Updated Inventory of Western Science and Knowledge Relevant to the Ring of Fire

Final Report and Recommendations

Wyndham Research Inc.
Bracebridge, Ontario

On behalf of

The Regional Assessment Working Group for the Ring of Fire

March 2026

Executive Summary

The Regional Assessment (RA) for the Ring of Fire area is a federal assessment process led by 15 First Nations and the Impact Assessment Agency of Canada (IAAC) under the Canadian federal *Impact Assessment Act*, 2019 (IAA). It was initiated in recognition that multiple, interrelated development proposals, particularly mining and associated linear infrastructure, are being contemplated within a large, ecologically sensitive, and culturally significant region of northern Ontario. The assessment is intended to address issues that cannot be adequately considered through project-by-project impact assessments alone. The primary purpose of the RA is to improve understanding of the environmental, health, social, and economic effects of past, existing, and potential future development in the Ring of Fire area. It seeks to:

- Establish a **shared baseline** of regional conditions;
- Identify **key pathways of cumulative effects**, risks, and uncertainties;
- Assess how development scenarios could affect **valued components** such as water, peatlands, wildlife and wildlife habitat, fish and fish habitat, species at risk, climate change interactions, and Indigenous well-being; and
- Provide **strategic information, guidance, and recommendations** to inform future decision-making processes.

Fifteen First Nations co-lead the RA:

Aroland First Nation
Attawapiskat First Nation
Constance Lake First Nation
Eabametoong First Nation
Fort Albany First Nation
Ginoogaming First Nation
Kashechewan First Nation
Long Lake #58 First Nation
Marten Falls First Nation
Missanabie Cree First Nation
Moose Cree First Nation
Neskantaga First Nation
Nibinamik First Nation
Webequie First Nation, and
Weenusk First Nation.

The RA does not approve or reject projects, nor does it replace individual project assessments. Instead, it is intended to provide a regional context and evidence base to support more consistent, efficient, and defensible future decisions. The scope includes both biophysical and human environment components, with particular emphasis on peatland-dominated ecosystems of the Hudson and James Bay Lowlands, large river systems, and regional connectivity.

Indigenous participation and knowledge are integral to the process. The RA is designed to respect Indigenous rights, incorporate Indigenous Knowledge alongside Western science, and reflect the interests and priorities of First Nations whose territories overlap the assessment area.

This Project

The Impact Assessment Agency of Canada (IAAC) retained Wyndham Research Inc. to assist with updating Western science and knowledge on topics relevant to the Ring of Fire (RoF) area since the publication of the 2010 report of the Ontario Far North Science Advisory Panel, *Science for a Changing Far North*. The current project seeks to document areas where knowledge has changed or remained constant since 2010, identify known or suspected gaps, and provide recommendations to inform IAAC's Regional Assessment activities outside Traditional Knowledge led by the RA First Nation Partners.

This report constitutes the third and final stage of the work. It summarizes information obtained from a scan of scholarly and technical literature published since 2010 and interviews with 17 key informants from a wide range of backgrounds.

Results

The literature scan and the interviews converged strongly on the need for watershed-scale, cumulative, climate-integrated, and governance-reformed planning. The interviews added emphasis on enforceable limits, precautionary action, and structural shared authority beyond advisory processes. There was virtually no disagreement on any topic, although emphasis on specific topics varied from interviewee to interviewee.

The following conclusions are essentially identical across the literature scan and the key informant interviews:

- Hydrology must anchor assessment design.
- Watershed-scale framing is essential.
- Roads are cumulative multipliers.
- Mercury is a high-sensitivity contaminant risk.
- Carbon loss is potentially irreversible.
- Climate change amplifies all other risks.
- Governance reform is necessary.
- Data gaps and fragmentation undermine credible assessment.

Recommendations

Scope and Scale of Impact Assessment

Recommendation 1: Adopt a nested, watershed-based impact assessment framework. Formally adopt watershed boundaries (5–6 major watersheds) as primary assessment units, with nested sub-watersheds and receptor-specific scales (e.g., caribou herd ranges, sturgeon river systems).

Recommendation 2: Treat roads as regional infrastructure, not standalone projects. Assess roads and linear corridors as access-enabling networks with cumulative hydrological, ecological, and social effects.

Science and Monitoring Priorities

Recommendation 3: Make hydrology the monitoring core. Re-establish and expand regional hydrometric networks (stream gauges, water table wells, groundwater monitoring) as the foundation of cumulative effects monitoring.

Recommendation 4: Implement a peatland carbon and methane monitoring strategy. Develop a coupled hydrology–carbon monitoring framework that tracks water table depth, carbon flux, and methane emissions.

Recommendation 5: Adopt a precautionary mercury framework. Shift from “monitor and adapt” to proactive sulphate control and biomonitoring triggers.

Recommendation 6: Strengthen lake sturgeon and caribou monitoring. Invest in telemetry and movement studies for lake sturgeon and caribou, integrated with Indigenous knowledge.

Governance and Decision Architecture

Recommendation 7: Establish a co-governed science and monitoring panel. Create a formal co-governed body to define indicators, thresholds/limits, triggers, and acceptable uncertainty.

Recommendation 8: Design and embed an adaptive management process and governance structure. Consider developing Trigger Action Response Plans (TARPs) for hydrology, mercury, carbon, and species indicators.

Data and Transparency Actions

Recommendation 9: Audit, recover, and centralize publicly-funded datasets and require industry data disclosure.

Recommendation 10: Use modern remote sensing (LiDAR, SAR, high-resolution imagery), including drone technology, to refine peatland, wetland, and habitat classification, with special attention to updating the Ecological Land Classification system for the ecodistrict level and wetland mapping more generally.

Policy and Precaution

Recommendation 11: Consider development of formal peatland protection and cumulative effects policies.

Recommendation 12: Require that climate change be integrated into all infrastructure design. Require climate-forward designs for roads, tailings facilities, water management systems and other infrastructure.

Recommendation 13: Formally adopt a precautionary hierarchy in effects assessment and mitigation. Avoidance of impacts should be the highest priority, followed by minimization of impacts, and restoration, with compensation used only as a last resort.

Capacity and Community Engagement

Recommendation 14: Build community-based monitoring capacity. Shift from fly-in science to community-based environmental monitoring networks that bring deep knowledge of the landscape.

Table of Contents

Executive Summary i
1 Introduction 1
1.1 Purpose and Objectives 1
1.2 Regional Assessment Governance and Participation 1
1.3 This Project 2
1.4 This Report 2
2 Overview of the Literature Scan 4
2.1 Regulatory and Policy Context 4
2.2 Governance Challenges, Opportunities, and Models 4
2.3 Geology, Soils, and Geomorphology 5
2.4 Carbon and Methane Flux 6
2.5 Peatlands and Permafrost 6
2.6 Air Quality 7
2.7 Hydrology 7
2.8 Water Quality 8
2.9 Mercury 9
2.10 Terrestrial Ecosystems 10
2.11 Natural Disturbance Processes Including Fire 10
2.12 Biological Diversity 11
2.13 Mammals 11
2.14 Birds 12
2.15 Fish 13
2.16 Species and Spaces of Conservation Concern 14
2.17 Distribution and Function of Native Assemblages 14
2.18 Productivity, Decomposition, and Nutrient Cycling 15
2.19 Ecosystem Resilience 16
2.20 Connectivity 17
2.21 Thresholds of Landscape Change 17
2.22 Protected Areas 18
2.23 Invasive and Non-Native Species 18
2.24 Climate Change 19

3 Overview of Key Informant Interviews 20
3.1 Scale and Scoping Are Critical 21
3.2 Hydrology as the Organizing Variable 21
3.3 Peatlands Are Globally Significant Carbon Stores 22
3.4 Mercury Methylation Risk Is High 23
3.5 Climate Change Is an Overarching Stressor 24
3.6 Cumulative Effects Must Be Understood at a Regional Scale 25
3.7 There Is a Need for Adaptive Management 26
3.8 Policy Gaps 27
3.9 Governance Gap and the Need for Shared Authority 28
3.10 Data Fragmentation and Accessibility 29
3.11 Species-level Observations 30
3.12 Ecological Thresholds 32
3.13 Social Impacts 33
3.14 Recent Advances in Monitoring Technology 34
3.15 Mitigation Measures 35
4 Comparison of Literature Scan and Interview Results 37
5 Nested Watershed Studies as a Tool for Cumulative Effects Assessment 40
5.1 The Value of Nested Watershed Studies in Impact Assessment 40
5.2 Examples of Nested Watershed Studies Elsewhere 42
Mackenzie Valley/Mackenzie River Basin (Canada) 42
Alberta Oil Sands Region 42
European Water Framework Directive and Implications for Assessment of Mining Projects 43
5.3 Implications for Regions Like the Ring of Fire 44
6 Comparison with Recommendations in Earlier Reports 45
6.1 Alignment of Core Conclusions 45
6.2 Alignment of Reported Environmental Trends 46
6.3 Implementation Status of 2010 Far North Science Advisory Panel Recommendations 50
7 Recommendations 56
7.1 Scope and Scale of Impact Assessment 56

Recommendation 1: Adopt a nested, watershed-based impact assessment framework. 56
Recommendation 2: Treat roads as regional infrastructure, not standalone projects. 57
7.2 Science and Monitoring Priorities 57
Recommendation 3: Make hydrology the monitoring core. 57
Recommendation 4: Implement a peatland carbon and methane monitoring strategy. 57
Recommendation 5: Adopt a precautionary mercury framework. 58
Recommendation 6: Strengthen lake sturgeon and caribou monitoring. 58
7.3 Governance and Decision Architecture 58
Recommendation 7: Establish a co-governed science and monitoring table. 58
Recommendation 8: Design and embed an adaptive management process and governance structure. 59
7.4 Data and Transparency Actions 59
Recommendation 9: Audit, recover, and centralize publicly funded datasets 59
Recommendation 10: Use modern remote sensing (LiDAR, SAR, high-resolution imagery), including drone technology, to refine peatland, wetland, and habitat classification 60
7.5 Policy and Precaution 60
Recommendation 11: Consider development of formal peatland protection and cumulative effects policies. 60
Recommendation 12: Require that climate change be integrated into all infrastructure design. 61
Recommendation 13: Formally adopt a precautionary hierarchy in effects assessment and mitigation. 61
7.6 Capacity and Community Engagement 61
Recommendation 14: Build community-based monitoring capacity. 61
Appendix A: 63
Potential Strategic Research Priorities 63
A1 Potential Strategic Research Priorities 64
Priority 1: Regional Hydrologic–Infrastructure Modelling 64
Priority 2: Peatland Carbon and Methane Observatory Network 64
Priority 3: Mercury Baseline and Trigger Framework 64
Priority 4: Cumulative Connectivity Modelling 65

Priority 5: Climate–Development Scenario Integration 65
Priority 6: Identification and Quantification of Ecological Limits 65
Priority 7: Integrated Open Data Platform 65
Priority 8: Conservation Network Optimization 66
Priority 9: Infrastructure Design Experiments 66
Priority 10: Co-Developed Ecological Limits and Disturbance Caps 66
Appendix B: 67
Three Example Nested Watershed Study Designs 67
B1 Option 1: Large-Scale Nested Watershed Study with Remote Sensing, Acoustic Monitoring and eDNA 68
B.1.1 Recommendations for nested structure (tiers) 68
Tier A - “Process” Micro-Catchments (0.1–10 km^2) 68
Tier B - “Response” Meso-Catchments (10–500 km^2) 69
Tier C - “Cumulative” Major Basins (500–20,000+ km^2) 69
B.1.2 Study design logic: gradients and before-after-control-impact 69
B.1.3 Recommended minimal core monitoring suite and optional modules 70
Core Monitoring Suite (Do Everywhere at Tier B/C; Intensively at Tier A) 70
Optional Monitoring Modules (Deploy Where Relevant) 70
Site Selection Criteria 71
B.1.4 Governance and shared authority 71
Decision-Relevant Outputs 71
An Example Three- to Five-Year Rollout 71
B2 Option 2: Lower-Cost Version 72
Approximate Scale (Order of Magnitude) 72
Study Components 72
B3 Option 3: High-Innovation Flagship Research Proposal 73
B.3.1 Core Innovation Themes 73
Molecular Biosensing of Watersheds 73
AI-Driven Remote Sensing Integration 73
Carbon–Hydrology–Connectivity Coupling 73
Indigenous Co-Governance of Environmental Intelligence 73
B.3.2 Flagship Technical Additions 73
B.3.3 Potential Research Questions 74

B.3.4 Outputs 74
B4 Integration of New and Emerging Monitoring Technologies 77
B.4.1 Remote Sensing 77
Hydrology and Connectivity 77
Vegetation and Peatland Condition 77
Surface Disturbance Detection 78
Thermal Imaging (satellite or drone) 78
B.4.2 eDNA (Low-Disturbance Biodiversity Monitoring) 78
Fish and Aquatic Community Baselines 78
Benthic and Microbial Community Signals 78
B.4.3 Acoustic Monitoring 79
Ecoacoustic Biodiversity Monitoring 79
Aquatic Acoustic Monitoring 79
B.4.4 Continuous In-Situ Sensor Arrays 79
Core Sensors 79
Advanced Options 79
B.4.5 Greenhouse Gas and Carbon Monitoring Technologies 80
Eddy Covariance Towers (install at 1–2 flagship sites) 80
Chamber-Based Automated Systems 80
Drone-Based Methane Detection (emerging) 80
B.4.6 Hydrologic Monitoring Innovations 80
Distributed Temperature Sensing (Fibre Optic) 80
Low-Cost “Internet of Things” [IoT] Sensor Networks 80
B.4.7 Sediment and Geochemistry Tools 81
Turbidity-to-Load Modelling 81
Stable Isotopes 81
B.4.8 Data Integration Strategy 81

1 Introduction

The Regional Assessment (RA) for the Ring of Fire area is a federal assessment process led by 15 First Nations and the Impact Assessment Agency of Canada (IAAC) under the Canadian federal *Impact Assessment Act*, 2019 (IAA). It was initiated in recognition that multiple, interrelated development proposals, particularly mining and associated linear infrastructure, are being contemplated within a large, ecologically sensitive, and culturally significant region of northern Ontario. The assessment is intended to address issues that cannot be adequately considered through project-by-project impact assessments alone.

1.1 Purpose and Objectives

The primary purpose of the RA is to improve understanding of the environmental, health, social, and economic effects of past, existing, and potential future development in the Ring of Fire area. It seeks to:

- Establish a **shared baseline** of regional conditions;
- Identify **key pathways of cumulative effects**, risks, and uncertainties;
- Assess how development scenarios could affect **valued components** such as water, peatlands, wildlife and wildlife habitat, fish and fish habitat, species at risk, climate change interactions, and Indigenous well-being; and
- Provide **strategic information, guidance, and recommendations** to inform future decision-making processes.

The RA does not approve or reject projects, nor does it replace individual project assessments. Instead, it is intended to provide a regional context and evidence base to support more consistent, efficient, and defensible future decisions. The scope includes both biophysical and human environment components, with particular emphasis on peatland-dominated ecosystems of the Hudson and James Bay Lowlands, large river systems, and regional connectivity.

1.2 Regional Assessment Governance and Participation

The RA is co-led by the First Nation Partners and Impact Assessment Agency of Canada (IAAC) working together as a Working Group (the Regional Assessment Working Group, or RAWG), with support from a roster of experts who provide independent scientific and technical advice. Federal departments (e.g., Environment and Climate Change Canada, Natural Resources Canada, Fisheries and Oceans Canada), the Province of Ontario, Indigenous governments and organizations, and other knowledge holders contribute data, analyses, and perspectives to the Regional Assessment process.

Indigenous participation and knowledge are integral to the process. The RA is designed to respect Indigenous rights, incorporate Indigenous Knowledge alongside Western science, and reflect the interests and priorities of First Nations whose territories overlap the assessment area. Fifteen First Nations co-lead the RA. They are: Aroland First Nation, Attawapiskat First Nation, Constance Lake First Nation, Eabametoong First Nation, Fort Albany First Nation, Ginoogaming First Nation, Kashechewan First Nation, Long Lake #58 First Nation, Marten Falls First Nation, Missanabie Cree First Nation, Moose Cree First Nation, Neskantaga First Nation, Nibinamik First Nation, Webequie First Nation, and Weenusk First Nation.

1.3 This Project

The Impact Assessment Agency of Canada (IAAC) retained Wyndham Research Inc. to assist with updating Western science and knowledge on topics relevant to the Ring of Fire (RoF) area. The 2010 report *Science for a Changing Far North* (the report of the Ontario Far North Science Advisory Panel; available at https://www.arcgis.com/home/item.html?id=c82bc90a6f25498ab5581ea8d01f18ed) provides a baseline against which current knowledge can be compared. The current project seeks to document areas where knowledge has changed or remained constant since 2010, identify known or suspected gaps, and provide recommendations to inform IAAC's Regional Assessment activities outside Traditional Knowledge led by the RA First Nation Partners.

The work will be conducted in three main stages:

- Review of background materials (literature scan)
- Key informant interviews
- Final report and recommendations

1.4 This Report

As noted above, this project uses *Science for a Changing Far North* as the baseline for determining where and how Western science and knowledge about the Ring of Fire region may have changed since 2010. This report constitutes the third and final stage of the work. It summarizes information obtained from a scan of scholarly and technical literature published since 2010 and interviews with 17 key informants from a wide range of backgrounds.

Section 2 summarizes the main findings of the literature scan; Section 3 provides an overview of interview results; and Sections 4-6 compare these findings with those of previous reports, including *Science for a Changing Far North*. Section 7 presents recommendations for next steps, organized under six categories:

- Scope and scale of impact assessment
- Science and monitoring
- Governance and decision architecture
- Data and transparency actions

- Policy and precaution
- Capacity and community engagement

In this report, the term “Ring of Fire” (or “RoF”) refers to the mineral deposits area. The term “Assessment Area” refers to the designated assessment area for the RA as specified in the Terms of Reference; see Figure 1.

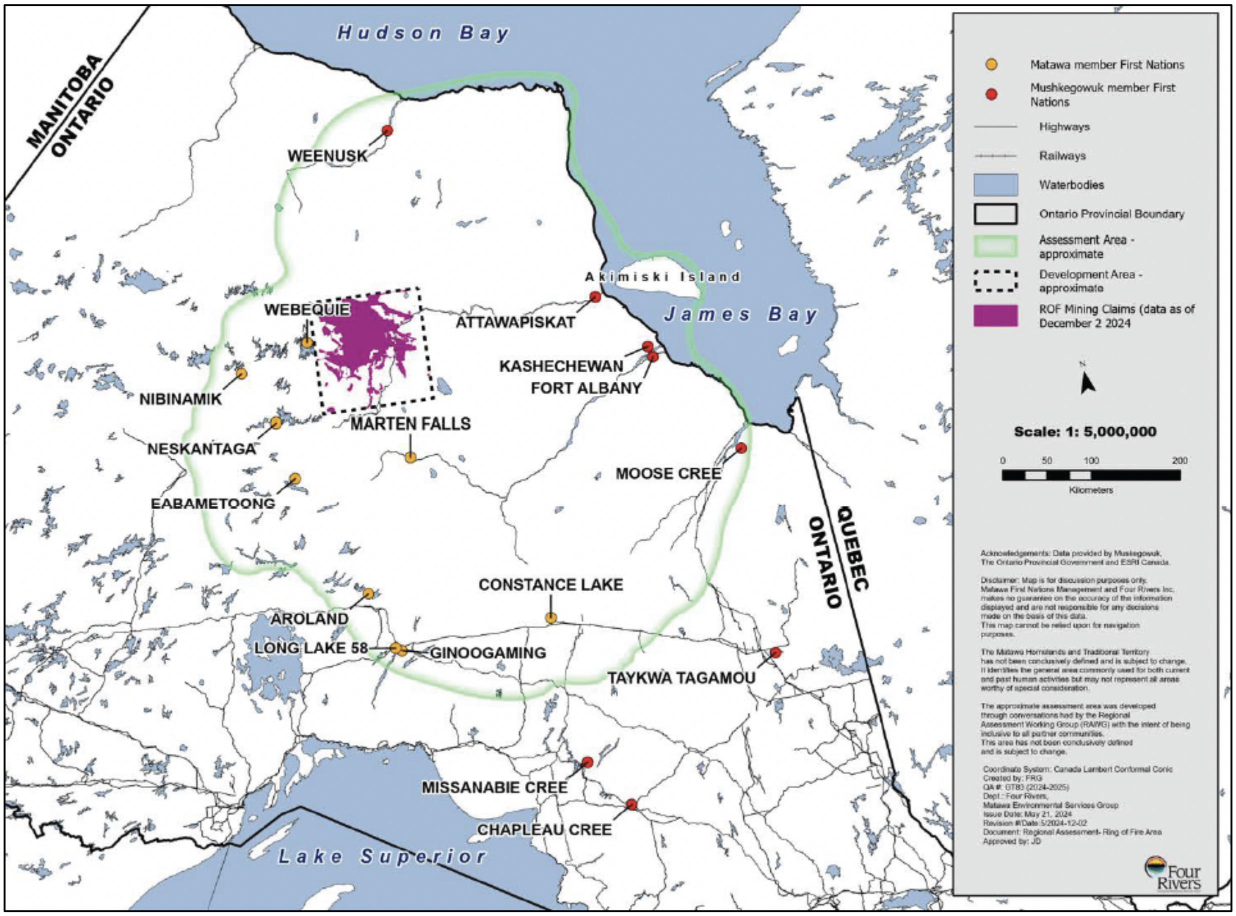

Figure 1. Assessment area for the Regional Assessment in the Ring of Fire Area. Source: https://iaac-aeic.gc.ca/050/documents/p80468/158865E.pdf.

