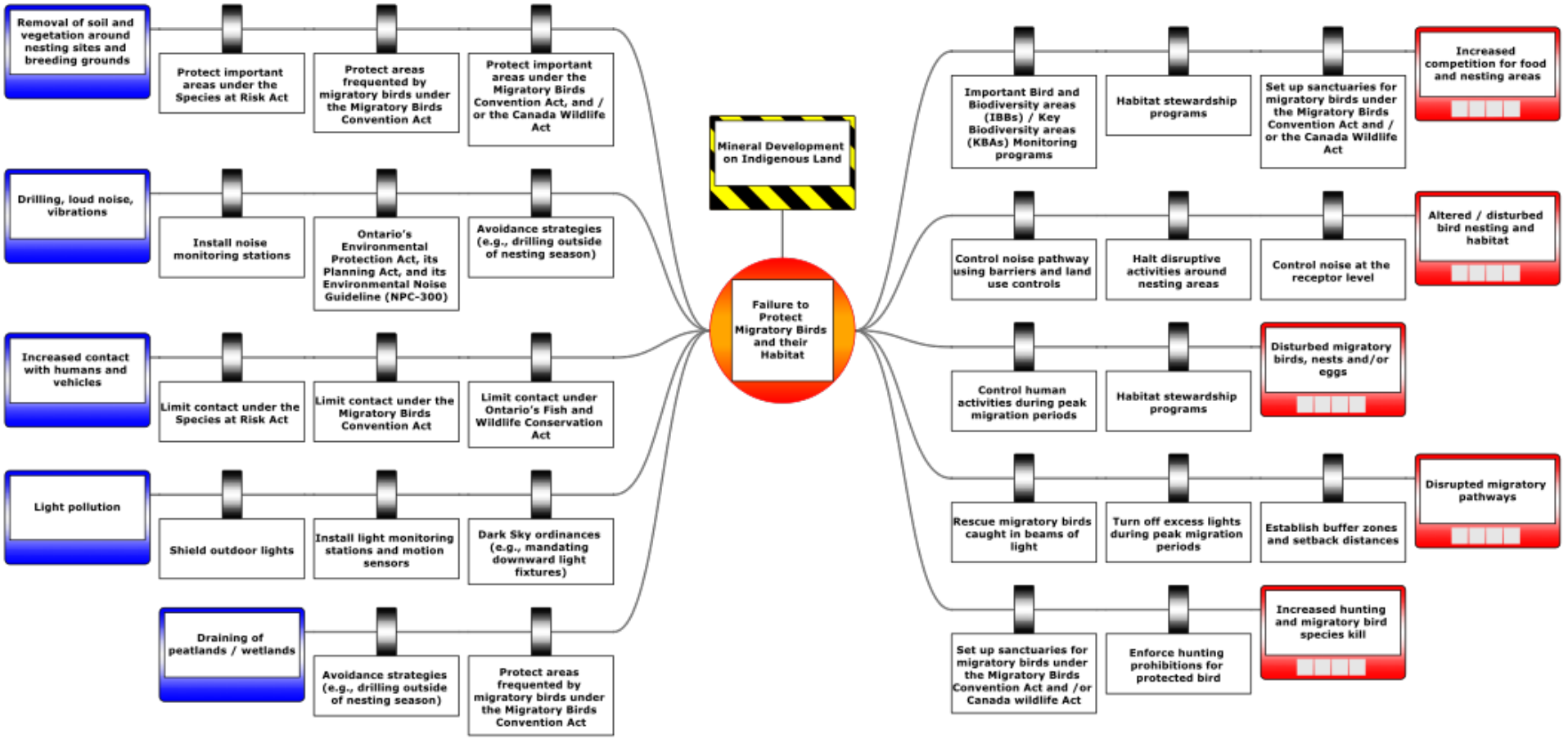


Figure A-2b. Risk Analysis Related to Fish and Wildlife Disturbances: Failure to Protect Migratory Bird Species and Their Habitat.

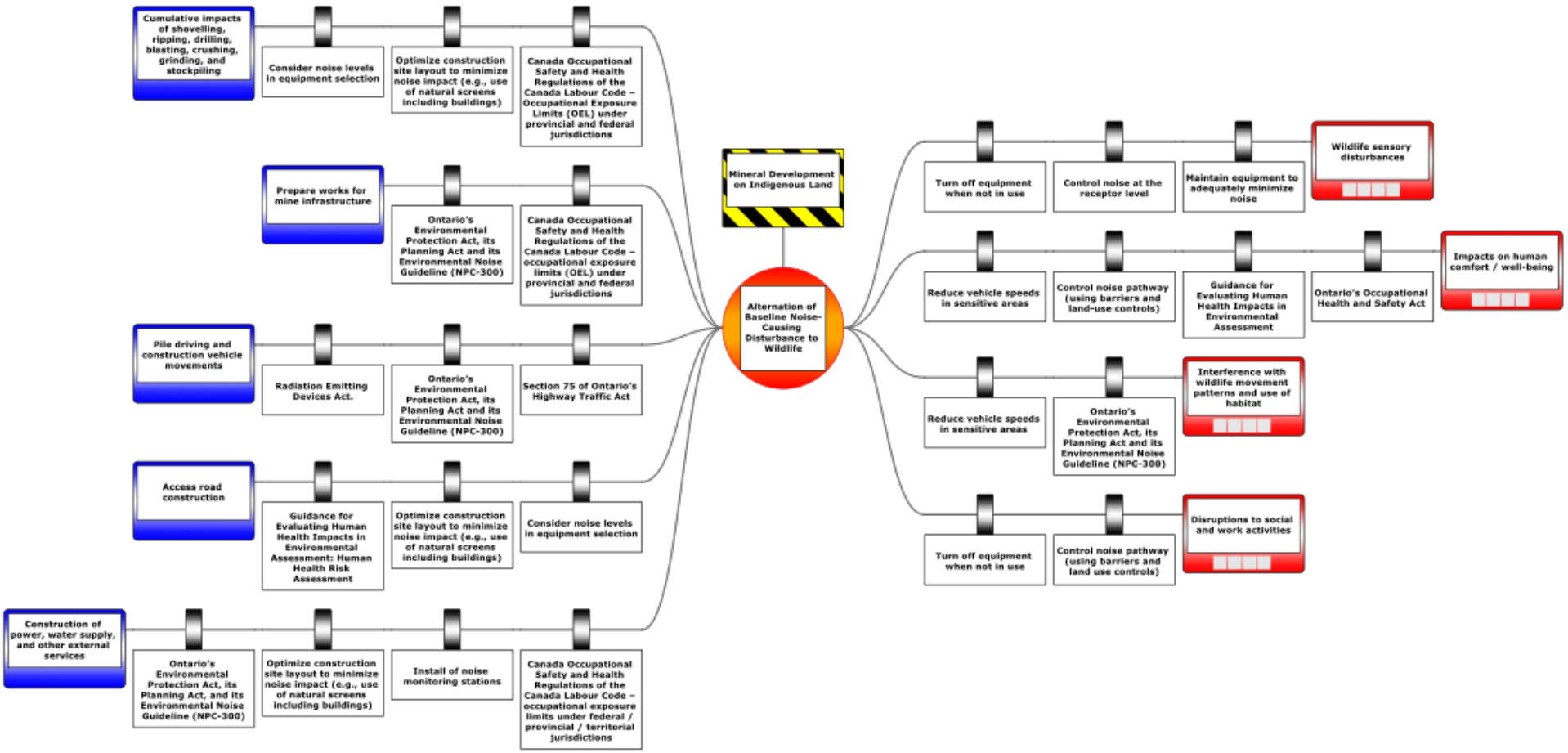


Figure A-2c. Risk Analysis Related to Fish and Wildlife Disturbances: Alteration of Baseline Noise-Causing Disturbance to Wildlife.