Disclaimer: *This report is not intended to be a comprehensive review of the scholarly and technical literature or expert views on Western science relevant to the Ring of Fire. Rather, it provides a preliminary, high-level review of key topics and questions and is intended to guide further discussion by the Regional Assessment Working Group.*

The opinions and recommendations contained in this report reflect the views and perspectives of the author.

2 Overview of the Literature Scan

The complete literature scan has been provided to the RAWG as a separate appendix. The following sections include examples of relevant literature drawn from that scan, either as footnotes or as embedded hyperlinks.

2.1 Regulatory and Policy Context

The literature scan reveals the evolution of governance for the Ring of Fire (RoF) from fragmented oversight through the enactment of the Ontario *Far North Act, 2010*. More recently, there has been a shift to centralized, streamlined permitting, including the *Protect Ontario by Unleashing Our Economy Act* (Bill 5) and the new "One Project, One Process" permitting model, which mark a shift toward expedited development. The 2021 UN Declaration on the Rights of Indigenous Peoples (UNDRIP) is also an important change since 2010 and now influences how project reviews and Indigenous rights are operationalized across Canada, including in the RoF. Other recent advances through this time were the initiation of the federal Regional Assessment (RA) and enhanced federal-provincial cooperation arrangements.

2.2 Governance Challenges, Opportunities, and Models

The core governance challenge for the RoF is that the region sits at the intersection of provincial resource authority, federal environmental jurisdiction, and constitutionally protected Indigenous rights. No single institution has ever had clear, overarching authority for regional planning. Over the years, this has led to confusion about who leads planning, resulting in project-by-project decisions without a shared regional vision. The literature scan emphasized the key point that regional planning is essential: project-by-project governance consistently fails in ecologically complex regions like the Assessment Area[1].

These challenges have prompted considerable creative and collaborative thinking about potential governance models, including Indigenous-led and co-led governance, as is currently reflected in co-leadership of the federal RA. This shift is significant because it moves governance from managing impacts to collaborative shaping of development pathways, creating space for Indigenous law, knowledge and priorities to influence regional outcomes. The recent literature supports the conclusion that

---

[1] See for example Atlin, C. and Gibson, R., 2017. Lasting regional gains from non-renewable resource extraction: The role of sustainability-based cumulative effects assessment and regional planning for mining development in Canada. *The Extractive Industries and Society*, *4*(1), pp.36-52; Che, T.Q. and Hickey, G.M., 2021. Assessing the potential for collaborative governance to support cumulative effects assessment in the Indigenous Cree territory of Eeyou Istchee, Canada. *Journal of environmental management*, *298*, p.113444; and Chetkiewicz, C. and Lintner, A., 2014. Getting it right in Ontario's Far North-the need for a regional strategic environmental assessment in the ring of fire (wawangajing). Wildlife Conservation Society Canada and EcoJustice Canada. Available at https://ecojustice.ca/wp-content/uploads/2022/12/Getting-it-Right-in-Ontarios-Far-North.pdf

effective governance in large, infrastructure-dependent regions like the Ring of Fire requires regional-scale assessment and planning institutions co-developed with, and exercising shared authority alongside, Indigenous peoples, and that cumulative effects assessment and management frameworks must be both scientifically and culturally credible[2].

2.3 Geology, Soils, and Geomorphology

The literature scan demonstrated that current geological mapping of mineralization is significantly improved since 2010. Peatlands dominate surface conditions, with organic soils meters thick in some areas. Permafrost is discontinuous and embedded within peatland systems, but those systems are already changing in response to climate warming[3]. Hydrology is a dominant driver in this region. Hydrologic alteration, not footprint size, determines the scale of impact: small footprint does not mean small effect in peatlands[4]. Relief is low and flowpaths are diffuse through most of the Assessment Area region, so linear corridors such as roads and embankments are the main geomorphic/hydrologic stressors[5]. The implication is that corridor design must be treated as watershed engineering, not just transportation engineering. Recent research also demonstrated that dewatering and groundwater drawdown can cause subsidence and lasting hydrophysical change, with implications for RoF mine water management. High-resolution soil and permafrost data remain limited for this area; updated data may be necessary for infrastructure risk modelling.

---

[2] See for example Antwi, E.K., Boakye-Danquah, J., Nadon, D.D.M., Kistabish, M.J., Matthews, T., Darko, A.N., Yohuno, P.T. and Egunyu, F., 2025. Socioeconomic framework and indicators for assessing cumulative effects of resource development on indigenous nations. *The Extractive Industries and Society*, *24*, p.101735 and Muir, B.R., 2022. Consequences and implications of British Columbia's failed cumulative effects assessment and management framework for indigenous peoples. *Environmental Impact Assessment Review*, *95*, p.106764.

[3] See for example Muir, G., Brown, G.S., Balasubramaniam, K. and Hu, B., 2025. Active layer thermal regime varies across landforms in a subarctic wetland. *FACETS*, *10*, pp.1-14; and Harris, L.I., Olefeldt, D., Pelletier, N., Blodau, C., Knorr, K.H., Talbot, J., Heffernan, L. and Turetsky, M., 2023. Permafrost thaw causes large carbon loss in boreal peatlands while changes to peat quality are limited. *Global Change Biology*, 29(19), pp.5720-5735.

[4] See for example Balliston, N.E., McCarter, C.P.R. and Price, J.S. 2018. Microtopographical and hydrophysical controls on subsurface flow and solute transport: A continuous solute release experiment in a subarctic bog. *Hydrological Processes*, 32(19): 2963-2975; and Albert-Saiz, M., Lamentowicz, M., Rastogi, A. and Juszczak, R., 2025. Unveiling water table tipping points in peatland ecosystems: Implications for ecological restoration. Catena, 257, p.109149.

[5] See for example Dabros, A., Antwi, E. K., Waldron, C., Darko, A. N., and Higgins, K. L. 2025. Risk assessment of potential impact of mining development (linear infrastructure) on peatland ecosystems in the Ring of Fire region, Northern Ontario. Frontiers in Environmental Science, 13, 1676633. https://doi.org/10.3389/fenvs.2025.1676633; and Balliston, N.E. and Price, J.S., 2023. Aquifer depressurization and water table lowering induces landscape scale subsidence and hydrophysical change in peatlands of the Hudson Bay Lowlands. Science of the Total Environment, 855, p.158837.

2.4 Carbon and Methane Flux

The literature scan revealed that carbon and methane fluxes in the Assessment Area are governed mainly by hydrologic change. Intact peatlands in the Assessment Area are long-term net CO_2 sinks. Across the broader region, the Hudson Bay Lowlands are estimated to store ~30 Pg of carbon, with methane emissions being highly water table-dependent[6]. Those processes are not uniform across the region, for example, fen vs. bog carbon balance responses differ under climate warming[7]. Data on these processes are limited, with few direct flux measurements available within the RoF footprint. Carbon vulnerability under warming is, however, increasingly well-modeled.

2.5 Peatlands and Permafrost

Peatlands are now understood as hydrologically connected landscape systems[8]. Permafrost in the Assessment Area is discontinuous and linked to peat plateaus and has been observed to decline over recent decades. Since 2010, there have been significant advances in quantification of peat thickness and carbon storage at regional scales. Another key advance is improved understanding of where permafrost thaw will most strongly reorganize land cover and hydrologic connectivity. There is also now better evidence on the potential impact of industrial disturbance on peatland water tables and functions, and how climate warming will deepen thaw and alter hydrology[9].

---

[6] See for example Packalen, M.S., Finkelstein, S.A. and McLaughlin, J.W., 2014. Carbon storage and potential methane production in the Hudson Bay Lowlands since mid-Holocene peat initiation. *Nature communications*, 5(1), p.4078.

[7] See for example Balogun, O., Bello, R. and Higuchi, K., 2024. Long-term response of peatland carbon exchange to climatic changes in the Hudson Bay Lowlands. *Journal of Geophysical Research: Biogeosciences*, 129(5), p.e2023JG007873; and Helbig, M., Humphreys, E.R. and Todd, A., 2019. Contrasting temperature sensitivity of CO_2 exchange in peatlands of the Hudson Bay Lowlands, Canada. *Journal of Geophysical Research: Biogeosciences*, 124(7), pp.2126-2143.

[8] See for example Dabros, A., Antwi, E. K., Waldron, C., Darko, A. N., and Higgins, K. L. 2025. Risk assessment of potential impact of mining development (linear infrastructure) on peatland ecosystems in the Ring of Fire region, Northern Ontario. Frontiers in Environmental Science, 13, 1676633. https://doi.org/10.3389/fenvs.2025.1676633; Li, Y., Han, D., Rogers, C.A., Finkelstein, S.A., Hararuk, O., Waddington, J.M., Barreto, C., McLaughlin, J.W., Snider, J. and Gonsamo, A., 2025. Peat depth and carbon storage of the Hudson Bay Lowlands, Canada. *Geophysical Research Letters*, 52(2), p.e2024GL110679; and Ou, C., LaRocque, A., Leblon, B., Zhang, Y., Webster, K. and McLaughlin, J., 2016. Modelling and mapping permafrost at high spatial resolution using Landsat and Radarsat-2 images in Northern Ontario, Canada: Part 2-regional mapping. *International Journal of Remote Sensing*, 37(12), pp.2751-2779.

[9] See for example Dabros, A., Antwi, E. K., Waldron, C., Darko, A. N., and Higgins, K. L. 2025. Risk assessment of potential impact of mining development (linear infrastructure) on peatland ecosystems in the Ring of Fire region, Northern Ontario. Frontiers in Environmental Science, 13, 1676633. https://doi.org/10.3389/fenvs.2025.1676633; and Harris, L.I., Richardson, K., Bona, K.A., Davidson, S.J., Finkelstein, S.A., Garneau, M., McLaughlin, J., Nwaishi, F., Olefeldt, D., Packalen, M., Roulet, N.T., Southee, M., Strack, M., Webster, K., Wilkinson, S. and Ray, J. 2022. The essential carbon service provided by northern peatlands. *Frontiers in Ecology and the Environment*, 20(4), pp.222-230.

High-resolution, permafrost distribution mapping is still limited for the Assessment Area, making it difficult to quantify how planned infrastructure could intersect permafrost-sensitive terrain. The mechanisms of water table and flow-path alteration are well understood, but the likely cumulative, landscape-scale impact of multiple linear features and potential dewatering sources across RoF planning scenarios is still unclear. Peatlands and permafrost systems are known to shift abruptly under certain conditions, for instance from plateau to collapsed wetlands/ponded mosaic, but site-specific thresholds are not yet well understood for the Assessment Area[10]. These gaps constrain the ability to predict cumulative effects or to distinguish climate-driven trends from development-related change.

2.6 Air Quality

The literature scan revealed very few Assessment Area-specific air quality studies and baseline air quality in the region is poorly characterized. Anticipated concerns include development-related dust and diesel emissions, and wildfire smoke. Monitoring frameworks would likely need expansion if development proceeds. An important advance since 2010 is the development of reliable air quality monitoring approaches using battery and solar/wind powered shelters and field-ready samplers suitable for sub-zero conditions and infrequent servicing[11]. Long-range transport is known to dominate many metals in background atmospheric deposition, with mercury the clearest example[12]. Key knowledge gaps include spatial representativeness and effects propagation across the region, and winter and shoulder season air quality. Dust and air emissions could affect sensitive receptors, including Indigenous Peoples via exposure pathways, but the evidence base for exposure/pathway quantification remains limited without long time series and multi-media monitoring. Robust cumulative effects assessment methodologies for air quality in the Assessment Area are still in their infancy.

2.7 Hydrology

The literature scan confirmed that hydrology is the central organizing variable within the Assessment Area, where ultra-low-relief terrain makes systems highly sensitive to

---

[10]See for example Albert-Saiz, M., Lamentowicz, M., Rastogi, A. and Juszczak, R., 2025. Unveiling water table tipping points in peatland ecosystems: Implications for ecological restoration. Catena, 257, p.109149.

[11]See for example Su, Y., Sofowote, U., Munoz, A., Noble, M., Charron, C., Todd, A., Celo, V., Dabek-Zlotorzynska, E., Kryukova, A. and Switzer, T., 2021. Baseline air monitoring of fine particulate matter and trace elements in Ontario’s Far North, Canada. Applied Sciences, 11(13), p.6140.

[12] See for example McDonough, A.M., Bird, A.W., Luciani, M.A. and Todd, A.K., 2022. Establishing trace element concentrations for lichens and bryophytes in the ring of fire region of the Hudson Bay Lowlands, Ontario, Canada. Environmental Monitoring and Assessment, 194(3), p.226; and Brazeau, M.L., Poulain, A.J., Paterson, A.M., Keller, W.B., Sanei, H. and Blais, J.M., 2013. Recent changes in mercury deposition and primary productivity inferred from sediments of lakes from the Hudson Bay Lowlands, Ontario, Canada. Environmental Pollution, 173, pp.52-60.

disturbance[13]. Water table elevation is the master control on peatland hydrology and many downstream effects. Hydrology in this region is strongly seasonal; however, continuous winter observations remain limited relative to what is needed to assess fish habitat, ice-jamming, and winter water balance in peat-dominated catchments. The literature scan demonstrated that roads can behave as dams/drains across peat landscapes, and that dewatering impacts are likely to extend well beyond mine footprints[14]. There is good empirical evidence that certain disturbances can trigger long-lived changes (subsidence, altered conductivity, altered flowpaths), but precise thresholds are not reliably transferable across peatland types without local calibration. Regional wetness patterns and surface water persistence are now quantifiable with long satellite time series, but dense hydrology field networks for the Assessment Area are sparse and long-term hydrometric datasets are limited. Cumulative watershed-scale modelling remains underdeveloped. Recent findings demonstrate that aquitard properties can control hydrologic impact and magnitude, but aquitard maps at decision scale are often incomplete[15].

2.8 Water Quality

The literature scan demonstrated that baseline water quality data are limited and fragmented, especially winter/shoulder season water quality under ice and in breakup pulses. Metals speciation and bioavailability are not well mapped within the Assessment Area. Research since 2010 has shown that local processes (geology, wetlands, vegetation cover) strongly influence lake water chemistry in the region, indicating that water quality is tied to terrain and hydrological context more than simply distance from the Shield to the lowlands[16]. Peatlands influence dissolved organic

[13] See for example Kline, M., 2014. *Peatland-Stream Hydrological and Biogeochemical Connectivity in the James Bay Lowland, Ontario*. Unpublished MSc thesis, The University of Western Ontario (Canada); and Dabros, A., Antwi, E. K., Waldron, C., Darko, A. N., and Higgins, K. L. 2025. Risk assessment of potential impact of mining development (linear infrastructure) on peatland ecosystems in the Ring of Fire region, Northern Ontario. Frontiers in Environmental Science, 13, 1676633. https://doi.org/10.3389/fenvs.2025.1676633.

[14] See for example Kettridge, N., Turetsky, M.R., Sherwood, J.H., Thompson, D.K., Miller, C.A., Benscoter, B.W., Flannigan, M.D., Wotton, B.M. and Waddington, J.M., 2015. Moderate drop in water table increases peatland vulnerability to post-fire regime shift. Scientific reports, 5(1), p.8063; and Balliston, N. E. and Price, J. S. 2023. Aquifer depressurization and water table lowering induces landscape scale subsidence and hydrophysical change in peatlands of the Hudson Bay Lowlands. *Science of the Total Environment, 855*, 158837. https://doi.org/10.1016/j.scitotenv.2022.158837

[15] See for example Kompanizare, M., and Price, J.S., 2014. Analytical solution for enhanced recharge around a bedrock exposure caused by deep-aquifer dewatering through a variable thickness aquitard. *Advances in Water Resources*. 74, 102-115; and Balliston, N., Sutton, O. and Price, J., 2024. Solute depletion and reduced hydrological connectivity in subarctic patterned peatlands disturbed by mine dewatering. *Science of The Total Environment*, *913*, p.169442.

[16] See for example Ulanowski, T.A. and Branfireun, B.A., 2013. Small-scale variability in peatland pore-water biogeochemistry, Hudson Bay Lowland, Canada. *Science of the Total Environment*, 454, pp.211-218.

carbon (DOC), acidity, and nutrient dynamics[17]. Recent studies demonstrate that altered water movement caused by mining dewatering can change solute pathways and water chemistry, with implications for downstream aquatic ecosystems[18]. Paleolimnological studies reveal changes in plankton communities linked to climate warming, which correspond with shifts in water quality and ecological status over time; this work helps to establish long-term reference conditions for water quality in the region[19]. However, separating climate-driven hydrologic change, multiple corridors and crossings, exploration pads/aggregate sources, and future mine water management into distinct water quality signals is still challenging without coordinated regional monitoring and shared baselines across proponents.

2.9 Mercury

The Assessment Area exhibits high sensitivity to methylmercury production in flooded/impounded systems, and there is clear evidence that sulphate loadings, in some cases driven by hydrologic fluctuations, can increase methylation[20]. Fish consumption risks are a concern, especially for local communities that rely on traditional foods. While there is now improved empirical characterization of percent methylmercury in fish muscle by species, size, and age (which directly affects how risk is interpreted from common "total Hg" measurements), baseline mercury data are incomplete and may be out of date[21]. There have also been advances in understanding

[17] See for example Preston, M.D., Smemo, K.A., McLaughlin, J.W. and Basiliko, N., 2012. Peatland microbial communities and decomposition processes in the James Bay Lowlands, Canada. *Frontiers in microbiology*, *3*, p.70.

[18] See for example Balliston, N.E. and Price, J.S., 2023. Aquifer depressurization and water table lowering induces landscape scale subsidence and hydrophysical change in peatlands of the Hudson Bay Lowlands. *Science of the Total Environment*, *855*, p.158837.

[19] See for example Jeziorski, A., Keller, B., Dyer, R.D., Paterson, A.M. and Smol, J.P., 2015. Differences among modern-day and historical cladoceran communities from the "Ring of Fire" lake region of northern Ontario: identifying responses to climate warming. *Fundam Appl Limnol*, *186*, pp.203-216.

[20] See for example Coleman Wasik, J.K., Engstrom, D.R., Mitchell, C.P., Swain, E.B., Monson, B.A., Balogh, S.J., Jeremiason, J.D., Branfireun, B.A., Kolka, R.K. and Almendinger, J.E., 2015. The effects of hydrologic fluctuation and sulfate regeneration on mercury cycling in an experimental peatland. *Journal of Geophysical Research: Biogeosciences*, *120*(9), pp.1697-1715; and Kirkwood, A.H., Roy-Léveillée, P., Branfireun, B.A. and Basiliko, N., 2021, October. Mercury, Methylmercury, and Microbial Communities in a Degrading Palsa of the Hudson Bay Lowlands, Far North Ontario. In Regional Conference on Permafrost 2021 and the 19th International Conference on Cold Regions Engineering (pp. 49-59). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784483589.005

[21] See for example Lescord, G. L., Johnston, T. A., Branfireun, B. A., and Gunn, J. M. 2019. Mercury bioaccumulation in relation to changing physicochemical and ecological factors across a large and undisturbed boreal watershed. Canadian Journal of Fisheries and Aquatic Sciences, 76(12), 2165-2175. https://doi.org/10.1139/cjfas-2018-0465; and Lescord, G.L., Johnston, T.A., Branfireun, B.A. and Gunn, J.M., 2018. Percentage of methylmercury in the muscle tissue of freshwater fish varies with body size and age and among species. Environmental Toxicology and Chemistry, 37(10), pp.2682-2691. https://doi.org/10.1002/etc.4233

the processes that drive mercury bioaccumulation across many sites (including permafrost thaw peatlands) in a large, relatively undisturbed boreal watershed[22]. This improves the evidence base for how physical, chemical, and ecological gradients co-structure mercury patterns and holds promise for predicting how hydrologic change in the Assessment Area could affect mercury outcomes. Peatland and permafrost controls on mercury methylation, however, remain poorly understood; links between hydrologic alteration and mercury response pathways are also unclear. There is no Assessment Area-specific guidance on acceptable mercury change relative to baseline or early-warning indicators (e.g., sulphate, dissolved organic matter, water concentrations of methyl mercury), or decision triggers for mitigation or design modification.