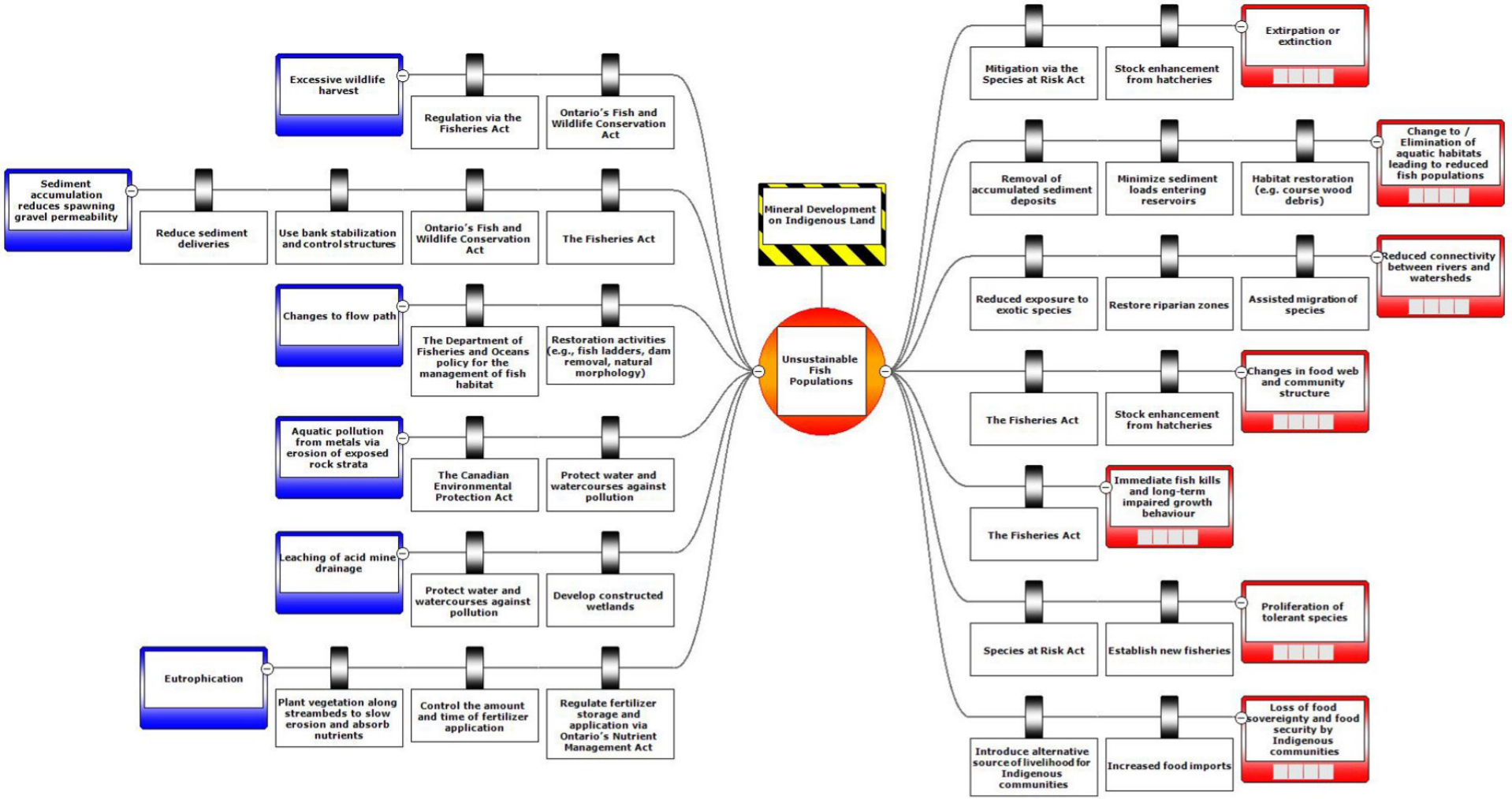


Figure A-2d. Risk Analysis Related to Fish and Wildlife Disturbances: Unsustainable Fish Populations.

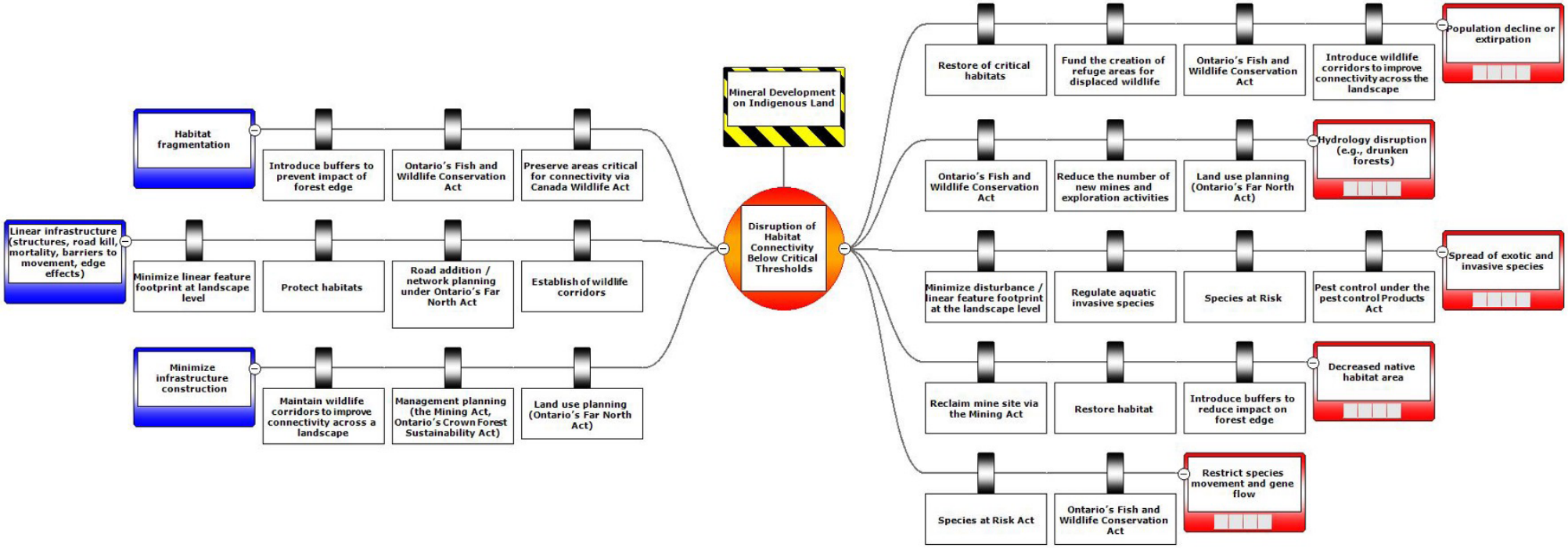


Figure A-3a. Risk Analysis Related to Habitat and Biodiversity Disturbances: Disruption of Habitat Connectivity Below Critical Thresholds.