2.10 Terrestrial Ecosystems

The literature scan confirmed that the Assessment Area is a peatland-dominated system where ecology is tightly coupled to hydrology. Forest–peatland ecotones are sensitive to climate and disturbance, and hydrology and fire regimes influence vegetation structure. Productivity patterns vary across peatland types[23]. Assessment Area core field data density is still low for many taxa and ecosystem processes and the magnitude and spatial extent of functional fragmentation from new access are not well understood. Winter and shoulder-season ecology (movement, energetics, habitat use) is poorly described. Peatland restoration/recovery effectiveness at Assessment Area scales is poorly proven and disturbance–climate interactions remain uncertain[24].

2.11 Natural Disturbance Processes Including Fire

Much of the literature on natural disturbance processes in the Assessment Area focuses on wildfire. A major advance since 2010 is that fire regimes are being re-characterized with better national data and clearer trends, making it possible to quantify trends in area burned, fire occurrence, seasonality, and related regime descriptors over multi-decadal periods, with eco-zone level reporting. New insights reveal that fire regimes are shifting under climate warming and fire-peat-carbon feedbacks are increasingly well understood[25]. Fire risk is now integrated into broader

---

[22] See for example Martins, B.M., Hintelmann, H., Pilote, M., Cesário, R., Gambardella, N., Costa, J., Magalhães, C. and Canário, J., 2025. Seasonal patterns of mercury dynamics in thermokarst lakes from sporadic permafrost. *Environmental Pollution*, p.127030.

[23] See for example Wang, Q., 2022. Examining Large-scale Peatland Patterns in the Hudson Bay Lowland. Unpublished MSc thesis, McGill University (Canada).

[24] See for example Nelson, T.A., Coops, N.C., Wulder, M.A., Perez, L., Fitterer, J., Powers, R. and Fontana, F., 2014. Predicting climate change impacts to the Canadian boreal forest. *Diversity*, *6*(1), pp.133-157.

[25] See for example McLaughlin, J. and Webster, K., 2014. Effects of climate change on peatlands in the far north of Ontario, Canada: A synthesis. *Arctic, Antarctic, and Alpine Research*, 46(1), pp.84-102; and Coogan, S.C., Robinne, F.N., Jain, P. and Flannigan, M.D., 2019. Scientists' warning on wildfire—a Canadian perspective. *Canadian Journal of Forest Research*, 49(9), pp.1015-1023.

"disturbance and carbon" accounting for peatlands. More generally, disturbance is increasingly treated as compound and interactive: multiple disturbances can occur sequentially, and human access/infrastructure can change ignition patterns and suppression realities. Paleo-fire records help estimate carbon vulnerability, but future fire frequency/severity projections remain uncertain[26].

2.12 Biological Diversity

Before 2010, the Assessment Area was often characterized as biologically "simple" boreal terrain. More recently, it has been reframed as part of a globally significant intact ecosystem with high functional and compositional importance. Research since 2010 has emphasized landscape integrity, connectivity, and intactness as biodiversity attributes in their own right, rather than characterizing biodiversity simply as species counts. Fine-scale ecological differentiation is now central to understanding biodiversity in the Assessment Area. Current research recognizes that small hydrological changes (e.g., from roads or altered drainage) can cause disproportionately large biodiversity shifts, even where total disturbed area is small[27]. Understanding of wildlife use of the Assessment Area has also improved since 2010. Despite these advances, species-level inventories, especially for invertebrates, microorganisms, and fish, remain sparse within the RoF footprint, and there is little or no long-term population trend data. Biodiversity responses to combined climate and development scenarios remain uncertain. Cumulative habitat fragmentation risks are poorly quantified.

2.13 Mammals

The literature scan revealed that mammal biodiversity is now understood as landscape-dependent, not site-dependent. There is now stronger evidence that the Assessment Area functions as movement and security habitat for wide-ranging mammals rather than as a core population centre. Recent research reflects a shift toward understanding connectivity, access density, and disturbance regime as primary predictors of mammal persistence[28], and recognition that low apparent mammal density does not imply low

---

[26] See for example Davies, M.A., McLaughlin, J.W., Packalen, M.S. and Finkelstein, S.A., 2023. Using Holocene paleo-fire records to estimate carbon stock vulnerabilities in Hudson Bay Lowlands peatlands, *Facets* (Ott), 8, 1-26; and Da Silva, K.A., Snyder, R.A., Packalen, M.S., McLaughlin, J.W., Peteet, D.M. and Finkelstein, S.A., 2022. Mineral inputs, paleoecological change, and Holocene carbon accumulation at a boreal peatland in the Hudson Bay Lowlands, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *596*, p.110996.

[27] See for example Bao, W., Zeng, X., Luo, C., Zhang, H., Qu, Y. and Xu, N., 2022. The relationship between hydrological connectivity changes inside and outside biodiversity hotspots and its implication for sustainable environmental management. *Sustainability*, *14*(11), p.6654; and Wilkie, C., Law, A., Thackeray, S.J., Ward, C., August, T., Baker, A., Belmont, J., Carvalho, L., Chapman, D., Dobel, A. and Miller, C., 2025. Landscape-Scale Responses of Freshwater Biodiversity to Connectivity and Stressors. *Global Ecology and Biogeography*, *34*(6), p.e70069.

[28] See for example McFarlane, S., Van Mierlo, V., Manseau, M., Kroeze, A., Eberhardt, E. and Girard, J., 2025. Bioclimatic, terrain, and specific peatland composition are major drivers of woodland caribou

ecological importance. Woodland caribou are a central concern, and the potential for increased predator access through linear infrastructure like roads is seen as a major risk[29]. Movement ecology is incompletely understood. There is now more explicit understanding that faunal indicators are linked to forest structure, especially for species like woodland caribou. These studies highlight connections between forest condition, habitat structure, and species persistence and provide a functional ecological context for forest-landscape conservation and management. Updated telemetry data and systematic mammal inventories within the RoF footprint are limited and long-term population trend data are largely absent. Empirical data on post-disturbance recovery in peatland systems are sparse.

2.14 Birds

A key advance since 2010 is recognition that the Hudson Bay Lowlands support continental migratory networks, so the Assessment Area must be reframed as part of a continental bird system, not a local hotspot[30]. Peatlands are critical breeding habitat for birds, and research since 2010 has improved understanding of peatland-specialist and wetland-dependent species (e.g., shorebirds, waterfowl, songbirds) and how they use open peatlands. Seasonal use is now seen as central to avifauna assessment. Since 2010, knowledge of birds in the Assessment Area has improved mainly through integration of large datasets, not local surveys. Much of this work has been accomplished through expansion of citizen science and monitoring datasets (e.g., breeding bird inventories, migration observations) that now extend into parts of the Far North. Insights gained through this work are increasing, shifting the framing of potential impacts on avifauna as indirect and cumulative. Examples include evidence that linear infrastructure and access alter predator communities, nest success, and species composition and that disturbance can favour generalist or southern species, reducing

---

winter habitat suitability in northern Ontario. *Canadian Journal of Zoology*, 103, pp.1-18; and Fryxell, J.M., Avgar, T., Liu, B., Baker, J.A., Rodgers, A.R., Shuter, J., Thompson, I.D., Reid, D.E., Kittle, A.M., Mosser, A., Newmaster, S.G., Nudds, T.D, Street, G. M., Brown, G. S., and Patterson, B. 2020. Anthropogenic disturbance and population viability of woodland caribou in Ontario. *The Journal of Wildlife Management*, 84(4), pp.636-650.

[29] See for example Environment and Climate Change Canada. 2024. *Scientific Assessment of Federal and Provincial Frameworks for the Conservation of Boreal Caribou in Ontario*. Science Assessment Report. ECCC, Gatineau, QC; and Johnson, C.A., Sutherland, G.D., Neave, E., Leblond, M., Kirby, P., Superbie, C. and McLoughlin, P.D., 2020. Science to inform policy: linking population dynamics to habitat for a threatened species in Canada. *Journal of Applied Ecology*, 57(7), pp.1314-1327; and Benoit-Pépin, A., Feldman, M.J., Imbeau, L. and Valeria, O., 2024. Use of linear features by mammal predators and prey in managed boreal forests. *Forest Ecology and Management*, *561*, p.121911.

[30] See for example Lamb, J.S., Paton, P.W., Osenkowski, J.E., Badzinski, S.S., Berlin, A.M., Bowman, T., Dwyer, C., Fara, L.J., Gilliland, S.G., Kenow, K. and Lepage, C., 2020. Assessing year-round habitat use by migratory sea ducks in a multi-species context reveals seasonal variation in habitat selection and partitioning. *Ecography*, *43*(12), pp.1842-1858; and Environment and Climate Change Canada. 2013. Bird Conservation Strategy for Bird Conservation Region 7 in Ontario: Taiga Shield and Hudson Plains. August 2013. Available at https://nabci.net/wp-content/uploads/BCR-7-ON-FINAL-Aug-2013.pdf.

boreal integrity[31]. There is also recognition that edge effects can propagate far beyond cleared areas in open peatland systems[32]. Systematic breeding bird inventories within the RoF footprint remain sparse and quantitative data on nest success, productivity, and survival are largely absent. Species-specific thresholds of disturbance tolerance are poorly defined and avian response to infrastructure fragmentation remains uncertain.

2.15 Fish

Fish research since 2010 reflects a regional perspective in how fish populations are considered in the context of larger hydrologic and geologic systems. At the same time, recent research reflects a shift from treatment of fish habitat in the region as broadly homogeneous, toward analysis that emphasizes the importance of peatland hydrology, flow stability, and water chemistry in controlling fish distribution and productivity. This shift requires consideration of catchment-scale water balance and connectivity, including connections with hydrologic systems outside the region. Fish communities in the Assessment Area were historically assumed to be resilient because of low exploitation and low density. Post-2010 research reframes them as slow-recovering and disturbance-sensitive. There is now stronger evidence that DOC, nutrients, and naturally low pH are important factors in determining the structure of fish assemblages[33]. Changes in DOC and metal mobility can also influence fish populations via impacts on fish health and food webs. These findings suggest that even subtle water quality changes, even when water quality is "within guidelines," may still be biologically significant in peat-dominated systems. Lake sturgeon, a species at risk, are present within the large rivers and are a culturally important species. Connectivity disruptions

---

[31] See for example Environment and Climate Change Canada. 2013. Bird Conservation Strategy for Bird Conservation Region 7 in Ontario: Taiga Shield and Hudson Plains. August 2013. Available at https://nabci.net/wp-content/uploads/BCR-7-ON-FINAL-Aug-2013.pdf.

[32] See for example Kalukapuge, T., Leston, L.F., Martínez-Lanfranco, J.A. and Bayne, E., 2024. Response of boreal songbird communities to the width of linear features created by the energy sector in Alberta, Canada. *Avian Conservation and Ecology*, *19*(2).

[33] See for example Paterson, A. M., Keller, W., Rühland, K. M., Jones, F. C., & Winter, J. G. (2014). An exploratory survey of summer water chemistry and plankton communities in lakes near the Sutton River, Hudson Bay Lowlands, Ontario, Canada. Arctic, Antarctic, and Alpine Research, 46(1), 121–138; Rautio, M., Dufresne, F., Laurion, I., Bonilla, S., Vincent, W.F. and Christoffersen, K.S., 2011. Shallow freshwater ecosystems of the circumpolar Arctic. *Ecoscience*, *18*(3), pp.204-222; Rühland, K.M., Hargan, K.E., Jeziorski, A., Paterson, A.M., Keller, W. and Smol, J.P., 2014. A multi-trophic exploratory survey of recent environmental changes using lake sediments in the Hudson Bay Lowlands, Ontario, Canada. Arctic, Antarctic, and Alpine Research, 46(1), pp.139-158; and Solomon, C.T., Jones, S.E., Weidel, B.C., Buffam, I., Fork, M.L., Karlsson, J., Larsen, S., Lennon, J.T., Read, J.S., Sadro, S. and Saros, J.E., 2015. Ecosystem consequences of changing inputs of terrestrial dissolved organic matter to lakes: current knowledge and future challenges. *Ecosystems*, *18*(3), pp.376-389.

(e.g., culverts, road crossings) are a key risk to fish communities[34]. Long-term population trend data are largely absent. Species-specific tolerance thresholds for sediment, flow change, and water quality remain poorly quantified for peatland systems. Seasonal connectivity and winter habitat use are poorly understood.

2.16 Species and Spaces of Conservation Concern

Several species at risk occur in the region, including woodland caribou, wolverine, lake sturgeon, and some migratory bird species[35]. However, the presence and distribution of some species at risk and their habitats within the Assessment Area remain uncertain. Demographic baseline data and forecasting models designed for the Assessment Area context are limited or lacking entirely[36]. Cumulative effects thresholds for species at risk habitat remain a major uncertainty, with a limited evidence base oriented to potential impacts and mitigation for biodiversity, species at risk habitat, and peatlands. Protected "spaces" are fragmented and lack an overarching management framework (and see Section 2.22).

2.17 Distribution and Function of Native Assemblages

The literature scan demonstrated growing recognition that the Assessment Area landscape is not uniform, but rather a peatland-dominated ecosystem mosaic comprising bogs, fens, patterned peatlands, shallow wetlands, and low-gradient rivers whose structure and biodiversity are governed primarily by hydrology. It is now understood that these are active, vulnerable systems whose functional alteration has cascading biological effects. There is increasing recognition that peatland

---

[34] See for example Heim, K. C., Wipfli, M. S., Whitman, M. S., Arp, C. D., Adams, J., and Falke, J. A. 2015. Seasonal cues of Arctic grayling movement in a small Arctic stream: the importance of surface water connectivity. *Environmental Biology of Fishes*. https://doi.org/10.1007/s10641-015-0453-x.

[35] See Committee on the Status of Species at Risk in Ontario (COSSARO). 2017. Ontario Species at Risk Evaluation Report for Lake Sturgeon (*Acipenser fulvescens*): Saskatchewan-Nelson River populations ,Southern Hudson Bay-James Bay populations, and Great Lakes-Upper St. Lawrence populations. November 2017. Available at https://cossaroagency.ca/wp-content/uploads/2018/06/Accessible_COSSARO_Evaluation_LakeSturgeon_FINAL_20FEB2018_SP.pdf; Committee on the Status of Species at Risk in Ontario (COSSARO). 2014. Ontario Species at Risk Evaluation Report for Wolverine (*Gulo gulo*). December 2014. Available at https://cossaroagency.ca/wp-content/uploads/2017/12/AccessibleCOSSAROevalWolverine.pdf; and Ontario Ministry of Natural Resources and Forestry. 2014. *Integrated Range Assessment for Woodland Caribou and their Habitat: Far North Ranges*. Available at https://files.ontario.ca/environment-and-energy/species-at-risk/Far-North-Ranges-EN.pdf.

[36] See for example Dyson, M., Endicott, S., Simpkins, C., Turner, J.W., Avery-Gomm, S., Johnson, C.A., Leblond, M., Neilson, E.W., Rempel, R., Wiebe, P.A., Baltzer, J.L., Hughes, J., Stewart, F.E.C. 2024. Effective conservation decisions require models designed for purpose: a case study for boreal caribou in Ontario's Ring of Fire. bioRxiv 2022.06.01.494350; doi: https://doi.org/10.1101/2022.06.01.494350.

transformation may be effectively irreversible on human timescales[37]**.** Native species assemblages in the Assessment Area are now understood as low-density but functionally critical**,** relying on landscape continuity rather than local population centers. The Boreal Shield/Hudson Bay Lowlands boundary is now seen as ecologically important for some species, such as woodland caribou. Assessments increasingly focus on landscape integrity and access density as determinants of assemblage viability[38]. Paleoecology studies of aquatic invertebrate assemblages in Assessment Area lakes provide centuries-long reference conditions and show that climate-driven shifts are already underway, independent of industrial development[39]. Although field inventories remain sparse, spatial understanding of ecosystems and assemblages improved substantially with rapid development of advances in remote sensing and satellite imagery processing capability. As a result, ecosystem and assemblage distribution can now be assessed continuously, rather than inferred from scattered points. Climate change is now seen as integral to interpreting species-ecosystem function[40]. Fine-grained species assemblage mapping is incomplete (e.g., species presence, distribution, density) and habitat quality indicators are not consistently mapped at decision-useful scales. Understanding of ecosystem process thresholds and responses to disturbance remains poor.

2.18 Productivity, Decomposition, and Nutrient Cycling

The region's biogeochemistry is dominated by peatlands, where water table position controls productivity and decomposition. Across northern peatlands, including the Hudson Bay Lowlands, waterlogged (anoxic) conditions slow decomposition, allowing peat and nutrients bound in peat to accumulate over millennia. Recent research has demonstrated that when the aerated zone expands (e.g., via drying or drainage),

---

[37] See for example McLaughlin, J.W. and Packalen, M.S., 2021. Peat carbon vulnerability to projected climate warming in the Hudson Bay Lowlands, Canada: A decision support tool for land use planning in peatland dominated landscapes. *Frontiers in Earth Science*, 9, p.650662.

[38] See for example McFarlane, S., Van Mierlo, V., Manseau, M., Kroeze, A., Eberhardt, E. and Girard, J., 2025. Bioclimatic, terrain, and specific peatland composition are major drivers of woodland caribou winter habitat suitability in northern Ontario. *Canadian Journal of Zoology*, 103, pp.1-18; and Fryxell, J.M., Avgar, T., Liu, B., Baker, J.A., Rodgers, A.R., Shuter, J., Thompson, I.D., Reid, D.E., Kittle, A.M., Mosser, A., Newmaster, S.G., Nudds, T.D, Street, G. M., Brown, G. S., and Patterson, B. 2020. Anthropogenic disturbance and population viability of woodland caribou in Ontario. *The Journal of Wildlife Management*, 84(4), pp.636-650.

[39] See for example Jeziorski, A., Keller, B., Dyer, R.D., Paterson, A.M. and Smol, J.P., 2015. Differences among modern-day and historical cladoceran communities from the "Ring of Fire" lake region of northern Ontario: identifying responses to climate warming. *Fundam Appl Limnol*, *186*, pp.203-216.

[40] See for example Dabros, A., Antwi, E. K., Waldron, C., Darko, A. N., and Higgins, K. L. 2025. Risk assessment of potential impact of mining development (linear infrastructure) on peatland ecosystems in the Ring of Fire region, Northern Ontario. Frontiers in Environmental Science, 13, 1676633. https://doi.org/10.3389/fenvs.2025.1676633

decomposition accelerates and nutrient availability can shift[41]. Process syntheses and reviews relevant to the Assessment Area repeatedly identify hydrologic alteration (e.g., through drawdown, impoundment, changed flow paths, and/or fire) as a major driver of shifts in plant communities, decomposition rates, and nutrient dynamics, including post-disturbance regime shifts in some contexts[42]. Permafrost features influence runoff, water storage, and carbon/nutrient export pathways, and a large share of nutrient cycling is internal and slow, with strong bog/fen differences. Water table position controls decomposition rates and drainage accelerates carbon loss. Local, Assessment Area-specific rates (net primary productivity, litter decay constants, peat carbon turnover, nutrient mineralization) are not well understood and thresholds for functional change under infrastructure are unclear. The net direction and magnitude of disturbance-related nutrient export to rivers is uncertain.

2.19 Ecosystem Resilience

The literature scan confirms a point made in previous sections: that hydrology is the master control on resilience for most Assessment Area ecosystems. Peatlands can be highly persistent but some hydrologic disturbances create long-lasting or irreversible changes, where recovery times exceed project lifespans[43]. Even a moderate water table drop has been shown to increase vulnerability to post-fire regime shift, so that recovery after fire can push the system toward a different state[42]. Thresholds of change are not well-understood and recovery timeframes and trajectories are not well-constrained at decision-relevant scales. Recent research reflects the understanding that resilience is not uniform across peatland types and settings, and resilience under combined climate and development stress is highly uncertain.