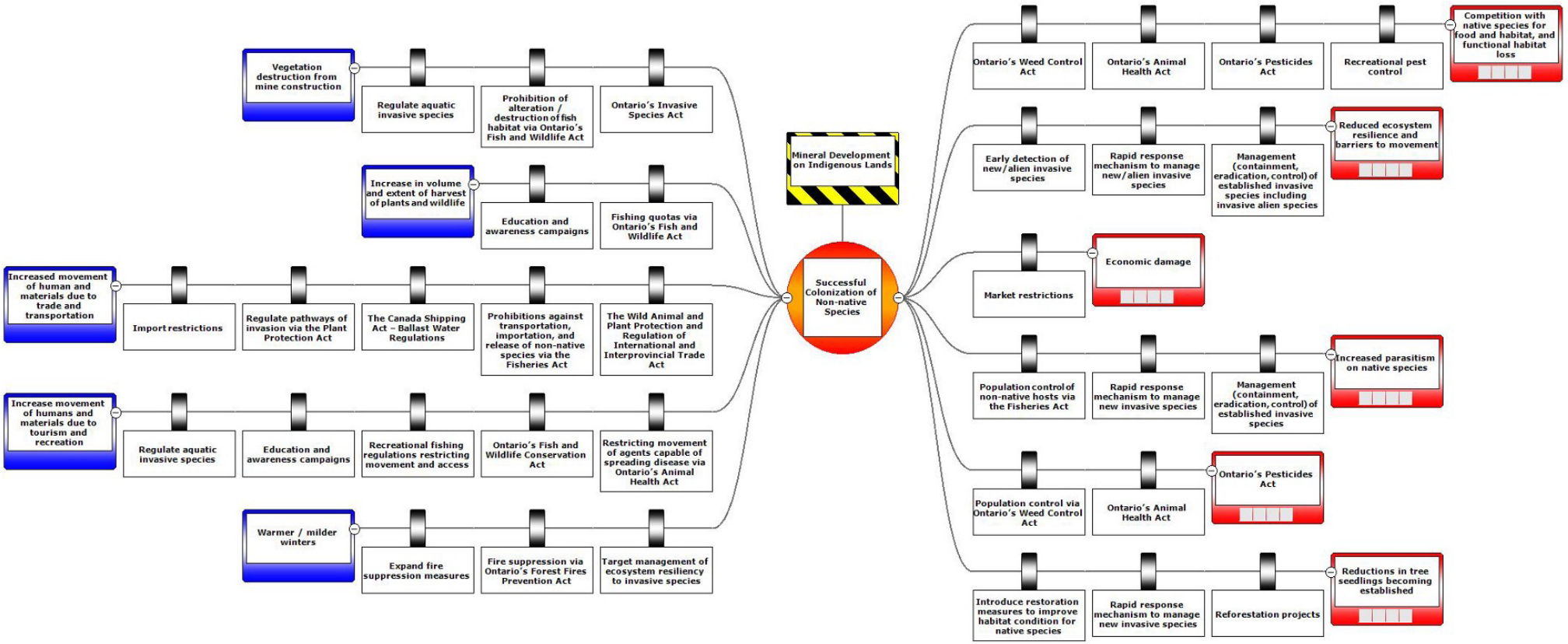


Figure A-3b. Risk Analysis Related to Habitat and Biodiversity Disturbances: Successful Colonization of Non-native Species.

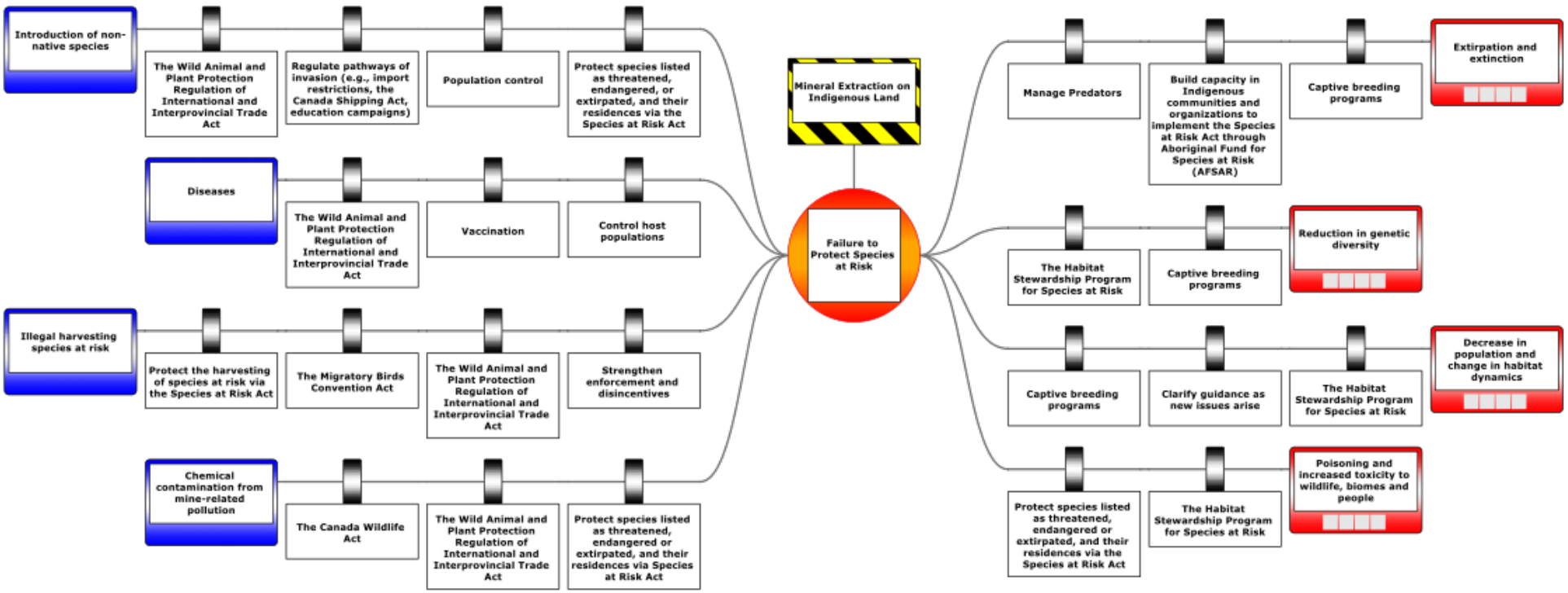


Figure A-3c. Risk Analysis Related to Habitat and Biodiversity Disturbances: Negative Population Growth for Species at Risk.

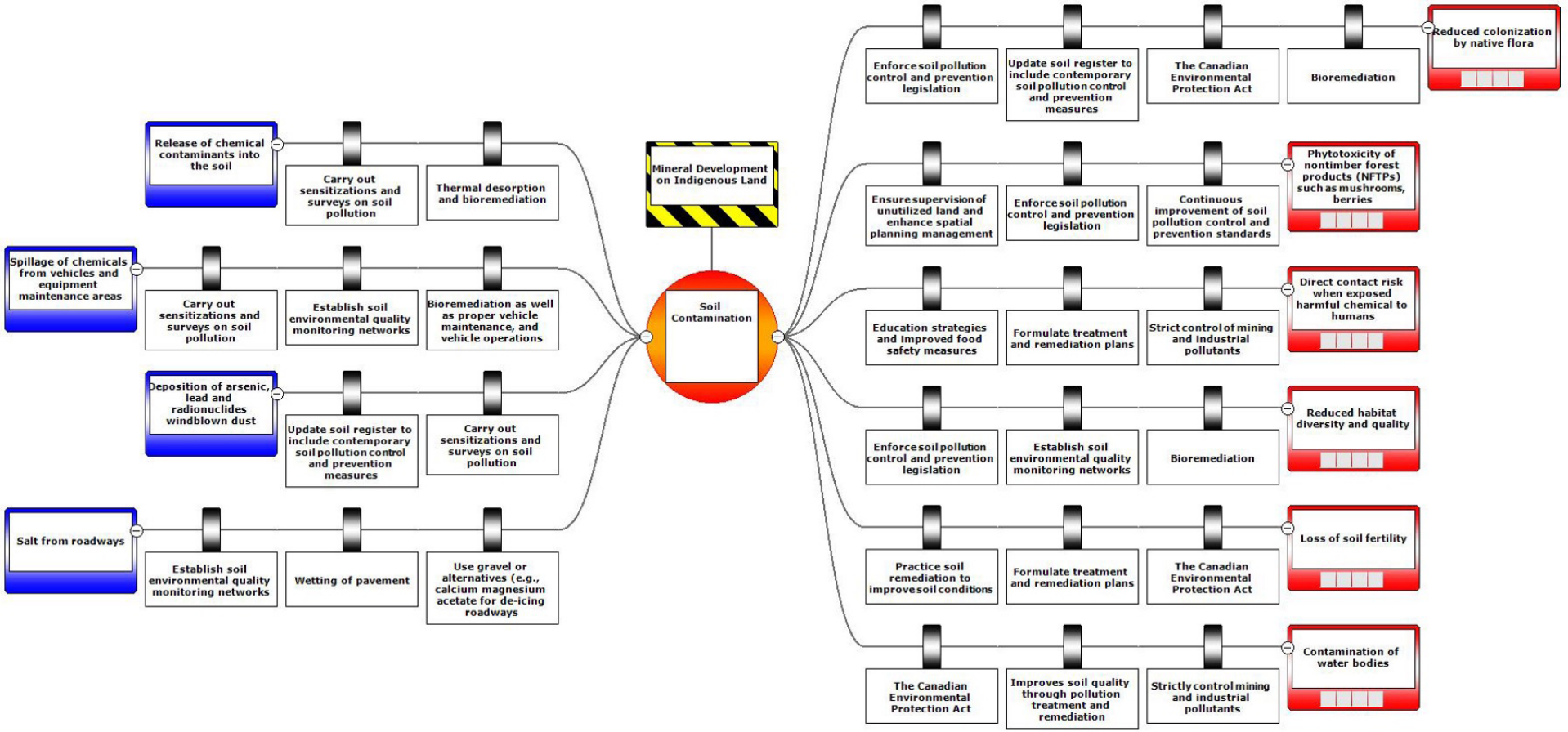


Figure A-4a. Risk Analysis Related to Soil, Air and Wildfire Disturbances: Soil Contamination.

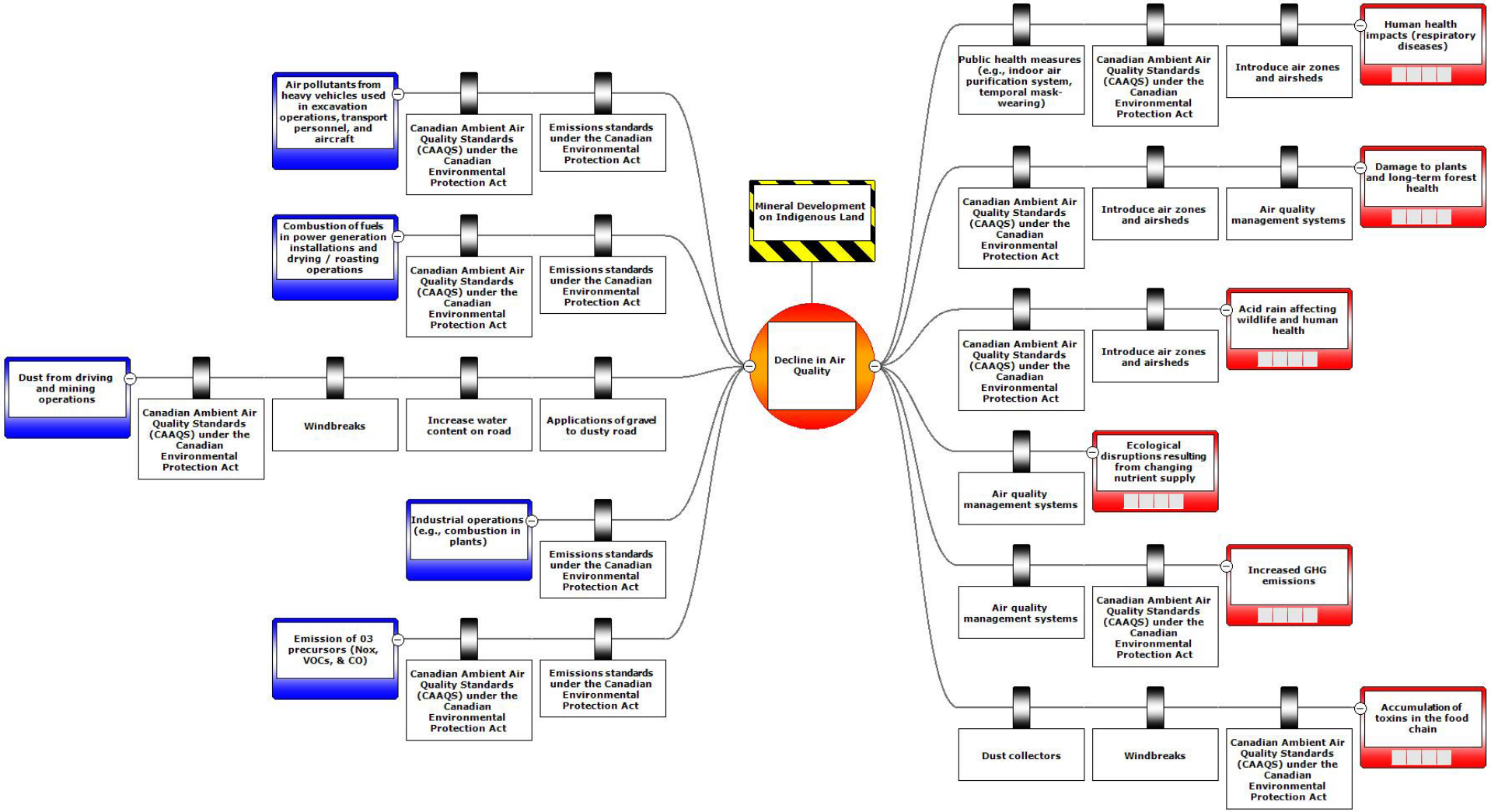


Figure A-4b. Risk Analysis Related to Soil, Air and Wildfire Disturbances: Decline in Air Quality.