---

[41] See for example Preston, M.D., Eimers, M.C. and Watmough, S.A., 2011. Effect of moisture and temperature variation on DOC release from a peatland: Conflicting results from laboratory, field and historical data analysis. *Science of the total environment*, *409*(7), pp.1235-1242; and Harris, L.I., Richardson, K., Bona, K.A., Davidson, S.J., Finkelstein, S.A., Garneau, M., McLaughlin, J., Nwaishi, F., Olefeldt, D., Packalen, M., Roulet, N.T., Southee, M., Strack, M., Webster, K., Wilkinson, S. and Ray, J. 2022. The essential carbon service provided by northern peatlands. *Frontiers in Ecology and the Environment*, 20(4), pp.222-230.

[42] See for example Kettridge, N., Turetsky, M.R., Sherwood, J.H., Thompson, D.K., Miller, C.A., Benscoter, B.W., Flannigan, M.D., Wotton, B.M. and Waddington, J.M., 2015. Moderate drop in water table increases peatland vulnerability to post-fire regime shift. Scientific reports, 5(1), p.8063.

[43] See for example Balliston, N. E. and Price, J. S. 2023) Aquifer depressurization and water table lowering induces landscape scale subsidence and hydrophysical change in peatlands of the Hudson Bay Lowlands. *Science of the Total Environment, 855*, 158837. https://doi.org/10.1016/j.scitotenv.2022.158837; and McLaughlin, J., Packalen, M. and Bharat Shrestha, B.S., 2018. Assessment of the vulnerability of peatland carbon in the Albany Ecodistrict of the Hudson Bay Lowlands, Ontario, Canada to climate change. Ontario Ministry of Natural Resources and Forestry. Climate Change Research Report CCRR-46.

2.20 Connectivity

Post-2010 literature emphasizes that ecological connectivity in the Assessment Area is best understood as three coupled connectivities: terrestrial movement/connectivity (caribou and other wide-ranging mammals) shaped by access and fragmentation; hydrologic connectivity across peatlands controlling ecosystem function and resilience, highly sensitive to linear infrastructure; and aquatic network connectivity (fish passage and seasonal habitat access) driven by road crossing density and design. Hydrologic connectivity underpins ecological connectivity, while roads and other corridors fragment landscapes. Connectivity is increasingly reframed from "wildlife corridors" to landscape integrity and access density. The landscape is naturally highly connected at large scales, especially via rivers and wetlands, and connectivity is multi-layered and cross-ecosystem, with aquatic, wetland and terrestrial linkages tightly coupled[44]. Assessment Area-specific work identifies linear infrastructure as a central risk pathway, but the dose-response problem remains: the spacing, density, and design of corridors that push peatland systems past connectivity thresholds are not yet bounded with Assessment Area-specific empirical thresholds. The caribou/large-mammal literature demonstrates that linear features alter movement and risk[45], but functional connectivity outcomes are context-dependent and strongly influenced by season, feature type, and landscape configuration. The Assessment Area's scale and peatland matrix make local inference difficult without dense telemetry/camera or Indigenous knowledge.

2.21 Thresholds of Landscape Change

Since 2010, the most important advances in knowledge about thresholds of landscape change relevant to the Assessment Area have been about turning "cumulative effects" into quantifiable (or at least defensible) tipping points, especially for caribou range condition, peatland hydrologic integrity, and aquatic network continuity. The post-2010 threshold advances collectively point to three important tipping domains: access and cumulative disturbance thresholds (caribou range condition)[46]; hydrologic thresholds in peatlands (water table lowering/depressurization/fragmentation leading to persistent change)[47]; and connectivity/function thresholds in aquatic networks (fish passage,

---

[44] See for example Elmes, M.C., Petrone, R.M., Volik, O. and Price, J.S., 2022. Changes to the hydrology of a boreal fen following the placement of an access road and below ground pipeline. Journal of Hydrology: Regional Studies, 40, p.101031.

[45] See for example Benoit-Pépin, A., Feldman, M.J., Imbeau, L. and Valeria, O., 2024. Use of linear features by mammal predators and prey in managed boreal forests. *Forest Ecology and Management*, *561*, p.121911.

[46] See for example Government of Canada. 2017. Species at Risk Act Recovery Strategy Series Report on the Progress of Recovery Strategy Implementation for the Woodland Caribou (*Rangifer tarandus* caribou), Boreal population, in Canada for the Period 2012-2017 Woodland Caribou, Boreal population.

[47] See for example Balliston, N. E. and Price, J. S. 2023. Aquifer depressurization and water table lowering induces lcandscape scale subsidence and hydrophysical change in peatlands of the Hudson

seasonal habitat access)[48]. Quantitative disturbance thresholds are not well established, but non-linear responses are likely in peat systems, and probably depend on peatland type, peat depth and connectivity. Thresholds of habitat function for key wildlife, caribou in particular, remain unclear, and drawdown thresholds for subsidence are not well constrained.

2.22 Protected Areas

Since 2010, the biggest advances in knowledge about protected areas relevant to the Assessment Area are less about finding new candidate parks and more about how protection is designed, governed, and justified in a peatland-dominated, Indigenous-homeland landscape. Recent research shows that protected areas are increasingly framed as networks (connectivity and representation) rather than as standalone designations, but current protected areas within and adjacent to the Assessment Area do not form a comprehensive network[49], and connectivity between protected spaces is limited. There is increased focus on governance and relationships in protected areas management, but regional-scale conservation planning remains incomplete.

2.23 Invasive and Non-Native Species

The literature scan confirms that current levels of invasive species are likely to be low within the Assessment Area, largely due to the remoteness of the region, although it is also clear that knowledge of invasives is limited because of weak monitoring coverage. Baseline data for non-fish aquatic invasive species is especially thin. The post-2010 literature supports three practical conclusions: access is the primary risk amplifier (new roads/corridors and other access create the vectors and disturbed substrates that enable invasions and dramatically increase invasion risk)[50]; absence of evidence is not evidence of absence in the Far North (monitoring gaps are real and documented); and risk-based planning and early detection (prevention/biosecurity) is the only credible

---

Bay Lowlands. *Science of the Total Environment, 855*, 158837. https://doi.org/10.1016/j.scitotenv.2022.158837

[48] See for example Breeuwer, A., Robroek, B.J., Limpens, J., Heijmans, M.M., Schouten, M.G. and Berendse, F., 2009. Decreased summer water table depth affects peatland vegetation. Basic and Applied Ecology, 10(4), pp.330-339.

[49] See for example Auditor-General of Ontario. 2023. Conserving the Natural Environment with Protected Areas. Available at: https://www.auditor.on.ca/en/content/annualreports/arreports/en23/1-25FU_protectedareas_en23.pdf.

[50] See for example Booth, S.W., Midgley, N.G., Clewer, T. and Turner, L., 2025. The impacts of access infrastructure on temperate and boreal peatlands. *Scientific Reports*, 15(1). https://doi.org/10.1038/s41598-025-28323-9; Dabros, A., Antwi, E.K., Waldron, C., Darko, A.N., and Higgins, K.L. 2025. Risk assessment of potential impact of mining development (linear infrastructure) on peatland ecosystems in the Ring of Fire region, Northern Ontario. *Frontiers in Environmental Science*,13. https://doi.org/10.3389/fenvs.2025.1676633; and Langor, D.W., Cameron, E.K., MacQuarrie, C.J., McBeath, A., McClay, A., Peter, B., Pybus, M., Ramsfield, T., Ryall, K., Scarr, T. and Yemshanov, D., 2014. Non-native species in Canada's boreal zone: diversity, impacts, and risk. *Environmental Reviews*, *22*(4), pp.372-420.

first line of defense, and is now supported by stronger provincial regulatory and policy tools than existed in 2010. It is unclear which invading species are likely to be true invasives or range-shifting native species not currently present in the Assessment Area. The future risk level depends heavily on road development and corridor density, and the Assessment Area has not yet experienced that full pressure.

2.24 Climate Change

Since 2010, the biggest advances in climate change relevant to the Assessment Area focus on how climate warming interacts with peatlands, hydrology, permafrost, fire risk, and aquatic ecosystems in the Hudson Bay Lowlands/Far North setting. Principal advances relate to mechanistic understanding of peatland carbon and greenhouse gas responses to warming and moisture change[51]; spatially-explicit decision support for peat carbon vulnerability and planning[52]; and Ontario technical vulnerability reporting that is directly usable in land-use planning and impact assessment[53]. There is broad agreement that climate change must be incorporated as an integral component of cumulative effects and scenario-based assessment. There is clear evidence that the region is already warming, with the largest, most robust signal in cold-season temperature. Precipitation is increasing overall, and the snow-rain balance is shifting. The Hudson Bay and James Bay sea-ice seasons are shortening, which feeds back on regional climate and coastal ecosystems. Permafrost thaw and hydrologic change are expected and indeed already observed within the Assessment Area, and methane release risk may increase as a result. Climate-forward modelling, especially the interaction of climate change with development corridors and water management, is essential but tools remain incomplete.

---

[51] See for example McLaughlin, J. and Webster, K., 2013. Effects of a changing climate on peatlands in permafrost zones: a literature review and application to Ontario's Far North (No. CCRR-34, pp. iii+-151); and McLaughlin, J. and Webster, K., 2014. Effects of climate change on peatlands in the far north of Ontario, Canada: A synthesis. *Arctic, Antarctic, and Alpine Research*, 46(1), pp.84-102.

[52] See McLaughlin, J.W. and Packalen, M.S., 2021. Peat carbon vulnerability to projected climate warming in the Hudson Bay Lowlands, Canada: A decision support tool for land use planning in peatland dominated landscapes. *Frontiers in Earth Science*, 9, p.650662.

[53] See example McLaughlin, J., Packalen, M. and Bharat Shrestha, B.S., 2018. Assessment of the vulnerability of peatland carbon in the Albany Ecodistrict of the Hudson Bay Lowlands, Ontario, Canada to climate change. Ontario Ministry of Natural Resources and Forestry. Climate Change Research Report CCRR-46.

3 Overview of Key Informant Interviews

We conducted interviews with 17 key informants from a variety of backgrounds, including current or former government scientists, academic researchers, representatives of environmental non-government organizations, and independent consultants. Overall, the interviews revealed strong consensus that many of the central challenges facing the Ring of Fire (RoF) are not primarily scientific gaps, but scale mismatch, governance fragmentation, and insufficient integration of cumulative effects and climate risk. The complete interview report, including all interview transcripts, has been submitted to the RAWG as a separate appendix. The following sections include example comments extracted from the interviews.

Key findings include:

- **Scale and scoping are critical,** with broadscale approaches recommended, for example nested watershed studies and herd-scale assessment for caribou
- **Hydrology is the organizing variable** of the system and the greatest vulnerability.
- **Peatlands are globally significant carbon stores**, with risk of irreversible loss.
- **Mercury methylation risk is unusually high in the Assessment Area.** Current "monitor and adapt" approaches are inadequate to protect human health.
- **Climate change is an overarching stressor**, and is already affecting hydrology, fish thresholds, fire risk and mercury methylation; future climate impacts are highly uncertain.
- **Cumulative effects are critical and must be understood at local to regional scales,** especially the interactive effects of climate change and development activities. Project-by-project review is insufficient to manage cumulative effects.
- **There is a need for adaptive management**, given high uncertainty associated with climate change.
- **The lack of a peatland policy and associated governance** is an obstacle to regional planning and cumulative effects assessment.
- **Governance structures lack shared authority and enforceable thresholds.** Indigenous participation without decision leverage was viewed as insufficient. Interviewees praised the deep knowledge Indigenous Peoples have of this landscape and the value their perspectives bring to monitoring and assessment.
- **Significant publicly funded data exist** but are fragmented, inaccessible, or outdated.
- **Recent advances in remote sensing and monitoring technology** show promise for broad-scale monitoring in the Assessment Area but must be supported by ground-truthing.

- **Mitigation measures** are available but lack consensus-based support. Given high uncertainty, prevention is greatly preferred over mitigation after the fact.

3.1 Scale and Scoping Are Critical

Interviewees consistently emphasized that ecological processes, species movement, hydrologic connectivity, and Indigenous rights operate at watershed, herd, and regional scales, not at the footprint of individual mines or roads. The most consistent recommendation was adoption of a nested watershed framework, focusing on five to six major watersheds, with receptor-specific sub-scales for caribou, lake sturgeon, and other valued components. Without a multi-scale assessment framework extending across major river basins, interviewees warned that cumulative effects will remain structurally under-assessed.

Example comments:

- I suggest a nested watershed study to incorporate any number of interests, such as stream and ground water rates, water quality, peatland carbon storage and greenhouse gas fluxes, and plant and wildlife diversity, among other interests. (Government Scientist #3).
- You need to do long-term studies and then scale up. A multi-scalar approach is important. Using watersheds as the basis makes the most sense. That also correlates well with vegetation patterns. If you assess this region at too large a scale, you lose the process-based understanding. (University Researcher #1)
- Roads will inevitably intersect with N-S and E-W caribou movement corridors. When you break up the ability of caribou to use a large landscape, it's the first step to range impacts. So Webequie and Marten Falls Roads are not separate projects but should be considered at the broadest possible range. You would be dividing an area that currently has unlimited access/use. (Government Scientist #4)

3.2 Hydrology as the Organizing Variable

Interviewees described hydrology as the key organizing variable in the Assessment Area: the driver of carbon storage and methane flux; the primary pathway for mercury transport; and the main determinant of fish habitat and peatland stability. Hydrology was described as highly sensitive to roads and dewatering but at the same time deeply uncertain under climate change. Interviewees expressed concern about how the dismantling of key stream gauge networks and lack of long-term streamflow data now impedes understanding of peatland hydrology at a regional scale. Groundwater monitoring is sparse but climate impacts are already apparent in permafrost thaw and wetland drying. Interviewees saw the re-establishment of hydrologic monitoring networks as both foundational and achievable. Interviewees repeatedly mentioned the value of nested watershed studies in understanding hydrologic impacts at multiple scales.

Example comments:

- Hydrology is both the biggest threat and the biggest unknown. (University Researcher #3)
- Hydrology runs carbon, bugs, soil, peat; it's essential in mercury transport. Downstream will get wetter with disturbance, while upstream will get drier; effects could extend for hundreds of km; climate change will exacerbate those effects. (Government Scientist #3)
- Water, hydrologic change, is the biggest worry for me. We know what to watch for in terms of mercury methylation, but not how a future climate will change those conditions. Hydrologic change will have a massive impact on mercury risk. (University Researcher #6)
- Linear development will be the biggest issue, especially road crossings that alter the connectivity of stream networks. Road crossings can be barriers to fish but also major silt sources; small streams are especially important. (Government Scientist #2)
- I suggest a nested watershed study to incorporate any number of interests, such as stream and ground water rates, water quality, peatland carbon storage and greenhouse gas fluxes, and plant and wildlife diversity, among other interests. ...Uncertainties could be tested at different scales within a nested watershed study, as well. (Government Scientist #3).
- A multi-scalar approach is important. Using watersheds as the basis makes the most sense. That also correlates well with vegetation patterns. If you assess this region at too large a scale, you lose the process-based understanding. (University Researcher #1)
- Watershed-scale assessment is best, with a focus on the five or six largest watersheds. The watershed boundaries should be the assessment boundaries. (ENGO Representative #4)

3.3 Peatlands Are Globally Significant Carbon Stores

Interviewees described the Hudson Bay Lowlands as globally important and among the largest peatland carbon stores anywhere in the world. They expressed concern about the potential for development-related shifts in carbon and methane dynamics, and irrecoverable loss of peatland carbon stores. They noted that methane amplifies warming impacts; hydrologic alteration (drainage) can shift peat systems from sink to source; and irrecoverable losses are possible but to date poorly integrated into impact assessment. They observed that the current focus on rapid development emphasizes economic values over protection of ecosystem services and stressed the importance of incorporating carbon accounting as a central component in impact assessment.

Example comments:

- The GHG consequences of development are probably my top concern... One of the things we now know more clearly than when the Science Panel report was published in 2010 is the importance of avoiding irrecoverable carbon losses. Those considerations, the GHG implications of development more generally, do not appear in any EA. (ENGO Representative #4)
- Generally speaking, the peatlands are net sinks for CO_2 and net sources for methane, just under normal conditions. But the amount of CO_2 that's taken up is much more than the methane, and depending on the time frame that you're looking at, which could be anywhere from a few years up to a century scale, the contribution of the methane to global warming potential is going to change. Right now, people are estimating 35 times the global warming potential of methane compared to CO_2. So even though you have lower methane levels being released, you could have a lot higher global warming potential being released. (Government Scientist #3)
- A big challenge is quantifying how much carbon is present... And road building also has an impact on carbon storage and GHG and causes changes in chemistry, even from dust off the road. (University Researcher #5)
- One of the most decision-relevant questions—how drainage/road corridors shift peat hydrology and carbon loss over time—takes multi-year data and strong models that are still uncertain. (Independent Consultant #2)

3.4 Mercury Methylation Risk Is High

Several interviewees drew attention to the fact that the Assessment Area is highly sensitive to sulphate-driven methylation, to the point that any non-zero change could cause a pulse in methylation. Concerns included elevated background mercury, largely arising from atmospheric deposition; inadequate baseline data; risk of bioaccumulation in fish consumed by local communities; and lack of rapid-response protocols. Interviewees noted that response to elevated sulphate or mercury concentrations must not be years of additional study, but rather prompt diagnosis and immediate remedial action with affected communities as active partners in decision making.

Example comments:

- This is the most sensitive landscape for mercury methylation in North America. It's a profoundly sulphate-limited environment...The headwaters in the Shield portion are the most sensitive landscape type of methylation: low nutrient concentrations, soft water, low pH, and high dissolved carbon. Any sulphate above zero, above background levels, will increase methylation. (University Researcher #2)
- Methylmercury bioaccumulation... risk [is] particularly urgent where there is known vulnerability to cumulative contamination and bio-accumulative harm; "monitor and adapt" is not adequate protection. (Independent Consultant #2)

- We now understand that many factors drive mercury methylation, including factors at the landscape level, bacterial activity and type of bacteria, and the type and amount of organic matter…When we change the water chemistry or the landscape, there is a potential to change these processes…We can't use Grassy Narrows or Minimata, Japan, as comparisons. Those are very specific, acute instances where mercury was intentionally, nefariously, discharged into the environment. The situation in the Ring of Fire is different. We're talking about things like indirect effects of alteration to hydrology, not direct addition of mercury. Mercury will only be entering the system through atmospheric deposition and as a result of changes in the system, for example hydrologic changes. (University Researcher #6)

3.5 Climate Change Is an Overarching Stressor

Climate change was identified in almost every interview as a major uncertainty and force multiplier in virtually every aspect of this review. It was clear that climate warming is already underway and Assessment Area ecosystems are exhibiting those effects, for example in increasing exceedances of fish thermal thresholds and shrinking wetland size associated with peatland drying. A major theme that emerged in this review is the region's hydrologic connectivity across peatlands, controlling ecosystem function and resilience while highly sensitive to linear infrastructure. For example, as peatlands dry under climate warming, there are shifts in the fire regime and consequences for fire-peat-carbon feedbacks; development activities are likely to accelerate these changes. Another key theme is that infrastructure design cannot rely on historical information but rather must be climate-resilient and designed for future extremes. Interviewees emphasized that impact assessment must be climate-forward, not climate-neutral, and climate effects must be considered interactively with development scenarios.