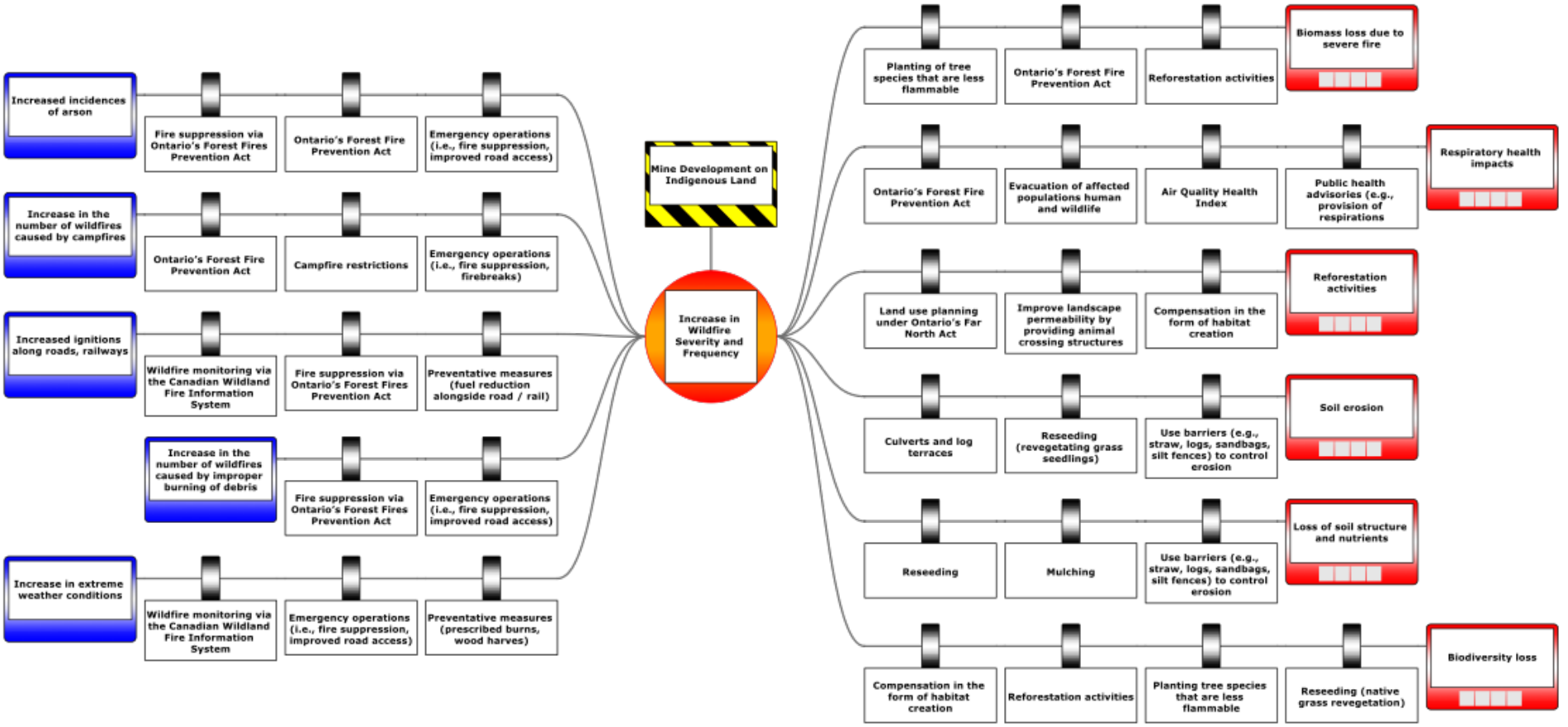


Figure A-4c. Risk Analysis Related to Soil, Air and Wildfire Disturbances: Increase in Wildfire Severity and Frequency.

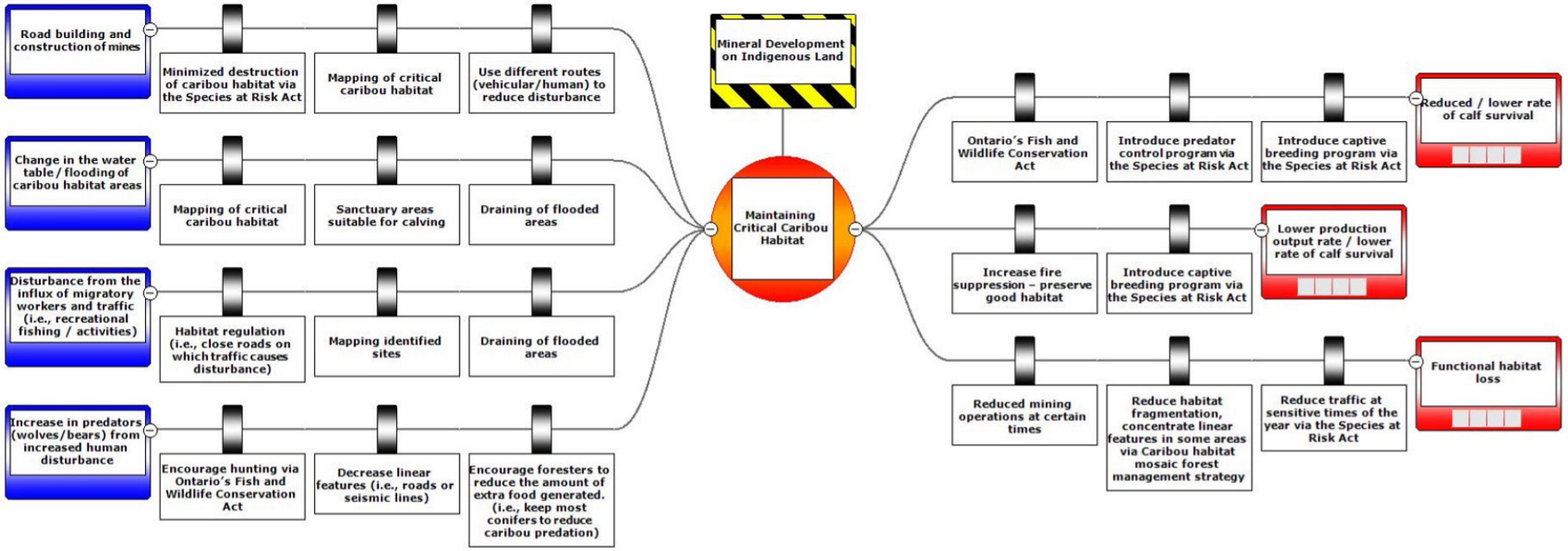


Figure A-5. Risk Analysis Related to Maintaining Critical Caribou Habitat Against Disturbance from Potential Resource Development.

Appendix B: Legislation listed in Bowtie risk analysis diagrams

Federal	Provincial
Canada Occupational Health and Safety Regulations (SOR/86-304)	*Animal Health Act*, 2009, S.O. 2009, c. 31
Canada Shipping Act, 2001 (S.C. 2001, c. 26)	*Crown Forest Sustainability Act*, 1994, S.O. 1994, c. 25
Canada Wildlife Act (R.S.C., 1985, c. W-9)	*Endangered Species Act*, 2007, S.O. 2007, c. 6
Canadian Environmental Assessment Act, 2012 (S.C. 2012, c. 19, s. 52)	*Environmental Assessment Act*, R.S.O. 1990, c. E.18
Canadian Environmental Protection Act, 1999 (S.C. 1990, c. 33)	*Environmental Management Act*, SBC 2003
Canadian Navigable Waters Act (R.S.C., 1985, c. N-22)	*Environmental Protection Act*, R.S.O 1990, c. E.19
Firearms Act (S.C. 1995, c. 39)	*Far North Act*, 2010, S.O. 2010, c. 18
Fisheries Act (R.S.C., 1985 c. F-14)	*Fish and Wildlife Conservation Act*, 1997, S.O. 1997, c. 41
Impact Assessment Act (S.C. 2019, c. 28, s. 1)	*Forest Fires Prevention Act*, R.S.O. 1990, c. F.24
Migratory Birds Convention Act, 1994 (S.C. 1994, c. 22)	*Highway Traffic Act*, R.S.O. 1990, c. H.8
Pest Control Products Act (S.C. 2002, c. 28)	*Invasive Species Act,* 2015, S.O. 2015, c. 22 - Bill 37
Plant Protection Act (S.C. 1990, c. 22)	*Lakes and Rivers Improvement Act,* R.S.O. 1990, c. L3
Radiation Emitting Devices Act (R.S.C., 1985, c. R-1)	*Nutrient Management Act*, 2002, S.O. 2002, c. 4
Safe Drinking Water for First Nations Act (S.C. 2013, c. 21)	*Mining Act*, R.S.O. 1990, c. M.14
Species at Risk Act (S.C. 2002, c. 29)	*Ontario Water Resources Act*, R.S.O. 1990, c. O.40
Wild Animal and Plant Protection and Regulation of International and Interprovincial Trade Act (S.C. 1992, c. 52)	*Occupational Health and Safety Act*, R.S.O. 1990, c. O.1
Wildlife Area Regulations (C.R.C., c. 1609)	*Pesticides Act*, R.S.O. 1990, c. P.11
	Planning Act, R.S.O. 1990, c. P.13
	Provincial Parks and Conservation Reserves Act, 2006, S.O. 2006, c. 12
	Weed Control Act, R.S.O. 1990, c. W.5

Appendix C: Criteria for scoring and valuation of impact

Criteria	Description	Impact factor	Score
Geographic Extent	Anticipated extent/ coverage of effects or area covered by effect	• Discrete (limited to area within metres from source) • Local (perceptible and limited to 5 km from source) • Regional (beyond 5 km from source)	0.33 0.66 1.00
Duration of impact	How long the impact is expected to last	• Effects lasting for 5 years • Effects lasting for 5–15 years • Effects lasting more than 15 years	0.33 0.66 1.00
Frequency of occurrence	Number of times impact is expected to occur	• Effect occurs once • Effect rarely occurs – more than twice • Effect occurs regularly – more than five times	0.33 0.66 1.00
Recoverability	Number of years required for human mediated restoration/ the degree to which effect can be reversed	• Involves reversible effects/short term restoration (50 years) • Involves partly reversible effects/medium term restoration (50-100 years) • Involves irreversible effects/cannot be restored	0.33 0.66 1.00
Severity/magnitude of impact	The degree of severity of the effect	• Undetectable change in effect compared to baseline • Projected change in is equal or close to allowable limit • Expected change in effect is greater than allowed limit	0.33 0.66 1.00
Receptor (human/ecosystem)	The valued components affected e.g., humans (affects livelihood) or non-human (affect moose, fish and benthic invertebrates)	• The receiving environment involves livelihoods • The receiving environment involves ecosystems • The receiving environment involves both livelihoods and ecosystems	0.33 0.66 1.00
Key stakeholder interest/considerations	Effect is concerns of key stakeholders (e.g., Indigenous communities) or the public	• Presence or absence of key stakeholder concerns/interest. • Presence is assigned the highest priority value of 1 and not present 0	0 1

Criteria	Description	Impact factor	Score
Significant global or national interest	Effect on VEC with significant global or national interest e.g., VEC under Ramsar Convention on Wetland	• Presence or absence of VEC with significant global or national interest. • Presence is assigned the highest priority value of 1 and not present 0.	0 1
Sources of impact: (Multiple/Single) Sources	Impacts originate from simple/single or complex/multiple dose-source relationships	• Involves simple/single source • Involves few sources (less than or equal to 5) • Involves complex/multiple dose-source relationships (more than 5 receptors)	0.33 0.66 1.00
Count (number of times it appears in risk analysis)	The number of times effect occurs in the risk analysis of various ecosystem components in comparison to the total number of effects under consideration	• Fraction of the number of times an effect occurs in the risk analysis and the total number of effects in the risk analysis	0-1

Adapted and modified from GoBC., 2013 and Antwi et al., 2023.

Appendix D: Summary of model impact categories, score and ranking

Major Impact Category	Impacts (individual count)	Geographic extent	Duration of impact	Frequency of occurrence	Recover-ability	Severity/ Magnitude of impact	Receptor (human/ ecosystem)	Sources of impact (Multiple/ Single)	Count (number of times it appears in risk analysis)	$\sum_{1}^{j} F_j$	Value for impacts T_i	Ranking for value impacts R_i	Value for major impact category T_{cat}	Ranking for value impact category R_{cat}
Destruction to wildlife habitat/ population	Wildlife sensory disturbance (2)	0.66	0.66	1	0.33	0.66	0.33	0.66	0.67	4.30	4.97	54	57.42	1
	Disruption of migratory pathways/ movement patterns and use of habitat by fauna (2)	1	1	1	0.33	1	0.33	0.66	0.67	5.32	5.99	13		
	Reduce / lower caribou calf survival	0.66	1	1	0.33	0.66	1	0.66	0.33	5.31	5.64	31		
	Functional habitat loss	0.66	1	0.66	1	1	0.66	1	0.33	5.98	6.31	9		
	Lower rate production output / lower calf survival	0.66	1	1	0.33	0.66	1	0.66	0.33	5.31	5.64	30		
	Disturbance to migratory birds nesting sites/ eggs	0.66	0.66	0.66	0.33	1	0.33	0.66	0.33	4.30	4.63	61		
	Increased hunting and migratory bird species kill	1	0.66	1	0.33	0.66	1	1	0.33	5.65	5.98	14		
	Restricted species movement and gene flow	0.33	1	1	0.33	0.66	0.33	0.66	0.33	4.31	4.64	57		
	Extirpation or extinction (3)	1	1	0.66	1	1	0.33	0.66	1.00	5.65	6.65	3		
	Reduced connectivity of rivers and watersheds	1	1	0.66	0.66	0.66	0.66	1	0.33	5.64	5.97	22		
	Cascading impacts on other wildlife	1	1	0.66	1	0.66	0.33	1	0.33	5.65	5.98	14		