Example comments:

- In my mind, the biggest uncertainties relate to scale and hydrology. How water will move in the future will have a massive impact on methylation risk. Climate is already bringing permafrost melt and that is shifting mercury release. If we increase the amount of water moving around, it will mobilize mercury. That's especially true if we have drought followed by wet conditions – that enhances the methylation process. (University Researcher #6)
- The biggest issue is the uncertainty. It's not the warmer temperatures, it's the new distribution of precipitation, the uncertainty of it, the extremes, probably very dry conditions followed by very intense rainfall. In the very dry periods, there will be more decomposition and therefore higher dissolved organic carbon (DOC). Then the intense rainfall will flush it all out. The methyl mercury will stick to the DOC and flush out with it. (University Researcher #1)
- We need to be thinking about the 90th percentile of the climate change projections, not the mean. We must capture the extreme events. Climate change

is accelerating, especially in the north, and especially since 2015, maybe 2010. If that trend is real, and I believe it is, we must reconsider our current practice of 30-year predictions. It's not enough. Too much can happen in 30 years – it disguises the trend. (University Researcher #4)

- Climate change will have a large overarching effect on the future impacts of any industrial applications in the north, particularly operations as potentially long-lived (many decades, possibly centuries) as a Ring of Fire mining industry would be. All infrastructure components and waste treatment facilities must be designed to deal with major future changes in climate, in particular the effects on water…Failure to adequately plan for future changes in water cycles could be catastrophic in the long-term. Future climate change is a big "wild card" that needs to be seriously considered in the design of any mining facilities and associated infrastructure like roads and waste disposal systems. (Government Scientist #1)

3.6 Cumulative Effects Must Be Understood at Local to Regional Scales

Interviewees repeatedly emphasized that project-by-project assessment is unacceptable because linear infrastructure, such as roads and power corridors, has the potential to create broad-scale hydrologic disruption; physical barriers to movement (e.g., fish, caribou); and increased access corridors for predators, invasive species, and humans. Evaluating the impacts of linear infrastructure such as roads as individual projects ignores their network effects and the potential interaction of other stressors, especially a changing climate. In addition, linear infrastructure creates opportunities for new access and therefore additional development ("roads breed roads"). Interviewees strongly recommended that linear infrastructure be assessed as a regional network because of its role in enabling human and predator access and the potential for regional-scale hydrologic effects. They emphasized that the vast and largely intact ecosystems of the Assessment Area require that the impacts of proposed development be assessed at multiple scales, from fine scales (to understand local processes); to meso-catchment scales of 10–500 km^2 (to understand system response to disturbance); to major river basin scales of 500–20,000+ km^2 (to assess cumulative effects).

Example comments:

- We need to be mindful of multiple stressors acting together over long time periods; we can't focus just on a single project, a single stressor or a limited time period. (Government Scientist #5)
- You can't be thinking project by project about impacts on birds. It's critical to think about cumulative effects, and that becomes important in deciding on the scale of study. You have X project footprint and X amount of habitat and X species present, but you also need to consider all of the <u>other</u> future activities

that might affect those species, and what offsetting might be required in the future. (ENGO Representative #1)

- My biggest concern is if we develop large scale mining beyond one or two mines. That's not climate smart. It will change the carbon dynamics. We don't know how much, or to what extent. (Independent Consultant #1)
- The big question is the configuration of development. What are we expecting over the next 10 years? We don't understand how the system works now. How are we supposed to understand what will happen in 10 years? Peatlands are resilient, with lots of internal feedbacks, but when you combine climate change with disturbance it could tip the peatlands over a threshold. (University Researcher #1)

3.7 There Is a Need for Adaptive Management

Interviewees were clear that planning decisions cannot rely on historical patterns. Climate and development are interactive forces that will shape system change in ways we cannot anticipate. It is essential to plan for a range of possible futures, including trigger action response plans. Pre- and post-development monitoring was not seen as sufficient. Rather, regular check-ins into the foreseeable future (some interviewees said "forever") are necessary, ideally in the context of evolving conceptual understanding of peatland systems. Each adaptive management cycle, typically five years, should begin with hypotheses about system response. At the end of each cycle, monitoring results should be compared with hypotheses: are results as expected, or are there surprises? If the latter, what was missed or misunderstood that could explain the difference? How should the conceptual model be adapted for the next cycle, and what do those changes mean for management response? Interviewees were clear that adaptive management (planning, monitoring, response) must involve pre-defined thresholds and responses, including rapid-response triggers, that are co-developed and jointly implemented with Indigenous communities.

Example comments:

- You need adaptive management, and adaptive monitoring, forever, into the foreseeable future...You need a Trigger Action Response Plan. So for example, if you expect to see a 5% drawdown in the water table, but you get 15%, something has to happen quickly. Why is that so much higher than you expected? There should be a trigger to increase your sampling frequency to figure out the mechanism (adaptive monitoring). And you may also need rapid technological intervention. That would be mine-specific... (University Researcher #2).
- Adaptive management is important. Our [First Nation] partner talks about that a lot. It would require a shift from fly-in science to having the community capacity for training, equipment, salaries – basically the support to do the work. It would be cheaper than helicopter work, though. There is definitely interest in the communities. Adaptive management is a process, not one and done...You need

to balance targeted information collection and careful adjustment of management plans to avoid “churn”, where you’re just changing things for the sake of change. You need to be able to track the impact of management action. (ENGO Representative #3)

- In the oil sands, there are requirements for wetland monitoring. If the monitoring detects large changes in hydrology, then you take immediate action. The type of action depends on the variables, but could a retrofit of a road, for instance where you’re seeing unexpected flooding. You would need to continue that monitoring all the way through the operational phase and post-closure, through reclamation to some point of certification that reclamation is complete. If there’s still evidence of disturbance, you should need to continue monitoring. (University Researcher #5)
- This is a huge and largely unimpacted landscape. The Moose and the Mattagami Rivers have hydroelectric development, some pulp and paper mills, but most of the rivers across the region are undisturbed. We have a rare opportunity for BACI [Before-After, Control-Impact] study before shovels hit the ground. I would encourage mindful consideration of that opportunity before monitoring begins. (University Researcher #6)

3.8 Policy Gaps

Interviewees identified several key policy gaps that they believe will hamper impact assessment in the Assessment Area:

- Peatland policy and associated governance
- Failure to balance ecosystem and economic values in a formal policy framework
- Lack of data standards and integrated databases
- Need for updates to and refinement of the Ontario Ecological Land Classification system, especially at the ecodistrict level

Without an overarching policy framework to guide land use planning and decision making, development in the Assessment Area is likely to proceed in a piecemeal fashion with inadequate consideration of cumulative effects.

Example comments:

- The province needs a peatland policy. If we’re uncertain about impacts, keeping those large peatland areas interconnected will be key. You need mapping and a participatory process but the policy piece is not there. As a government, we need to advance the policy piece. And the policy piece could be just in terms of guidance about what are cumulative effects? How do we consider them? (Government Scientist #5)
- We lack a comprehensive process – and the political will to support it – to ensure that cumulative effects are fully and transparently evaluated. The route of the

road now under consideration is based on political expediency, not science. Even decisions about the road were never considered publicly and transparently in comparison to alternatives. There's no coherent plan, no process for thinking about alternatives. There's nothing in place for managing cumulative effects. In part, that's because it's difficult to put together scenarios. People get caught up in trying to develop foreseeable scenarios, but it's more important to have a plausible range of scenarios rather than specific foreseeable examples. (ENGO Representative #4)

- We are not accounting for carbon impacts in impact assessment in Canada. We can do better. In Scotland, [there has been extensive work] to improve accounting of carbon impacts, for instance on groundwater-dependent wetlands, including peatlands. I don't see a good system here in Canada. (Independent Consultant #1)
- Any investment in refining the Ecological Land Classification network will pay off in spades in terms of future habitat classification. (Government Scientist #4)
- We need better mapping, especially of the boreal shield land cover. The current Ontario Land Classification map is a problem. (Independent Consultant #1)

3.9 Governance Gap and the Need for Shared Authority

Many interviewees emphasized the importance of developing thresholds, response triggers ("trigger action response plans") and decision rules jointly with Indigenous communities[54]. Indigenous participation without decision leverage was viewed as insufficient. Interviewees praised the deep knowledge Indigenous Peoples have of this landscape and the value their perspectives bring to assessment. One interviewee described monitoring partnerships with local communities as "powerful" and spoke about the huge value of their knowledge in guiding researchers to focus on the most significant areas, saving time and effort in a remote region where access is difficult.

Many interviewees spoke about the close connection local communities have to the land and its resources. Community members are noticing changes on the land but have no data to back up their observations, so their perspectives are often undervalued or ignored entirely. Interviewees saw this as a wasted opportunity to bring two important knowledge systems together in understanding and documenting Assessment Area systems. The path forward must be inclusive and respectful; shared authority is preferred.

Example comments:

---

[54] Trigger action response plans are already in use elsewhere in Canada and the world, and are intended to support management of and response to changing conditions before the situation results in harm to the environment or human health or damage to infrastructure. Canadian examples include guidance produced by the Province of British Columbia, the Mining Association of Canada, and fugitive dust emissions and mine tailings management programs for individual facilities.

- There is a jurisdiction / governance gap: [there is] no co-jurisdiction structure to co-define valued components, thresholds, methods, data ownership, and decision rules (what "enough knowledge" means). [There must be a] co-jurisdiction science table with decision leverage: co-define indicators, thresholds, models, acceptable uncertainty, and "stop /redesign" triggers (not advisory-only)…Timelines must match Indigenous protocols and knowledge-holder processes; otherwise "meaningful consent" is structurally impossible. (Independent Consultant #2)
- One of the biggest gaps is management…Is there a skill set that will evolve, and an emerging group of Indigenous trained biologists and conservation officers? It's the need to build capacity and skills. There are good jobs there…It would be a powerful thing to create associations among them, a community of practice as it were. With modern internet service, it would be feasible to keep representatives from different communities connected to work on these kinds of questions. There should be a Fish and Wildlife Technical Committee with each community having a member…It's important to maintain direct connections with the communities because all of the harm will go to the people. It's also a great way to introduce youth to career paths that they might not have considered. (University Researcher #3)

3.10 Data Fragmentation and Accessibility

Interviewees identified a variety of recurring issues with data fragmentation and accessibility, including:

- Outdated datasets for caribou (publicly available only to 2014), mercury, and other ecosystem components
- Discontinued hydrometric programs
- Industry-held mercury data and other datasets
- Limited or blocked access to reports and publicly-funded datasets

Interviewees expressed frustration about these issues, noting that data access and transparency are urgent prerequisites to credible impact assessment.

Example comments:

- MNR produced a large technical report on the Far North, as a way to summarize a variety of research projects in a user-friendly format with research highlights. The report was apparently publicly available and was very well received but is now hard to find. I'm sorry that I don't have a title or date of publication. (Government Scientist #4)
- MECP led a major EA effort in the region centred around Eagle's Nest, approx. 50-100 sq km; they designed surveys at different radii; this effort was led by Chris Charron, MECP; MNR and MDNM were also involved; they examined

~100% of fish habitat and found very few fish of interest. In that work, most of the fisheries resources were small bodied species in streams. There are no large lakes in the area, only small lakes, and they are distant from the three main communities; there is also a commercial fishing camp in this area. I don't know where that data is now. (Government Scientist #2)

- A lot of information has been collected by companies, mainly in the exploration stage: soil quality, peat depth, lots of data. That needs to be made publicly available. Even if you hold back the precise location details – say, within 30 m or even 100 m – it's better than none at all. The provincial EA process in Alberta requires that that data be made public. (University Researcher #5)
- Data exists, collected by government as part of the RoF baseline monitoring effort. There was community monitoring of different systems with a different river every year. Industry also has a lot of data acquired in the exploration phase that they aren't sharing with the public. (University Researcher #1)
- Our plan was to take existing data and movement information and use new habitat data to develop a new caribou model, but we couldn't get access to provincial caribou data. Data ownership was the issue. That data may be open now. I don't know where it is, where it's held...Another issue is that the most recent caribou data is from 2014 and is now out of date. More recent data has been collected but we weren't able to get access to it. (ENGO Representative #1)

3.11 Species-level Observations

Overall, interviewees identified few species that rely exclusively on the Assessment Area. Most experts indicated that the region does not support species uniquely dependent on it, although it has high ecological integrity and important habitats. Species-level vulnerability was generally not identified as a priority, except for caribou and lake sturgeon, although habitat integrity and cumulative impacts remain important considerations for many species.

- Most species are not uniquely dependent on the Assessment Area. The region supports typical northern ecosystems but few species depend solely on it. Bird, fish, and invertebrate communities appear broadly similar to those in other northern Ontario ecosystems. Coastal areas are important for waterfowl and sea ducks but are not considered a continental bottleneck for bird populations.
    - *Example comment:* There are few or no species that rely completely or considerably on the Ring of Fire. Sturgeon may be the sole exception, and largely because of its spiritual importance to First Nations communities. (University Researcher #3)
- Caribou are highly sensitive to development and were the most consistently identified species of concern in the interviews. Interviewees identified road construction, habitat fragmentation and disruption of movement corridors at the Shield-Lowlands boundary as the most important risks to caribou. Experts

stated that existing models for predicting impacts on caribou are inadequate or misapplied, and current publicly available data are outdated. Despite predictive uncertainty, interviewees widely agreed that development is likely to have negative effects on caribou populations.

  - *Example comment*: The most current publicly available caribou data is what the Far North Caribou Project produced in about 2014, so it's 12 years out of date (Government Scientist #4).
  - *Example comment:* We tried to use data in published reports to develop a model to assess impacts on caribou from potential development, but there are gaps in those reports, for example there are no estimates of the variation in effects size, or co-variates. We were forced to rework an existing model, but because existing models aren't built appropriately for our needs, we had limited success. (ENGO Representative #1)

- Interviewees identified lake sturgeon as the most important aquatic species, particularly because of its cultural importance for First Nations. Key issues include limited monitoring data, in large part because of large migration ranges in river systems, and potential cumulative impacts from hydropower and infrastructure. Interviewees considered Indigenous knowledge important for understanding lake sturgeon habitat needs and movement patterns.
  - *Example comment:* Lake sturgeon are the most imperilled group on the IUCN red list worldwide. Lake sturgeon in the far north are the last population on the plant to exist in intact rivers and not be considered endangered. Yet we have very limited monitoring of those populations. They are declining in the Moose River because of the hydropower development there. Their body size is smaller than it used to be. There was a commercial fishery in the 1960s and I suspect impacts persist from that time. Additional impacts on sturgeon are likely with the development of more hydropower. They must be considered in a cumulative effects framework, but we don't have enough data to start with. (ENGO Representative #3)
  - *Example comment*: The scale of road building impact could be species-specific. We would also need to consider sacred species of spiritual importance like sturgeon. (University Researcher #3)
- Interviewees confirmed that fish community diversity is relatively low in the Assessment Area, compared to southern systems. The main concerns identified by interviewees relate to the potential impacts of road construction on spawning habitat and movement corridors (e.g., hydrologic changes, increased siltation); increased fishing pressure due to road access; the potential for introduction of invasive and non-native species; and climate-driven temperature changes.
  - *Example comment:* We have little information on the movement of fish in rivers; there is probably more seasonal movement, seasonal patterns,

than we're seeing. You would need radiotelemetry and tagging to study fish movement in rivers; they probably move up into smaller tributaries in the spring, but we just don't know. The biggest uncertainty is harvestable fish; the biggest risk is increased access and its potential impact on harvest; road construction and changes in the abilities of species to use small tributaries for spawning habitat are also of concern. (Government Scientist #2)

- Bird populations within the Assessment Area were seen as regionally important but not unique to that area. The James Bay coastline in particular provides important breeding and moulting habitat for some waterfowl and sea ducks. Avifauna monitoring has improved in recent years, but drivers of changes in bird populations and species-specific behaviour remain poorly understood.
    - *Example comment:* Ken Abraham's work produced some baseline information on birds, but it wasn't focused on the Ring of Fire. It was more up toward the Hudson Bay coast, the Attawapiskat River. It wasn't as far inland. Some of the Abraham work is now out of date because of changes more generally affecting waterfowl, for example climate warming effects on wetland size and availability, and permafrost thaw, which are changing the availability of open water through that region. (ENGO Representative #1)

3.12 Ecological Thresholds

Interviewees reported very limited scientific knowledge about clear ecological thresholds in the Assessment Area. While ecological limits likely exist, scientifically defensible thresholds are rare, vary by species and ecosystem, and remain a major research gap. Several interviewees argued that the concept of a clear ecological threshold is often overly simplistic and/or used for policy convenience rather than reflecting ecological reality. Species responses to disturbance were described as depending on habitat configuration; behaviour of interest (e.g., nesting, migration); and local environmental conditions. Some interviewees suggested that 30–40% habitat disturbance has been known to cause measurable stress in wildlife populations, but determining precise limits is difficult because species respond differently depending on landscape context. Temperature thresholds for fish are however relatively well understood, with many cool-water species declining when temperatures exceed ~20°C.

Interviewees generally agreed that climate change complicates threshold predictions. Paleolimnological studies confirm that northern lakes are already undergoing change due to warming, and peatland systems are already demonstrating sensitivity to climate-related hydrologic changes; road construction and dewatering activities will exacerbate those effects. Permafrost in the region is already melting, with the potential to shift systems into a new state. For example, the presence of water over permafrost has been shown to cause formation of thermokarst fens and ponds, where altered vegetation communities with more vascular plants and more labile organic matter result in increased mercury methylation potential.

Example comments:

- Well, thresholds are mythological, aren't they? People are looking for a legal basis for decision making. We understand conceptually that there are limits to species tolerance, for example tolerance to habitat change. But the scale and context are also important. It's hard to come up with solid science-based thresholds. The burden of proof is on science, which can rarely deliver. There are limits – I prefer the word "limits" to "thresholds" – but finding those limits is hard. (ENGO Representative #4)
- We have no data to support specific thresholds. We lack general understanding of those potential impact responses. But anything that reduces wetland availability or use, for example increased turbidity that affects the invertebrate population, will affect foraging behaviour. Waterfowl are resilient, they're not super sensitive, not like caribou. There may be changes in where they nest but probably not population size or nesting success. (ENGO Representative #1)
- Temperature thresholds [for fish] are well understood. We use 20 degrees in northern waters – temperatures above that exclude many original species like lake trout, which will only survive below 18 degrees. In the northwest, shallow lakes will exceed that value from top to bottom. We saw mortality in the Sutton River, where temperatures reached 20 degrees. (University Researcher #3)

3.13 Social Impacts

Although this study focused on Western science, interviewees repeatedly emphasized that the social and cultural impacts of development on Indigenous communities are likely to be significant, particularly for communities whose food systems, health, and cultural practices depend on the land and water. Key concerns include:

- A long history of decision-making that failed to fully consider Indigenous knowledge and concerns (noted by several interviewees).
- Communities are already observing environmental changes but often lack formal monitoring data to support those observations.
- Drinking water and food security are of central concern to local communities, especially with respect to the safety of drinking water and bioaccumulation of mercury and other contaminants in traditional foods.
- Climate change could affect preferred food resources. For example, warmer lake water temperatures may cause the loss of fish species such as lake whitefish in shallow northern lakes, with direct cultural and nutritional impacts on First Nations communities.

- The need for improved monitoring and balanced communication about contaminant risks so that communities are better able to make informed decisions.

Example comments:

- The greatest threat of climate change is to people. It's direct, it's threats to their physical and mental health rather than to ecological systems. (University Researcher #3)
- I am very worried about the communities, the failure to take them seriously. These are the lands that are most traditionally accessed, and the communities have a tradition of guardianship. We need to respect that...They have a long history of not being listened to. Hydroelectric development on the Moose River, the De Beers project, they all ignored the First Nations. (University Researcher #1)
- Drinking water and food security/quality are huge concerns for the communities (Government Scientist #3)

3.14 Recent Advances in Monitoring Technology

Interviewees identified a variety of new and emerging technologies with the potential to support broad-scale monitoring of the Assessment Area and adjacent landscapes. Examples include:

- Satellite imagery and data interpretation
- Drone technology
- Acoustic monitoring
- eDNA
- Rapid sensing of aquatic toxicity
- New developments in biomonitoring approaches

While these advances show promise for future assessment within the Assessment Area, interviewees cautioned the need for ground-truthing and emphasized the value of community monitoring networks with deep knowledge of the landscape and its history. Appendix B, Section B4 discusses the potential application of several new and emerging technologies in Assessment Area monitoring.