Major Impact Category	Impacts (individual count)	Geographic extent	Duration of impact	Frequency of occurrence	Recover-ability	Severity/ Magnitude of impact	Receptor (human/ ecosystem)	Sources of impact (Multiple/ Single)	Count (number of times it appears in risk analysis)	$\sum_{1}^{j} F_j$	Value for impacts T_i	Ranking for value impacts R_i	Value for major impact category T_{cat}	Ranking for value impact category R_{cat}
Habitat loss/ alteration	Reduced fish population due to alteration/ elimination of aquatic habitats (2)	0.66	1	0.66	0.33	0.66	0.33	1	0.67	4.64	5.31	41	38.83	3
	Loss of habitat (2)	0.66	1	1	1	0.66		0.66	0.67	4.98	5.65	30		
	Destruction of wildlife habitat	0.66	1	0.66	0.66	0.66	0.33	1	0.33	4.97	5.30	42		
	Reduced habitat diversity	1	1	0.66	0.66	0.66	0.33	0.66	0.33	4.97	5.30	42		
	Damage to plants and animals' habitat	1	0.66	1	0.33	1	0.33	1	0.33	5.32	5.65	24		
	Altering of birds' nesting areas and habitat (2)	0.66	0.66	0.66	0.66	1	0.33	1	0.67	4.97	5.64	37		
	Changes in the structure and function of habitat	1	1	1	0.66	0.66	0.33	1	0.33	5.65	5.98	14		
Decline in human health and wellbeing	Reduced recreational uses of water	0.66	1	1	0.33	0.66	0.33	0.33	0.33	4.31	4.64	57	36.88	5
	Impacts on human comfort/ wellbeing	1	1	1	0.33	1	0.33	1	0.33	5.66	5.99	11		
	Disruptions to social and work activities	1	1	1	0.33	0.66	0.33	1	0.33	5.32	5.65	24		
	Economic damage	0.33	1	1	0.66	1	0.33	0.33	0.33	4.65	4.98	46		
	Respiratory and other human diseases (2)	1	0.66	1	1	0.66	0.33	0.66	0.67	5.31	5.98	21		
	Direct exposure to contaminated soil	0.33	1	1	0.66	0.66	0.33	1	0.33	4.98	5.31	39		
	Acid rain affecting human health	1	0.66	1	0.33	0.33	0.33	0.33	0.33	3.98	4.31	62		

Major Impact Category	Impacts (individual count)	Geographic extent	Duration of impact	Frequency of occurrence	Recover-ability	Severity/ Magnitude of impact	Receptor (human/ ecosystem)	Sources of impact (Multiple/ Single)	Count (number of times it appears in risk analysis)	$\sum_{1}^{j} F_j$	Value for impacts T_i	Ranking for value impacts R_i	Value for major impact category T_{cat}	Ranking for value impact category R_{cat}
Species invasion (loss of native species)	Spread of exotic and invasive species	0.66	1	1	1	0.66	0.33	1	0.33	5.65	5.98	14	37.85	4
	Reduced colonization by native flora	0.66	1	1	1	0.66	0.33	1	0.33	5.65	5.98	14		
	Decreased native habitat area	0.66	1	1	1	1	0.33	0.33	0.33	5.32	5.65	24		
	Competition with native species for food and space	0.66	1	1	0.33	0.33	0.33	0.66	0.33	4.31	4.64	57		
	Increased parasitism of native species	0.66	0.66	1	0.33	0.33	0.33	0.66	0.33	3.97	4.30	63		
	Proliferation of tolerant species	0.66	1	1	0.66	0.66	0.33	1	0.33	5.31	5.64	31		
	Biodiversity loss	0.66	1	1	0.66	0.66	0.33	1	0.33	5.31	5.64	31		
Loss of plant biodiversity	Decline of genetic fitness	0.33	1	1	1	0.33	0.33	1	0.33	4.99	5.32	38	38.87	2
	Reduction in genetic diversity	0.66	1	1	1	0.66	0.33	0.66	0.33	5.31	5.64	31		
	Reductions in tree seedling establishment	0.66	1	1	0.33	0.66	0.33	0.66	0.33	4.64	4.97	49		
	Biomass loss due to severe fire	0.66	0.66	0.66	0.33	1	0.33	1	0.33	4.64	4.97	49		
	Forest fragmentation	1	1	1	0.66	1	0.33	1	0.33	5.99	6.32	4		
	Damage to plants and long-term forest health	1	1	1	0.66	0.66	0.33	1	0.33	5.65	5.98	14		
	Changes in phenology	1	1	1	0.66	0.33	0.33	1	0.33	5.32	5.65	24		

Major Impact Category	Impacts (individual count)	Geographic extent	Duration of impact	Frequency of occurrence	Recover-ability	Severity/ Magnitude of impact	Receptor (human/ ecosystem)	Sources of impact (Multiple/ Single)	Count (number of times it appears in risk analysis)	$\sum_{1}^{j} F_j$	Value for impacts T_i	Ranking for value impacts R_i	Value for major impact category T_{cat}	Ranking for value impact category R_{cat}
Reduced surface and groundwater quality and quantity	Addition of suspended solids resulting in changes in water odour, colour, or taste	0.66	0.66	1	0.33	0.66	1	0.66	0.33	4.97	5.30	42	34.51	6
	Decreased water levels affecting temperature, chemistry, turbidity, or flow	1	1	1	0.33	0.33	0.33	0.33	0.33	4.32	4.65	55		
	Changes to pH or dissolved oxygen levels	0.66	1	1	0.33	0.33	1	1	0.33	5.32	5.65	24		
	Contamination of water bodies	1	0.66	1	0.33	0.66	1	1	0.33	5.65	5.98	14		
	Spikes in water volume flows	0.66	0.33	1	0.66	0.33	0.33	0.33	0.33	3.64	3.97	64		
	Hydrology disruption (drunken forests)	0.33	0.66	1	0.33	0.33	0.33	0.33	0.33	3.31	3.64	66		
	Change in peatland hydrology	0.66	1	1	0.66	0.66	0.33	0.66	0.33	4.97	5.30	42		
Destruction to soil condition	Loss of soil fertility	0.33	1	1	0.66	0.66	0.33	0.33	0.33	4.31	4.64	57	19.90	8
	Soil erosion	0.33	1	1	0.33	0.66	0.66	0.66	0.33	4.64	4.97	49		
	Loss of soil structure and nutrients	0.33	1	1	0.66	0.66	0.33	1	0.33	4.98	5.31	39		
	Ecological disruptions resulting from changing nutrient supply	0.66	1	1	0.66	0.66	0.33	0.33	0.33	4.64	4.97	49		