Example comments:

- Remote sensing technology has advanced significantly in recent years and could be used to update the Far North layers, for example the wetland layers, which are now dated. Remote sensing and acoustic recording units are the main two advances in monitoring technology since 2010. Our data collection potential is hugely increased with those tools. (ENGO Representative #1)
- In 2010, we had Landsat, now we have Sentinel 2 Europe, other technology. It's giving us orders of magnitude more information than we had 15 years ago. Mitch Bonney of the Canadian Centre for Remote Sensing says he can get resolution down to 30 cm. That's the scale of a laptop! When you add LiDAR to that, you'll be able to pick out leaves on trees. (University Researcher #4)
- We are using acoustic monitoring for birds, bats, shales, seals, even fish. Acoustic monitors are placed and then we disappear and the device collects the data. The challenge is that it creates a very large quantity of data that can be challenging to harness and prioritize. We're using AI for analyzing that output. (ENGO Representative #4)
- Better biodiversity detection for remote waters [is now possible using] eDNA. (Independent Consultant #2)
- Another emerging approach is dragonfly larvae. John Chételat (ECCC, adjunct at Carleton) has done a lot of work on that. (University Researcher #2)

3.15 Mitigation Measures

The interviews revealed very little consensus on mitigation approaches, although there was some agreement that habitat compensation approaches have not been demonstrated to be effective in most cases. Several interviewees commented on the difficulty of assessing mitigation effectiveness given high uncertainty associated with climate change effects. Some interviewees also emphasized the importance of developing site-specific and often species- or even behaviour-specific mitigation measures; this is a challenging task without a detailed development scenario available. Virtually every interviewee noted that, given the high uncertainty associated with future climate impacts, prevention is greatly preferred over mitigation after the fact.

Example comments:

- It's best to avoid the issue in the first place; habitat compensation is a poor second choice... (Government Scientist #2)
- Protecting the aquatic environment during and after construction is the safest strategy. (University Researcher #3)
- Mitigation is impossible for large scale impacts. One mine, we can manage, mitigate. If we were just talking about Eagle's Nest, we can manage that situation, the mine will be underground, and so on. The problem is with the

roads. It won’t just be one mine. The roads will drive the development of many mines. The challenge is when do you say “enough”? (Independent Consultant #1)

- ...once the [mercury] cat is out of the bag, you can’t get it back in. Remediation is difficult, expensive, and not successful. The approach must be preventive. (University Researcher #6)
- I think that decision making in impact assessment needs to include a preliminary stage where everybody understands the best available technology, whether it’s for road construction or tailings disposal or whatever. Everybody has to understand the extent, the power, of available technology. (University Researcher #4)
- Protecting carbon stocks in peatland is impossible but it’s something we should strive for. We need to be thinking about what measures we can use, the risk-reducing strategies, to minimize impacts on carbon storage in peatlands in the context of a changing climate. (University Researcher #4)
- If you compare the 90^{th} percentile climate change projections for 30 years, 20 years, 10 years, it’s clear that you get a much better view of the trend if you predict only 15 years into the future. But a mine will operate more than 15 years. A road will be in use for 50 years, maybe until the end of the century. We need to design those structures to be resilient in the context of rapid climate change.. (University Researcher #4)

4 Comparison of Literature Scan and Interview Results

The literature scan and the interviews converge strongly on the need for watershed-scale, cumulative, climate-integrated, and governance-reformed planning. The interviews added emphasis on enforceable limits, precautionary action, and structural shared authority beyond advisory processes. There was virtually no disagreement on any topic (although emphasis on specific topics varied from interviewee to interviewee). The only exception was fish community structure and species occurrence. All but one of the interviewees who spoke on that topic agreed that sufficient data exists to support decision making about freshwater fish other than sturgeon; the remaining individual believes strongly that knowledge of fish community structure in the Assessment Area is fragmented and incomplete. Interviewees did however agree that understanding of lake sturgeon migration patterns is weak, and data on methyl mercury in fish tissue is fragmented and probably now out of date.

The following conclusions are essentially identical across both reports:

- Hydrology must anchor assessment design.
- Watershed-scale framing is essential.
- Roads are cumulative multipliers.
- Mercury is a high-sensitivity contaminant risk.
- Carbon loss is potentially irreversible.
- Climate change amplifies all other risks.
- Governance reform is necessary.
- Data gaps and fragmentation undermine credible assessment.

Hydrology Is the Organizing Variable

The literature scan identified hydrology as central to carbon cycling, peat stability, mercury transport, fish habitat, and connectivity. It revealed significant advances in knowledge since 2010 but also persistent data gaps and lack of cumulative modelling.

In the interviews, hydrologic change was described repeatedly as both the most serious threat and the biggest unknown in the Assessment Area. Climate change is already altering hydrologic systems across the region. Watershed-scale assessment will be necessary to evaluate the potential impacts of linear infrastructure and mine operations, such as dewatering.

Cumulative Effects Cannot Be Addressed Project-by-Project

Results of the literature scan show a clear understanding that impacts occur at multiple scales and that local impacts can propagate across much larger regions. Assessment at the site level is important in understanding processes, but assessments at larger scales are necessary to understand system response to stressors. Cumulative effects are best understood at the regional scale, but this approach is not currently well supported by a robust policy framework. Roads must be assessed as networks.

The interviews confirmed this point, noting that linear infrastructure like roads cannot be assessed project-by-project but must rather be assessed as a regional network that incorporates all planned development to the degree possible. Similarly, watersheds, herds, and migratory corridors exceed project footprints at must be understood at the scale of those processes.

Carbon and Methane Risks Are Globally Significant

The literature scan confirmed the Hudson Bay Lowlands as a globally significant carbon store. Methane flux in the region is complex and very likely to be altered under climate change, even in the absence of development.

The interviews added stronger concern about the potential for irrecoverable carbon loss and noted that current environmental impact processes often underweight or ignore the potential greenhouse gas implications of development.

Mercury Risk Is High and Poorly Constrained

Both the literature scan and the interviews identified mercury methylation as a high-risk pathway with insufficient baseline data. The literature scan identified sulphate-driven methylation sensitivity and baseline data gaps and uncertainties, while one interview described the region as possibly the most sensitive landscape for methylation in North America.

The interviews also revealed a shift in understanding of methylation processes since 2010 and noted that some earlier work has now been discredited because of methodological concerns. There was also concern that methyl mercury bioaccumulation is irreversible and therefore of high concern to local communities, who rely heavily on fish for their diet. “Monitor and adapt” was not seen as an adequate approach for this contaminant. Rather, interviewees recommended action triggers that would allow rapid response if methyl mercury increases are detected.

The Need to Integrate Climate Effects with Assessment of Development Impacts

Both the literature scan and the interviews identified warming trends, permafrost thaw, and methane feedbacks as climate-related influences within the Assessment Area. Climate was seen as an overarching stressor interacting with development. The interviews in particular emphasized the role of climate in compounding risk and system instability. There was strong agreement that development impacts must be assessed in the context of a changing climate and associated high uncertainty. It was clear that infrastructure cannot be built to historical baselines but must be designed for resilience and a range of possible climate-influenced futures.

Governance Should be Shared

The literature scan drew attention to the lack of statutory co-management boards for the Assessment Area. Interviewees also emphasized this governance gap and emphasized the need for shared authority. In both stages of work, consultation alone was viewed as insufficient without structural joint decision-making.

Both the literature scan and the interviews indicated that structural governance reform is likely necessary to improve the legitimacy and long-term effectiveness of decision-making. The scientific understanding of system vulnerability has advanced significantly since 2010, but institutional mechanisms for managing that vulnerability have not kept pace.

5 Nested Watershed Studies as a Tool for Cumulative Effects Assessment

A key message that emerged throughout the literature scan and in virtually every interview was that the impacts of development will not be limited to the project footprint but will likely propagate across the broader region. This creates challenges in establishing assessment scope and scale. Indeed, as the interviews made clear, impact assessment must proceed at multiple scales.

5.1 The Value of Nested Watershed Studies in Impact Assessment

As discussed in Section 3,2, interviewees repeatedly recommended the use of nested watershed studies: monitoring and analysis conducted at multiple, hierarchically related watershed scales (e.g., headwater sub-catchments within larger basins), as a basis for impact assessment, because they:

- link local disturbance to downstream ecological effects;
- improve causal inference and monitoring sensitivity, including detection of change;
- support model development and adaptive management; and
- enable cumulative effects analysis across scales.

Nested watershed studies support impact assessment by providing measurable, defensible evidence about how ecosystems respond to development. They strengthen cumulative effects assessment by integrating multiple indicators and allow simultaneous monitoring of hydrology, water quality, sediment transport, biodiversity, and carbon and methane flux. Perhaps most important, nested watershed studies provide the spatial framework necessary to assess cumulative effects, including climate-driven stressors, across multiple infrastructure corridors and project footprints.

A nested watershed approach organizes environmental monitoring and analysis across a hierarchy of connected catchments, from small headwater streams and sub-basins to larger rivers and entire basins, to understand how ecological processes and human impacts scale through hydrological networks. Studying multiple watersheds embedded within one another allows comparison of relatively undisturbed “reference” catchments with areas influenced by development, track how local disturbances propagate downstream, and distinguish natural variability from development-related change.

This approach is particularly valuable in impact assessment because it links site-level activities (such as roads or mines) to cumulative effects at larger landscape and watershed scales. It helps to establish credible baseline pre-development hydrological and ecological data, reference conditions, and estimates of natural variability and therefore provides a robust foundation for before-after-control-impact (BACI) analyses. For example, a headwater sub-catchment upstream of a planned road corridor can be compared with a similar sub-catchment downstream to isolate effects on water quality, including sediment transport and nutrient loads. Ideally, a nested watershed monitoring framework would be established in advance of development to provide baseline information for assessment of post-development effects.

Other advantages of nested watershed studies include:

- **Early detection of impacts and ecological change before they propagate through the system**. Small headwater watersheds often respond more quickly and clearly to disturbance than large river systems. This is especially important for sensitive systems like peatlands, which are already undergoing climate-related change.
- Improved insight into **how local impacts scale up through hydrological networks**, supporting analysis of whether local disturbances remain local or accumulate downstream. Some impacts may not be detected at the site scale but become measurable at broader scales: a critical consideration in cumulative effects assessment.
- Impact assessments often rely heavily on predictive models. Nested watershed data provide calibration and validation datasets to support better parameter estimates and **improve predictive modelling** of hydrologic and habitat connectivity, pollutant transport, and carbon flux.
- Nested monitoring can support **identification of nonlinear responses or tipping points**, for example, thresholds in turbidity affecting fish spawning or hydrologic thresholds affecting peatland stability.
- Nested watershed studies can also **identify specific sub-catchments or tributaries that contribute disproportionately to impacts**, allowing regulators and managers to target monitoring, mitigation and restoration measures where they will be most effective.
- A nested watershed monitoring framework also provides the continuous feedback essential to **support adaptive management and rapid response** – important approaches that were identified in many interviews – and identification of unexpected impacts and how they propagate through the system.

Appendix B provides examples of three nested watershed study designs: a typical large-scale design incorporating a variety of innovative monitoring technologies; a lower-cost version with fewer monitoring sites; and a high-innovation study design geared to leading edge research. These example framework designs are purely hypothetical and are provided only for illustrative purposes.

5.2 Examples of Nested Watershed Studies Elsewhere

Nested watershed designs are already used in several large-scale regional environmental monitoring and impact-assessment systems. The following examples illustrate how hierarchical watershed frameworks help link local disturbances to regional cumulative effects, which is often the central challenge in impact assessment.

Mackenzie Valley/Mackenzie River Basin (Canada)

Several monitoring programs in the Northwest Territories (NWT) use hierarchically nested watershed units to organize cumulative effects monitoring across the Mackenzie basin. One example is the NWT Cumulative Impact Monitoring Program (NWT-CIMP), which has developed nested watershed mapping frameworks to analyze disturbances and environmental indicators across different spatial scales[55]. Key features of this program include:

- Monitoring indicators at multiple watershed orders (small catchments; sub-basins; and basin scale)
- Mapping linear disturbances (roads, seismic lines) by watershed units
- Integrating data across large regions with sparse monitoring networks

Researchers summarize disturbance density within 4th- or 5th-order (larger) watersheds, which helps to link local infrastructure development, hydrologic change, and cumulative landscape disturbance patterns. Nested watershed frameworks allow the Mackenzie system, one of the world's largest river basins, to be analyzed as a network of interacting sub-basins rather than a single system. This supports cumulative effects assessments across multiple jurisdictions and monitoring programs.

Alberta Oil Sands Region

Environmental monitoring in the Alberta oil sands region is organized around the Athabasca River basin and its tributary catchments[56]. Nested watershed studies in

---

[55] See for example Fraser, R.H., Deschamps, A., and Kokelj, S.V. 2015. *Nested watershed mapping as a reporting framework for the NWT Cumulative Impact Monitoring Program (NWT-CIMP): A Report for the NWT Cumulative Impact Monitoring Program* (Project: A Multiscale Assessment of Cumulative Impacts in the Northern Mackenzie Basin). Available via ResearchGate at https://www.researchgate.net/publication/337286911_Nested_Watershed_Mapping_as_a_Reporting_Framework_for_the_NWT_Cumulative_Impact_Monitoring_Program_NWT-CIMP_2015_Report_for_the_NWT_Cumulative_Impact_Monitoring_Program_Project_A_Multi-_scale_Assessme

[56] See for example Beausoleil, D., Munkittrick, K., Dubé, M.G. and Wyatt, F., 2021. Essential components and pathways for developing Indigenous community-based monitoring: Examples from the Canadian oil sands region. *Integrated Environmental Assessment and Management*, *18*(2), pp.407-427. See also Kienzle, S.W., 2012. *Water yield and streamflow trend analysis for Alberta watersheds*. Edmonton, Canada: Alberta Innovates, Energy and Environment Solutions; available at https://waterportal.ca/water-yield-streamflow-analysis/ or directly at https://waterportal.ca/dmdocuments/02_Water_Yield_and_Streamflow_Trend_Analysis_for_Alberta_Wa

Alberta's oil sands region, particularly around Fort McMurray and the Athabasca River, monitor water quality, tailings seepage, and environmental impacts across multiple scales. These studies often use hierarchical, multi-model approaches to track contaminants like F2 hydrocarbons and naphthenic acids from specific mines into broader aquatic ecosystems as a basis for assessing risks to wildlife and drinking water safety. For example, the Oil Sands Monitoring Program (OSM), a joint federal–provincial initiative, collects environmental data across multiple media (water, air, wildlife) and across different spatial scales to assess the cumulative effects of development. Surface water monitoring includes mainstem river monitoring; tributary watershed monitoring; and wetland and groundwater monitoring around individual mines. These datasets are used to characterize baseline variability, detect regional trends, and verify environmental impact assessment predictions. The nested structure allows scientists to determine whether observed changes originate from local mining activities, tributary watershed disturbances, or broader regional processes such as climate variability.

European Water Framework Directive and Implications for Assessment of Mining Projects

The EU Water Framework Directive (WFD) requires water quality management at the river basin level, including the monitoring of tributaries and sub-catchments[57]. This effectively creates a nested monitoring structure in which impacts from activities such as mining are assessed across multiple watershed levels. Requirements include monitoring of headwater streams, tributaries, and mainstem rivers; integration of local pollution sources with basin-scale water quality targets; and co-ordination across national borders for shared river basins.

Several European mine-water research programs evaluate the transport of pollutants from mine sites through watersheds, focusing on acid mine drainage and heavy metal transport. These studies highlight that mining impacts often extend through river networks beyond the mine footprint, requiring monitoring across connected catchments[58].

The nested watershed approach is also evident in regulatory and policy contexts. Mining impact assessments in northern Scandinavia increasingly evaluate impacts within entire river basins and sub-catchments, particularly where multiple mining projects affect the same watershed. Monitoring frameworks focus on headwater tributaries near mines; mid-basin water quality; and downstream ecological effects

---

tersheds_Kienzle_et_al%20(3).pdf#:~:text=agriculture%20in%20the%20prairies%20or%20the%20oil,McMurray%2C%20the%20question%20arises%20if%20there%20is&text=When%20the%20watersheds%20were%20nested%2C%20i.e.

[57] See for example Christian, W., 2005. *Mine water management and the Water Framework Directive*. Conference presentation, Proceedings of the Post-mining conference 2005, November 16-17, Nancy, France. Available at https://www.wolkersdorfer.info/publication/pdf/GISOSWolkersdorfer.pdf.

[58] See for example Wolkersdorfer, C. and Bowell, R., 2005. Contemporary reviews of mine water studies in Europe, Part 2. *Mine Water and the Environment*, *24*(1), pp.2-37.

extending to coastal systems. For example, environmental assessments for mining developments in northern Sweden and Finland typically examine the cumulative impacts on the river basin and its tributaries, including spawning rivers used by salmon. This approach is clear in Finland's response to Sweden under the Espoo Convention[59] regarding the proposed expansion of the Kaunis Iron AB mining project near Pajala, Sweden[60], which reflects a nested watershed approach to cumulative impact assessment. A central concern throughout the public and agency consultation process was the risk that mine operations could affect the Muonio River, which forms part of the international border between Sweden and Finland and flows into the Torne River and ultimately the Bothnian Bay. Because surplus water from the mine and its processing facilities may be discharged into the Muonio River, stakeholders emphasized the possibility of transboundary impacts on water quality, aquatic ecosystems, and fisheries in Finland. Authorities describe the Torne-Muonio River as "Europe's most important salmon river and ... of significant ecological, economic, tourist and cultural importance"[60], noting that the river currently has excellent ecological status and is protected under the Natura 2000 network. Any deterioration is therefore a significant concern.

5.3 Implications for Regions Like the Ring of Fire

These precedents suggest that nested watershed studies are particularly valuable where:

- development occurs across large remote landscapes;
- multiple projects affect connected ecosystems;
- baseline monitoring is limited; and
- impacts are mediated through hydrological connectivity.

In such contexts, nested watershed designs provide the spatial structure needed to link site-level environmental assessments with regional cumulative-effects analysis.

---

[59] The Espoo Convention is an international instrument that requires signatory Parties to assess the transboundary environmental impacts of certain activities at an early stage of planning; provide to the government and public of an affected country an opportunity to participate in the assessment; and ensure that the results of the assessment are taken into account in the final decision about the project. Canada participated in the development of the Convention and has ratified it, with a reservation limiting its application to federal legislative jurisdiction exercised in respect of environmental impact assessment. More information is available at https://www.canada.ca/en/environment-climate-change/corporate/international-affairs/partnerships-organizations/transboundary-environmental-impact-assessments.html.

[60] Available at https://www.ymparisto.fi/sites/default/files/documents/Finland%27s%20response%20-%20Kaunis%20Iron%20AB%205.12.2025.pdf.

6 Comparison with Recommendations in Earlier Reports

This section compares the results of the literature scan and interviews conducted in this project with the findings and recommendations of three older reports:

- The Far North Science Advisory Panel. 2010. *Science for a Changing Far North. The Report of the Far North Science Advisory Panel*. A report submitted to the Ontario Ministry of Natural Resources.
- Abraham, K.F., McKinnon, L.M., Jumean, Z., Tully, S.M., Walton, L.R. and Stewart, H.M. 2011. Hudson Plains Ecozone+ Status and Trends Assessment. *Canadian Biodiversity: Ecosystem Status and Trends 2010, Technical Ecozone Report*. Canadian Councils of Resource Ministers, Ottawa, ON. xxi + 445 pp.
- ESTR Secretariat. 2014. Boreal Shield and Newfoundland Boreal ecozones+ evidence for key findings summary. *Canadian Biodiversity: Ecosystem Status and Trends 2010, Evidence for Key Findings Summary Report No. 10*. Canadian Councils of Resource Ministers. Ottawa, ON. xv—194 p. http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1

6.1 Alignment of Core Conclusions

Together, these reports span more than 15 years of scientific assessment and policy framing for northern Ontario, including the Assessment Area.

Despite different purposes, the earlier reports and the current work align on several core conclusions, as follows:

1. Climate Change Is Transformative

- The 2010 Far North Science Panel report frames climate as a central management driver.
- The 2011 Boreal Shield ESTR report identifies climate-driven changes in fire, hydrology, and species trends.
- The 2014 Hudson Plains Report documents early climate effects, permafrost thaw, hydrologic shifts, and coastal change.
- The current literature scan and interviews treat climate as an overarching stressor requiring “climate-forward design” in development.

2. Hydrology Is Foundational

- The 2010 Far North Science Panel report recommends watershed-based planning units.
- The 2014 Hudson Plains Report dedicates extensive analysis to hydrological processes and carbon cycling.

- The current literature scan and interviews reflect the view that hydrology is the key organizing variable within the Assessment Area and must be the backbone of monitoring.

3. Carbon Storage Is Globally Significant

- The 2010 Far North Science Panel report explicitly recommends protecting carbon stores in land use planning.
- The 2014 Hudson Plains report details peatland carbon accumulation and vulnerability.
- The current literature scan and interviews identify a need for peatland carbon accounting integrated explicitly into impact assessment and scenario modelling.

4. Cumulative Effects Are Central

- The 2010 Far North Science Panel report recommends incremental planning and cumulative impact assessment.
- The 2014 Hudson Plains report identifies cumulative stressors and fragmentation.
- The current literature scan and interviews advise against project-by-project assessment as insufficient for assessment of cumulative effects, and instead emphasize the need for multi-scale assessment framed around major watersheds across the region.

6.2 Alignment of Reported Environmental Trends

Trends presented in this report align strongly with those described in the 2011 Hudson Plains and 2014 Boreal Shield ESTR reports. It is difficult to make direct comparisons because the two ESTR reports have different reporting formats and the current report describes an Assessment Area that extends across portions of both ecozones. A further difficulty was the paucity of recent data for the Assessment Area, reported both in the recent literature and in the interviews conducted for this project. Quantitative trend analysis was beyond the scope of the current work, but in any case would not have been feasible given the age and quantity of data available.

Several common themes did however emerge in comparing the 2011 Hudson Plains and 2014 Boreal Shield ESTR report with the results of the current wok. All three reports include findings of increasing climate-related impacts, including increasing permafrost thaw; increasing air and water temperatures; altered precipitation regimes (location-dependent); decreased sea ice; and increased mercury methylation risk. All three reports emphasize the uncertainty of climate impacts on ecozone resilience and capacity to continue supplying ecosystem services, and underline the need to assess the cumulative impacts of development in the context of a warming climate.

The following findings from the two ESTR reports parallel the findings discussed in Section 2 and 3 of the current report (note that in the interests of brevity, the footnotes and citations that appeared in the original text have been omitted in the following examples):

- The Assessment Area's **peatlands are a globally important carbon store**. If climate change, development, or a combination of the two causes carbon stored in the peatlands to be released to the atmosphere, there is likely be a positive feedback to atmospheric greenhouse gases.
  - **Boreal Shield ESTR**: "The Boreal Shield Ecozone+ will undoubtedly play an important role in Canada's future in a changing climate. Its vast forests and wetlands store huge amounts of carbon. Properly managed, these carbon stores can help to mitigate the effects of climate change."
  - **Hudson Plains ESTR**: "A large proportion of the ecozone's wetlands are peat-forming wetlands (bogs and fens), which also makes this ecozone Canada's largest peatland complex and the second largest at northern latitudes (>40-50°). The massive amount of carbon contained in these peatlands is stabilized by cold temperatures and high water levels, and peat has accumulated in the ecozone over thousands of years. These exceptional peatlands are significant for carbon storage and cycling at the global scale and, thus, for regulating the effects of accelerated (human-induced) climate change."
- Climate change, development, or a combination of the two will almost certainly result in **increased fire risk**, which could exacerbate greenhouse gas losses if large areas of peatland burn.
  - **Boreal Shield ESTR**: "Higher wildfire risk, earlier fire occurrence, and increased insect defoliation in the northeastern portion of the ecozone+ replaced closed-crown boreal forest stands with lichen-spruce woodlands. In the western part of the ecozone+, increased wildfire risk and mountain pine beetle invasion could lead to decreased ecosystem productivity and significant releases of stored carbon. Lower intensity fires were more abundant and occurred earlier in the season in dense, mature conifer forests...Natural disturbances in the Boreal Shield Ecozone+ appear to be changing. Early warnings include increasing wildfire risk in some regions."
  - **Hudson Plains ESTR**: "[B]y 2100, the projected increase in future fire risk is expected to bring at least the southern portion of the area's burn rate towards the upper limit of its range of natural variability during the last ~7,000 years... If carbon stored in the ecozone's peatlands is released to the atmosphere, the release could lead to a positive feedback to atmospheric greenhouse gases, which could be further exacerbated if

large areas of dry peatlands burn. Disturbances are in general expected to increase, including an increase in the area burned."

- Climate change will extend the range of southern species northward, increasing the likelihood of **invasive species** surviving in northern landscapes. Development will facilitate human access, use, and development, and create new vectors for the spread of non-native species.
    - **Boreal Shield ESTR**: "Invasive species affect ecosystem composition and structure by displacing native species and altering ecological processes. The relatively extreme climate, low biodiversity, and poor resource availability of the Boreal Shield Ecozone+ have thus far resisted invasions of non-native species relative to other ecozones+. Most invasive species occur in the southern part of the Boreal Shield Ecozone+, in the Great Lakes-St. Lawrence Forest (82–90 species) and Boreal transition areas (64–72 species) in Ontario and Quebec…Invasive species have been invading the boreal forest from southern Quebec and Ontario. Climate change and resource exploitation are expected to intensify the arrival and establishment of non-native species in this ecozone+."
    - **Hudson Plains ESTR**: "Presently, many stressors typical of more human-populated areas are comparatively unimportant in this ecozone, including nutrient loading, pesticides, acid precipitation, air pollution, light pollution, and invasive species…The numerous and varied resource development proposals, prospecting activities, and assessments of resource potentials in the ecozone, particularly in mining, hydroelectric, and wind-farming sectors, likewise suggest that development of additional roads and infrastructure is imminent. Further human access, use, and development inevitably follows, typically in association with habitat displacement, deterioration, and fragmentation; the introduction and spread of introduced and potentially invasive species; and declines in fish and wildlife populations – particularly sensitive species that occur at low densities, have large area requirements, are habitat specialists rather than generalists, and/or are particularly vulnerable to over-harvest (e.g., sturgeon, lake trout, wolverine, caribou, wolf)."
- Hydrology drives carbon storage and methane flux; is the primary pathway for mercury transport; and is the main determinant of fish habitat and peatland stability. **Alteration of wetland hydrological processes by human-induced disturbances** such as linear corridors and hydroelectric development will impact regional biodiversity and carbon and methane cycling, and these effects will be compounded by climate warming.
    - **Boreal Shield ESTR**: "Hydrological changes related to hydro-developments were also reported to cause changes in fish ecology, including spawning behaviour, presence of certain species, and an overall reduction in freshwater biodiversity… Dams and reservoirs alter the

physical landscape, interrupt hydrological regimes, and the process of impoundment introduces contaminants that can accumulate along the food chain. More specifically, dams interrupt fish migration, increase sedimentation, affect habitat for many species, and change water levels and water chemistry. The degree of impact depends on the size of the dams, their operation, and the ecosystems' biophysical characteristics."

  - **Hudson Plains ESTR**: "The effects of climate change on the resilience of this ecozone and its capacity to continue supplying ecosystem services are uncertain…Like elsewhere in Canada, changes in the hydrological regimes of some rivers in the Hudson Plains Ecozone are also associated with hydroelectric developments, including water diversions…"

- **The impacts of development are likely to extend for a considerable distance beyond the project footprint**.
  - **Boreal Shield ESTR**: "Hydroelectric dams and reservoirs have been the primary causes of wetland losses…Road construction and use increases sedimentation and alters the water balance of wetlands."
  - **Hudson Plains ESTR**: "The rivers in the Hudson Plains Ecozone are…also affected by hydroelectric developments in adjacent ecozones via hydrological connectivity. Such developments tend to have widespread environmental effects within watersheds, well beyond the immediate vicinity of the development itself." The report also states that the area affected by the Victor Mine development is "considerably larger than the mine itself" as a result of dewatering operations (withdrawals and discharges) that alter the regional water balance. Although a post-closure rehabilitation plan is in place, "certain areas will not be restored".

- **Development of a network of roads** is likely to alter the physical and chemical environment, modify aquatic and terrestrial animal behaviour, and increase wildlife mortality from construction activities and vehicle collisions. Both ESTR reports state that development of roads, mines, dams and reservoirs, power lines, and other industry results in fragmented landscapes.
  - **Boreal Shield ESTR**: "As of 2006, 64% of the total area of the Boreal Shield Ecozone+ was composed of intact terrestrial landscape fragments larger than 10 km^2. A terrestrial landscape fragment is defined as a contiguous mosaic, naturally occurring and essentially undisturbed by significant human influence. It is a mosaic of various natural ecosystem including forest, bog, water, tundra and rock outcrops. Most of these fragments were north of the limit of managed forest. Fragmented landscapes are a result of forest harvesting, roads, mining, dams and reservoirs, power lines, and industrial development."
  - **Hudson Plains ESTR**: Although likely to bring additional jobs to the ecozone's wage economy, the high potential for additional resource

> developments is of ecological concern, not only due to potential direct effects, but also because it drives the establishment of roads and other infrastructure... Roads and other infrastructure contribute fragmentation to the landscape and facilitate further human access, use, and development, along with associated influences on ecosystems and biota. For example, given likely development in the Ring of Fire area, future north-south fragmentation of the ecozone could conceivably occur from the adjoining of east-west developments – from the Ring of Fire east to the Victor mine and on to Attawapiskat at the coast...Cumulative impacts, especially those from roads and multiple hydroelectric developments in the Hudson Bay watershed, are a concern and need to be addressed effectively to help guide decisions about future development...Plans to develop roads and other regional infrastructure to service projects and communities would ideally be coordinated so as to limit overall road densities and, thus, maintain a high degree of ecosystem connectivity, intactness, and resilience."

None of the reports found a consistent increasing trend in mercury in fish tissue, although atmospheric concentrations of mercury are increasing.

Minor points to note are:

- The 2011 Hudson Plains report noted that coarse satellite imagery was not useful for monitoring assemblages because of its inability to distinguish wetland from tundra. The opportunities for using satellite imagery for monitoring discussed in the current report represent significant improvements in technology since the publication of the Hudson Plains report, with much higher resolution satellite imaging now available.
- The 2014 Boreal Shield and 2011 Hudson Plains ESTR reports flag hydroelectric dams, water diversions, and weirs as the most serious threats to hydrology and connectivity. While the current report raises concern about the potential impact of additional hydroelectric development in the Assessment Area, the literature scan and interviews reported here suggest that development-related linear infrastructure such as roads and power corridors, and mine development including dewatering activities, pose the most imminent threats to hydrologic and biological connectivity in the Assessment Area.

6.3 Implementation Status of 2010 Far North Science Advisory Panel Recommendations

The 2010 Far North Science Panel report anticipated:

- Challenges with scope and scale
- Carbon vulnerability
- Hydrologic risk

- Cumulative effects
- Need for adaptive governance

The current report concludes that the scientific logic of the 2010 report was sound and has been supported by the scholarly and technical literature published since then, although the institutional architecture envisioned by the Science Panel was never fully built or operationalized.

The following are some of the key recommendations from the 2010 report with a brief overview of the implementation status of each, and suggestions as to how they might be operationalized in the future.

Science Panel Recommendation 1. Create a coordinated government-wide strategy for the management of interim and ongoing development

The Science Panel recommended the creation of a coordinated government-wide strategy aimed at minimizing the adverse ecological impacts of interim development as community planning proceeds. They noted that project- or activity-specific approvals will fail to capture the cumulative impacts of development on ecological integrity over the region and over time.

Implementation status

- Not implemented.
- Despite recent advances in federal-provincial cooperation, for example the “One Project, One Process, One Decision” cooperation agreement, there is no single coordinated government-wide strategy for the management of interim and ongoing development within the Assessment Area.

Science Panel Recommendation 2: Designate the Ring of Fire as a Priority Management Area

The Science panel called for immediate designation of the Ring of Fire as a priority management area supported by an interim sub-regional planning process before major development proceeds.

Implementation status

- Partially implemented.
- The current Regional Assessment (RA) is the first formal attempt at sub-regional framing. However, development pressures and infrastructure planning have advanced without a binding sub-regional land use framework.

Future opportunity

- There is an opportunity to formally embed the RA into a statutory sub-regional planning framework with legal weight, and to define enforceable regional limits before project approvals.

- RA outputs could be aligned with binding land use instruments under existing legislation.

Science Panel Recommendation 3: Establish a Far North Land Use Strategy

The Science Panel recommended a region-wide strategic land use approach with the goal of protecting ecological integrity at the regional scale.

Implementation status

- Largely unimplemented at the regional scale.
- Community-based planning has occurred in some areas.

Future opportunity

- There is an opportunity to use watersheds or similar natural boundaries as planning units; see next point.

Science Panel Recommendation 3.5: Use Watersheds or Natural Boundaries as Planning Units

The Science Panel also recommended using watersheds or similar natural boundaries as planning units.

Implementation status

- No fully integrated watershed-scale land use architecture exists for the Assessment Area.
- Not institutionalized in Ontario's Far North planning framework.
- Assessment areas still partially politically defined.

Future opportunity

- There is an opportunity to adopt a nested watershed framework with 5–6 major watersheds established as primary assessment units. Appendix B provides examples of how this could be done.
- Protected areas, infrastructure planning, and cumulative limits could then be aligned with watershed boundaries.

Science Panel Recommendation 4: Plan Development Incrementally

Under this heading, the Science Panel recommended four strategies for development planning: assess and manage cumulative impacts; maintain and extend moratoria on large-scale water diversions; plan transportation and transmission corridors in a coordinated fashion; and prevent the introduction of invasive species. The implementation status of each is discussed below.

Science Panel Recommendation 4.1: Assess and Manage Cumulative Impacts

- Explicit cumulative effects assessment.
- Plan development incrementally.

Implementation status

- Conceptually acknowledged but structurally weak.
- Project-by-project reviews still dominate.
- Road proposals and infrastructure often assessed individually.

Future opportunity

- Operationalize cumulative assessment through:
    - Regional thresholds
    - Trigger–response frameworks
    - Road network evaluation rather than single corridors
- Embed cumulative caps into decision rules.

Science Panel Recommendation 4.2: Maintain and Extend Moratoria on Large-Scale Water Diversions

- Maintain moratorium on large hydroelectric development.
- Extend to inter-basin water diversions.

Implementation status

- No major diversions have been approved in the Assessment Area.
- However, hydrologic alteration risk from roads and dewatering was not fully anticipated in 2010 and is now understood to be a potentially serious concern.

Future opportunity

- Expand the spirit of this recommendation to include:
    - Strict controls on dewatering discharge
    - Regional hydrologic alteration thresholds
    - No-net-hydrologic-connectivity-loss principle

Science Panel Recommendation 4.3: Plan Transportation and Transmission Corridors in a Coordinated Fashion

- Coordinated corridor planning.
- Protect significant ecological features.
- Recognize community needs.

Implementation status

- Partially implemented.
- Corridor proposals still largely proponent-driven.
- Network-level hydrologic and predator access impacts under-assessed.

Future opportunity

- Evaluate roads as regional systems, not individual projects.
- Establish control parameters such as watershed-scale crossing density limits.
- Require corridor bundling and shared access strategies.

Science Panel Recommendation 4.4: Prevent the Introduction of Invasive Species

- Closely monitor access networks and use.
- Inspect and clean equipment to reduce the risk of accidental importation.
- Rehabilitation projects should use only native species.

Implementation status

- Partially implemented
- Ontario has implemented province-wide invasive species prevention legislation and strategies, which partially address the recommendation, especially the *Invasive Species Act*, 2015, and the Ontario Invasive Species Strategic Plan and related renewal efforts.
- Some technical guidance for mining and road development in the region includes best practices for preventing invasive species introduction, e.g., equipment cleaning protocols and invasive species monitoring.

Future opportunity

- Embed requirements for proactive invasive species monitoring and prevention before major development occurs.
- Establish early detection-monitoring systems for new road corridors, which are the main pathway for invasive species introduction in northern landscapes.

Science Panel Recommendation 5: Apply Adaptive Management with Continuous Learning

- Base decisions on best knowledge.
- Revisit and revise strategies as knowledge improves.

Implementation status

- Adaptive management referenced in impact assessment process and documents.

- Rarely tied to enforceable triggers or stop/redesign rules.

Future opportunity

- Convert adaptive management from a philosophical approach to a practical management framework including:
    - Co-governed, cyclical work planning and analysis of results
    - Collaborative learning that welcomes both Western and Indigenous knowledge systems
    - Predefined Trigger Action Response Plans (TARPs) and decision triggers
    - Automatic intervention thresholds

Science Panel Recommendation 6.1: Create a Far North Information System to Facilitate the Use of Best Available Knowledge, Including Aboriginal Traditional Knowledge

- Centralized knowledge system.
- Incorporation of Traditional Knowledge.
- Data inventory.

Implementation status

- No fully integrated, open-access, regional geospatial repository exists.
- Data fragmentation and outdated datasets were identified in the literature scan and key informant interviews.

Future opportunity

- Launch a regional data recovery and open access initiative.
- Centralize hydrology, caribou telemetry, mercury, and peatland datasets.
- Co-govern data access protocols.

7 Recommendations

The following sections recommend actions under six categories:

- Scope and scale of impact assessment
- Science and monitoring priorities
- Governance and decision architecture
- Data and transparency actions
- Policy and precaution
- Capacity and community engagement

The recommendations reflect repeated themes in the interviews: scale mismatch, hydrology risk, carbon and mercury vulnerability, cumulative effects, governance gaps, and data access barriers.

7.1 Scope and Scale of Impact Assessment

Recommendation 1: Adopt a nested, watershed-based impact assessment framework. Formally adopt watershed boundaries (5–6 major watersheds) as primary assessment units, with nested sub-watersheds and receptor-specific scales (e.g., caribou herd ranges, sturgeon river systems).

Rationale: Interviewees consistently stressed that ecological processes, cumulative effects, and Indigenous rights operate at watershed and herd scales, not project footprints.

Action:

- Define assessment units before evaluating development scenarios.
- Require all project-level submissions to report impacts within those watershed-scale units.

***Suggestion**: A two-day workshop, preferably in person, could bring together Indigenous knowledge keepers and Western scientists to propose a specific structure for a nested, watershed-based impact assessment framework.*

Appendix B provides three hypothetical examples of nested watershed study design. These examples are provided for illustrative purposes only and are not intended as recommendations for the Ring of Fire.

Recommendation 2: Treat roads as regional infrastructure, not standalone projects. Assess roads and linear corridors as access-enabling networks with cumulative hydrologic, ecological, and social effects.

Rationale: Roads were repeatedly described as the most significant impact multiplier (hydrology alteration, predator access, fish barrier effects, harvest pressure).

Action:

- Conduct scenario-based road network modelling.
- Evaluate hydrologic connectivity and predator/prey fragmentation at range scale.

7.2 Science and Monitoring Priorities

Suggestion*: A one- or two-day workshop on each topic area could bring together experts to confirm the state of the science and develop recommendations for enhanced monitoring strategies.*

Recommendation 3: Make hydrology the monitoring core. Re-establish and expand regional hydrometric networks (stream gauges, water table wells, groundwater monitoring) as the foundation of cumulative effects monitoring.

Rationale: Hydrology was identified as both the organizing variable and the greatest knowledge gap.

Action:

- Recover and restore previously installed streamflow gauges.
- Fund long-term (multi-decade) hydrologic monitoring.
- Integrate remote sensing with ground validation.

Recommendation 4: Implement a peatland carbon and methane monitoring strategy. Develop a coupled hydrology–carbon monitoring framework that tracks water table depth, carbon flux, and methane emissions.

Rationale: Irrecoverable carbon loss and methane amplification are central concerns not adequately incorporated in Environmental Assessment (EA) processes.

Action:

- Establish baseline multi-season data before major disturbance.
- Incorporate climate-adjusted carbon accounting into assessment.

Recommendation 5: Adopt a precautionary mercury framework. Shift from "monitor and adapt" to proactive sulphate control and biomonitoring triggers.

Rationale: The region was described as extremely sensitive to methylation, with little room for error.

Action:

- Prioritize sulphate monitoring at discharge points.
- Implement young-of-year fish biomonitoring.
- Establish rapid trigger–response protocols.
- Require public disclosure of historic and current industry mercury data.

Recommendation 6: Strengthen lake sturgeon and caribou monitoring. Invest in telemetry and movement studies for lake sturgeon and caribou, integrated with Indigenous knowledge.

Rationale: Both species were repeatedly identified as culturally significant and sensitive to fragmentation, with data gaps.

Action:

- Fund river-scale sturgeon movement studies.
- Update and publicly release caribou datasets.
- Evaluate herd-scale fragmentation risk.

7.3 Governance and Decision Architecture

Recommendation 7: Establish a co-governed science and monitoring table. Create a formal co-governed body to define indicators, thresholds ("limits"), triggers, and acceptable uncertainty.

Rationale: Interviewees described a governance gap and absence of shared authority over decision rules.

Action:

- Co-develop action thresholds and trigger–action response plans, including intensive monitoring where warranted.
- Co-define stop/redesign conditions.

Recommendation 8: Design and embed an adaptive management process and governance structure. Consider developing Trigger Action Response Plans (TARPs) for hydrology, mercury, carbon, and species indicators.