Major Impact Category	Impacts (individual count)	Geographic extent	Duration of impact	Frequency of occurrence	Recover-ability	Severity/ Magnitude of impact	Receptor (human/ ecosystem)	Sources of impact (Multiple/ Single)	Count (number of times it appears in risk analysis)	$\sum_{1}^{j} F_j$	Value for impacts T_i	Ranking for value impacts R_i	Value for major impact category T_{cat}	Ranking for value impact category R_{cat}
Food sovereignty and security (access, quality and quantity) - humans	Loss of food-sharing networks	1	1	1	1	1	1	0.33	0.33	6.33	6.66	1	24.29	7
	Accumulation of toxins in the food chain	1	1	1	0.66	0.66	1	0.66	0.33	5.98	6.31	9		
	Reduced subsistence	1	1	1	1	0.33	1	1	0.33	6.33	6.66	1		
	Phytotoxicity for NTFPs (e.g., mushrooms, berries)	0.33	1	1	1	0.33	0.33	0.33	0.33	4.32	4.65	55		
Destruction of fish population	Perpetual pollution and immediate fish kill leading to declined fish populations	1	0.66	1	0.66	0.66	1	0.66	0.33	5.64	5.97	22	17.61	9
	Reduced connectivity of rivers and watersheds	1	1	1	0.33	0.33	1	1	0.33	5.66	5.99	11		
	Perpetual pollution and long-term impaired growth behavior	1	1	1	0.66	0.66	0.33	0.66	0.33	5.31	5.64	31		
Climate variability	Intensification of extreme weather events and altered rainfall cycle	1	1	1	1	0.33	1	0.66	0.33	5.99	6.32	4	11.98	12
	Increased GHG emissions	1	1	1	0.33	0.33	1	0.66	0.33	5.32	5.65	24		
Destruction of peatland	Paludification and loss of carbon	1	1	1	0.33	0.33	0.33	0.66	0.33	4.65	4.98	46	13.60	10
	Reduced ecosystem resilience	0.33	1	0.66	0.66	0.66	0.33	1	0.33	4.64	4.97	49		
	Permafrost degradation	0.33	0.33	1	0.33	0.33	0.33	0.66	0.33	3.31	3.64	65		

Major Impact Category	Impacts (individual count)	Geographic extent	Duration of impact	Frequency of occurrence	Recover-ability	Severity/ Magnitude of impact	Receptor (human/ ecosystem)	Sources of impact (Multiple/ Single)	Count (number of times it appears in risk analysis)	$\sum_{1}^{j} F_j$	Value for impacts T_i	Ranking for value impacts R_i	Value for major impact category T_{cat}	Ranking for value impact category R_{cat}
Heightened tension/ dispute with communities	Loss of social license for development	1	0.66	0.66	0.33	1	1	1	0.67	5.65	6.32	8	11.30	13
	Social conflict	0.33	0.66	1	0.33	1	0.33	1	0.33	4.65	4.98	46		
Disruptions in food chain and web – plants and animals	Alterations in food web and community structure	1	1	1	0.66	1	0.33	1	0.33	5.99	6.32	4	12.65	11
	Increased competition for food and nesting areas	1	1	1	0.66	0.33	1	1	0.33	5.99	6.32	4		

Appendix E: Model calculation

To determine which impacts should be given priority during decision making, we used the following equation to compute numerical values of each impact:

$$T_i = S_i + U_i + C_i + \sum_{1}^{j} F_j \ \ldots$$

Where:

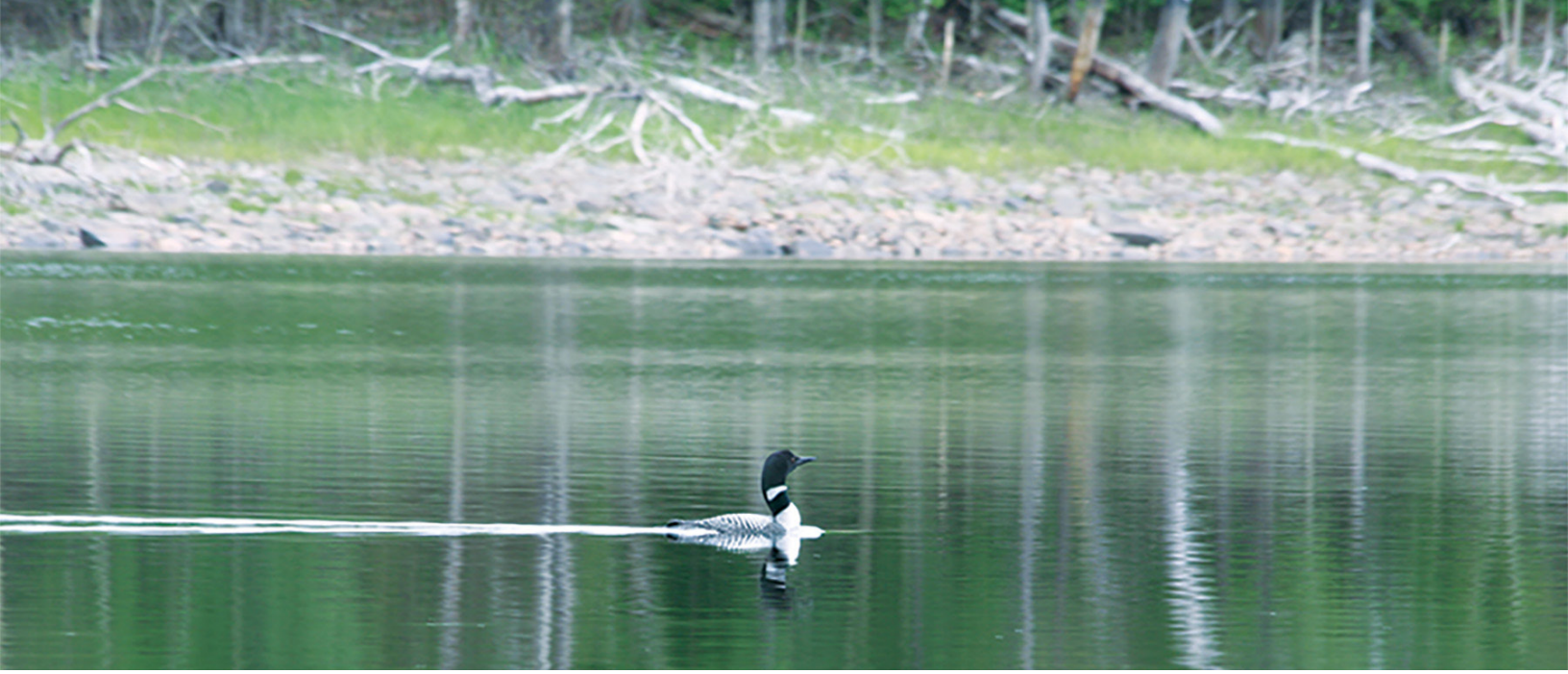
- T_i is the value of each impact under the study
- S_i is the impact factor of existing stakeholder interest or consideration for which the presence of stakeholder interest is assigned the highest priority value of 1, and absence is assigned the lowest value of 0
- U_i is the impact factor of any existing underlying issues of significant global or national interest. The presence of underlying issues is assigned the highest priority value of 1, and absence is assigned the lowest value of 0
- C_i is fraction of the number of times an effect occurs in the risk analysis compared and the total number of effects in the risk analysis for each impact
- $\sum_{1}^{j} F_j$ is summation of the impact factor F for each criterion, where j is the number of criteria, apart from S and U, F takes a value 0.33, 0.66 and 1 if it is classified as low, medium and high impact respectively

We then calculated T_{cat} , the value of the impact for a major category which is the summation of where T_i for impact within a major category. Appendix D shows calculated T_i impacts (summary of model impact categories, score and ranking).

Further on, we determined R_i as the rank of the value of each threat or impact under the study and R_{cat}, the rank of the value of the major category compared with all other major categories under the study.

The impacts are ranked according to the values $T_{1ST} > T_{2ND} > T_{3ND} > \ldots . T_{LAST}$ where T_{1ST} is the impact with the highest value and it is given the highest priority and is given the least priority.

Appendix D shows R_i and R_{cat} calculated for drivers of CE and impacts.



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