Rationale: Adaptive management provides an operational framework to support decision making in the context of ecological and climate uncertainty.

Action:

- Co-develop conceptual models/understanding of system structure and function and hypotheses of system response to future climate and development scenarios.
- Co-develop and implement targeted monitoring programs to track key indicator parameters.
- Co-design adaptive management and adaptive monitoring processes with annual work plans and cyclical review of progress.
    - Develop a five-year adaptive management plan and annual work plans
    - Review and discuss monitoring results on an annual basis; revise the next year's work plan as necessary.
    - Every five years, conduct a comprehensive review of observed conditions against predictions and revise conceptual models as necessary to explain differences.
    - Every five years, produce and implement a new five-year adaptive management plan and annual work plans for the next cycle.

Suggestion*: Many effective adaptive management models exist, with some in operation for decades. Commission a study to compile this information into a set of options for consideration by the RAWG.*

7.4 Data and Transparency Actions

Recommendation 9: Audit, recover, and centralize publicly funded datasets and require industry data disclosure.

Rationale: Interviewees identified widespread data fragmentation, paywalls, and intellectual property barriers as obstacles to effective management and impact assessment within the Assessment Area.

Action:

- Establish an open geospatial repository.
- Require industry data disclosure.

- Standardize metadata and QA protocols.

Recommendation 10: Use modern remote sensing (LiDAR, SAR, high-resolution imagery), including drone technology, to refine peatland, wetland, and habitat classification, with special attention to updating the Ecological Land Classification system for the ecodistrict level and wetland mapping more generally.

Rationale: Mapping gaps were repeatedly cited as limiting meaningful planning. Current remote sensing technologies hold promise for updating these maps.

Action:

- Invest in ground-truthing for remote sensing products.
- Update wetland and ecodistrict layers.
- Ensure public access to remote sensing products.

***Suggestion**: Host a two-day workshop for remote sensing experts, preferably in person, to develop a remote sensing strategy for the Assessment Area, including meaningful roles for Indigenous communities.*

7.5 Policy and Precaution

Recommendation 11: Consider development of formal peatland protection and cumulative effects policies.

Rationale: Multiple interviewees identified the absence of peatland governance as a critical gap that limits effective land use and development planning for the Assessment Area. A peatland management policy framework – not just for the Assessment Area, but for peatlands more generally – should treat peatlands as hydrologic and carbon systems first, and land-cover classes second. In practice, that means the policy should not rely on simple "wetland area lost/area compensated" rules. Instead, it should focus on maintaining water-table stability, hydrologic connectivity, carbon storage, and downstream water quality across whole peatland complexes. No project should proceed if it is likely to cause persistent water-table change, major connectivity disruption, or irreversible carbon loss in a peatland complex at site or watershed scale.

A workable peatland policy could be framed around peatland sensitivity zoning, for example:

- **Zone 1: "No-go" peatlands**, where development is prohibited in
    - Intact fens with strong groundwater dependence;
    - Peatlands with high carbon density;
    - Peatlands that maintain major downstream hydrologic connectivity;

    - Peatlands that support culturally critical uses or species; or
    - Peatlands where disturbance risks broad landscape drying or flooding
- **Zone 2: Conditional development areas,** in which development is permitted only if proponents can show:
    - No significant drawdown or impoundment beyond defined limits;
    - No major loss of connectivity;
    - No significant carbon release beyond approved thresholds; and
    - That no safer feasible alternative exists
- **Zone 3: Previously disturbed or lower-risk areas,** which may be preferred for infrastructure, subject to strict hydrologic design and monitoring.

Recommendation 12: Require that climate change be integrated into all infrastructure design. Require climate-forward design for roads, tailings facilities, water management systems and other infrastructure.

Rationale: Climate was described as an overarching stressor that is already affecting every part of the Assessment Area. It is critical that climate be considered in tandem with infrastructure design and placement.

Suggestion*: Host a virtual or in-person workshop or commission an expert report on peatland road engineering to develop design standards and alternative approaches for roads within the Assessment Area.*

Recommendation 13: Formally adopt a precautionary hierarchy in effects assessment and mitigation. Avoidance of impacts should be the highest priority, followed by minimization of impacts and restoration, with compensation used only as a last resort.

Rationale: Habitat compensation effectiveness is weak; peatland systems are difficult to restore.

7.6 Capacity and Community Engagement

Recommendation 14: Build community-based monitoring capacity. Shift from fly-in science to community-based environmental monitoring networks.

Rationale: Interviewees emphasized the value, sustainability, and legitimacy of a broad network of community monitors with deep knowledge of the landscape. Community-based monitoring also offers an opportunity for community capacity-building and meaningful employment, especially for youth.

Action:

- Establish a co-governed Fish and Wildlife Technical Committee.
- Provide stable funding for community-based training and equipment.
- Create annual knowledge-sharing forums.

Appendix A:

Potential Strategic Research Priorities

Disclaimer: *A reminder that this report is not intended to be a comprehensive review of the scholarly and technical literature reporting or expert views on Western science relevant to the Ring of Fire. The potential strategic research priorities described in this appendix reflect the views and perspectives of the author on a variety of key topics and are intended to guide further discussion by the Regional Assessment Working Group.*

A1 Potential Strategic Research Priorities

The literature scan revealed strong conceptual understanding of system vulnerability, but weak quantitative thresholds and insufficient cumulative-scale modelling. The most urgent research investments are therefore:

- Watershed-scale modelling
- Carbon and mercury risk quantification
- Connectivity and fragmentation analysis
- Climate-integrated scenario modelling
- Governance-linked threshold development

The following are proposals for priority future research topics.

Priority 1: Regional Hydrologic–Infrastructure Modelling

Objective: Develop cumulative watershed models that integrate roads, dewatering, permafrost thaw, and climate change.

Why: Hydrology is the master variable driving carbon, mercury, fish habitat, and peatland stability.

Outputs:

- Watershed-scale scenario modelling
- Insight into drawdown/subsidence thresholds
- Support for climate-forward design standards

Priority 2: Peatland Carbon and Methane Observatory Network

Objective: Establish long-term flux towers and eddy covariance sites within Assessment Area peat systems.

Why: Carbon irreversibility is a global climate risk and currently under-quantified within the Assessment Area, one of the last largely undisturbed peatland systems in the world.

Outputs:

- Site-specific emission factors
- Disturbance vs. warming comparisons
- Carbon tipping-point indicators

Priority 3: Mercury Baseline and Trigger Framework

Objective: Develop region-wide mercury baseline datasets and enforceable trigger thresholds.

Why: Methylation risk is high; current approach is reactive.

Outputs:

- Sulphate–methylation response curves
- Fish tissue biomonitoring program (including tissues like chum and brain important in Indigenous diets, in addition to muscle tissue)
- Support for development of Trigger Action Response Plans

Priority 4: Cumulative Connectivity Modelling

Objective: Quantify terrestrial and aquatic habitat connectivity under development scenarios, including road networks.

Why: Habitat fragmentation is the dominant biodiversity risk pathway.

Outputs:
- Caribou movement modelling
- Fish passage risk mapping
- Development of landscape permeability indices for ecological connectivity

Priority 5: Climate–Development Scenario Integration

Objective: Model future climate conditions (hydrology, fire, thaw) alongside infrastructure development scenarios.

Why: Infrastructure built for historic baselines will fail under future climate extremes.

Outputs:
- Joint climate–infrastructure risk assessments
- Development of adaptive design thresholds
- Development of resilience indicators

Priority 6: Identification and Quantification of Ecological Limits

Objective: Identify quantitative tipping points for peat subsidence, fish thermal stress, and carbon release.

Why: Non-linear change risk is repeatedly identified but poorly parameterized.

Outputs:
- Early-warning hydrologic metrics
- Carbon stability indicators
- Identification of landscape disturbance tipping points

Priority 7: Integrated Open Data Platform

Objective: Recover, update, and centralize publicly funded datasets (hydrology, telemetry, biodiversity).

Why: Data fragmentation undermines cumulative assessment.

Outputs:
- Public geospatial portal

- Version-controlled datasets with standardized metadata
- Cross-scale visualization tools

Priority 8: Conservation Network Optimization

Objective: Design a watershed-scale protected area network using climate-resilient connectivity modelling.

Why: Current protected areas are fragmented and not optimized in a regional network.

Outputs:
- Connectivity-based conservation design
- Climate refugia identification
- Gap analysis for SAR

Priority 9: Infrastructure Design Experiments

Objective: Pilot hydrologically neutral road and crossing designs in peatland terrain.

Why: Roads are the dominant structural impact driver.

Outputs:
- Experimental culvert, causeway and bridge designs
- Flow-permeable road templates
- Monitoring of pilot corridors

Priority 10: Co-Developed Ecological Limits and Disturbance Caps

Objective: Co-develop enforceable ecological thresholds with Indigenous governments.

Why: Science without decision triggers lacks impact. Co-development of ecological limits and disturbance caps offers an opportunity to bring together Western and Indigenous knowledge systems to support impact assessment for the RoF.

Outputs:
- Co-defined ecological limits
- Regional disturbance caps
- Adaptive management escalation rules and trigger action response plans

Appendix B:
Three Example Nested Watershed Study Designs

Disclaimer: *A reminder that this report is not intended to be a comprehensive review of the scholarly and technical literature reporting or expert views on Western science relevant to the Ring of Fire. Rather, it reflects the views and perspectives of the author on a variety of key topics and is intended to guide further discussion by the Regional Assessment Working Group.*

The example nested watershed study designs presented in this appendix are entirely hypothetical and are provided only for illustrative purposes; they are not intended as recommendations for the Ring of Fire.

B1 Option 1: Large-Scale Nested Watershed Study with Remote Sensing, Acoustic Monitoring and eDNA

The following is an example large-scale nested watershed study design suitable for the Ring of Fire/Hudson Bay Lowlands context, with peatland-dominated landscapes, limited baseline data, strong seasonality, and potential development pressures (roads, mines, dewatering, aggregate pits, borrow areas). The study design is intended to be mechanistic and scalable, innovative, but moderate in cost and risk.

The core idea is to use a **hierarchy of catchments** (small → medium → large) to connect:

- **process understanding** (small headwaters/peatland units),
- **cumulative effects** (meso-catchments),
- and **policy-relevant outcomes** (major rivers and downstream receiving waters).

This approach would use few intensively instrumented sites coupled with a broader network of lighter-touch monitoring. Conceptually, the flow is:

Mechanism (Tier A) → Watershed Response (Tier B) → Cumulative Signal (Tier C)

and

Field data → Sensor validation → Remote sensing scaling → Decision triggers

B.1.1 Recommendations for nested structure (tiers)

Tier A - "Process" Micro-Catchments (0.1–10 km^2)

Purpose: isolate mechanisms in peatlands and headwaters.

- **6–12 micro-catchments** chosen across key gradients:
  - peat depth and type (bog vs fen),
  - permafrost presence/absence (if relevant),
  - forested peat plateau vs open peatland,
  - natural fire history/burn severity,
  - proximity to proposed infrastructure corridor.
- **Instrumentation (high intensity):**
  - Water table wells/piezometers (peat profiles)
  - Discharge (weirs/flumes or rating curves)
  - Continuous sensors: temperature, conductivity, turbidity, dissolved oxygen
  - Event sampling during storms/snowmelt
  - Carbon: DOC/POC, DIC, CO_2/CH_4 flux (chambers/eddy at 1–2 sites)
  - Nutrients: TP, SRP, TN, NO_3, NH_4

- Metals of concern (context-specific): Fe, Mn; Hg/MeHg where food webs matter
- Sediment/erosion (where mineral interfaces exist)

Tier B - "Response" Meso-Catchments (10–500 km^2)

Purpose: integrate tributary networks and detect sub-watershed responses.

- **4–8 meso-catchments**, each containing several Tier A sites.
- Include at least:
  - 1–2 reference basins with minimal disturbance
  - 2–4 "development-influence" basins (basins where development is likely to occur)
- **Monitoring (medium intensity)**:
  - Streamflow at main stem and key tributaries
  - Continuous water quality at outlets
  - Seasonal synoptic surveys (spring freshet, mid-summer, fall)
  - Remote sensing products validated in-field (wetness, inundation, vegetation change)

Tier C - "Cumulative" Major Basins (500–20,000+ km^2)

Purpose: quantify cumulative effects at management scale.

- **At least 2–3 large river basins** that capture the main receiving systems relevant to communities and downstream ecosystems.
- **Monitoring (lower intensity but strategic):**
  - Long-term gauge enhancement (if WSC stations exist)
  - Continuous sensors at strategic nodes (upstream/downstream of key stressors)
  - Annual/biannual biological indicators (fish, benthos, eDNA)

B.1.2 Study design logic: gradients and before-after-control-impact

Use a **Before–After–Control–Impact (BACI)** backbone wherever development may occur.

- **Before:** at least 2 years of baseline (more if possible)
- **After:** multi-year, with extra sampling during construction and early operation
- **Control:** matched reference catchments (same ecozone/peat type) with no development
- **Impact:** catchments influenced by road crossings, borrow pits, dewatering, etc.

If development timing is uncertain, implement a paired-catchment design with reference sites and treat "impact" as conditional.

B.1.3 Recommended minimal core monitoring suite and optional modules

Core Monitoring Suite (do everywhere at Tier B/C; intensively at Tier A)

Hydrology

- discharge, stage, precipitation, snowpack
- water table depth (peatlands)
- connectivity/inundation mapping

Water quality

- DOC (and UV absorbance where feasible), TSS/turbidity
- TP/SRP, TN/NO_3/NH_4
- conductivity, temperature, pH, dissolved oxygen

Carbon and greenhouse gases

- DOC export at outlets (load estimates)
- CO_2/CH_4 flux at 1–2 flagship sites + upscaling approach

Optional Monitoring Modules (deploy where relevant)

- **Mercury/MeHg** (food web risk, fish consumption)
- **Metals** (Fe/Mn dynamics, potential mine-related signatures later)
- **Sediment source tracing** (if mineral soil disturbance becomes important)
- **eDNA/bioassessment** (community change detection, baseline biodiversity)

Biological Monitoring

Biology is often expensive and logistically difficult in these northern landscapes. Efficient biomonitoring could include:

- **eDNA metabarcoding** at Tier B outlets (2–4 times/year) for fish + macroinvertebrate signals
- **Sentinel fish sampling** in accessible reaches (every 2–3 years)
- **Benthic invertebrate indices** where methods are validated for peatland rivers (can be tricky; plan carefully)
- **Wetland vegetation plots** in Tier A peatlands (annual/biannual)

Remote sensing integration (critical for scaling)

Use field sites to calibrate watershed-scale indicators:

- Inundation/wetness (Synthetic Aperture Radar, or SAR)
- Species at risk
- Vegetation change/phenology (optical time series)
- Surface disturbance (roads, pads, borrow areas)
- Fire scars and recovery
- Peatland condition proxies (where feasible)

Remote sensing helps to connect point measurements to landscape inference and supports the nested study framework.

See Section B4 for additional detail on integration of new and emerging monitoring approaches into a nested watershed study design.

Site Selection Criteria

Choose sites to maximize inference and feasibility:

- Represent major **peatland types** and hydrologic settings
- Bracket likely **development stressors** (roads, dewatering, aggregates)
- Accessible enough for repeated sampling (helicopter/road/boat reality)
- Include **community-relevant** receiving waters (subsistence, cultural use)

B.1.4 Governance and shared authority

Build shared authority into design and operations to improve legitimacy and increase the likelihood of data use:

- Co-develop monitoring questions and site selection
- Indigenous-led data governance (access, use, interpretation)
- Training and paid field roles for local technicians
- Joint interpretation workshops annually

Decision-Relevant Outputs

Design the program so it produces:

- **Baseline ranges** and variability (not just point estimates)
- **Load estimates** (DOC, nutrients, sediments) at Tier B/C outlets
- **Threshold/trigger indicators** (e.g., water table drawdown magnitude/duration, DOC “darkening,” turbidity exceedances)
- A **cumulative effects dashboard** (even if simple)

An Example Three- to Five-Year Rollout

- **Year 1:** co-design + reconnaissance + install Tier B/C nodes; pick Tier A sites
- **Year 2–3:** full baseline (Tier A intensive; Tier B/C regular); remote sensing calibration
- **Year 4–5:** BACI “after” phase if development begins; otherwise continue baseline + stressor-response modelling

B2 Option 2: Lower-Cost Version

This option is designed for provincial/federal collaborative funding without major infrastructure build. It is intended to:

- Focus on baseline variability and early-warning indicators
- Use open-access satellite data
- Minimize helicopter dependency
- Avoid eddy covariance towers
- Avoid high-cost nutrient analyzers
- Lean toward load modelling instead of real-time chemistry

Approximate Scale (Order of Magnitude)

- Capital: Moderate (sensor stations, ARUs, eDNA lab processing)
- Annual O and M: Moderate but manageable
- Personnel: 1 postdoc + 2 technicians + community field roles

A study at this scale could be appropriate for funding under an NSERC Alliance grant; Canada Water Agency programs; Ontario research initiatives; and/or impact assessment follow-up.

Study Components

This study design would be reduced from Option 1 to include the following:

Tier A (2–3 sites only)

- Manual water table wells
- Seasonal DOC/nutrient sampling
- 1 methane chamber site
- Portable flow measurements

Tier B (3–4 sub-watersheds)

- One continuous sensor station per basin
- Seasonal grab samples (spring, summer, fall)
- 2× per year eDNA

Tier C (2 major basins)

- Leverage existing Water Survey of Canada gauges
- Install turbidity + temperature sensors only
- Annual eDNA

Remote Sensing

- Free satellite data (Sentinel-1 SAR, Sentinel-2)
- Limited drone flights (annual)

Acoustic Monitoring

- 6–10 ARUs rotating seasonally

B3 Option 3: High-Innovation Flagship Research Proposal

Example Working Title: *Connected Peatlands: Integrating Genomics, Remote Sensing, and Indigenous Knowledge to Detect Early Thresholds of Landscape Change*

A high-innovation nested watershed study in the Assessment Area could be CIFAR/NSERC/SSHRC competitive if it includes investigation/demonstration of:

- Novel integration of genomics + AI + peatland hydrology
- Climate change + development interface
- Indigenous co-governance embedded from design stage
- Global relevance (boreal peatlands worldwide)
- Strong HQP training component

B.3.1 Core Innovation Themes

Molecular Biosensing of Watersheds

- eDNA as a real-time biodiversity indicator
- Microbial community shifts as redox/oxygen proxies
- Metagenomics linked to carbon cycling

AI-Driven Remote Sensing Integration

- Machine learning to predict water table depth from SAR
- Early detection of peatland drying signatures
- Integration of acoustic biodiversity indices into predictive models

Carbon–Hydrology–Connectivity Coupling

- Peatland carbon flux scaling from Tier A → basin
- Detecting threshold transitions before hydrologic collapse
- DOC "darkening" as early warning signal

Indigenous Co-Governance of Environmental Intelligence

- Indigenous-led monitoring nodes
- Data sovereignty framework
- Two-Eyed Seeing integration
- Community-designed trigger thresholds

B.3.2 Flagship Technical Additions

- 1–2 eddy covariance towers
- Drone-based methane mapping
- Distributed temperature sensing along streams
- Automated UV–Vis DOC spectrophotometers
- Real-time dashboard with satellite uplink
- Coupled hydrologic–biogeochemical models

Interdisciplinary Components

Discipline	Role
Hydrology	Connectivity modelling
Environmental Genomics	eDNA + microbial signals
Remote Sensing	Wetness and vegetation scaling
Data Science	AI + early-warning systems
Social Science (SSHRC)	Governance, data sovereignty, risk perception
Indigenous Scholars	Co-designed knowledge frameworks

B.3.3 Potential Research Questions

1. Can molecular and acoustic signals detect peatland regime shifts before hydrologic collapse?
2. What are the earliest detectable indicators of road-induced hydrologic fragmentation?
3. How does climate warming alter DOC export and methane emissions in peatland basins?
4. Can AI-based integration of SAR + field data predict threshold transitions?
5. How can cumulative effects dashboards be co-governed under Indigenous data sovereignty?

B.3.4 Outputs

- Peer-reviewed interdisciplinary publications
- Basin-scale early-warning models
- Indigenous-led data governance framework
- Policy-ready cumulative effects thresholds
- Open data + decision-support dashboard

Table B.1. Summary of the three nested watershed study options described in Appendix B. The options differ mainly in cost, technological complexity, and research ambition, while retaining the same core nested watershed framework (Tier A–B–C). Option 1 emphasizes a robust operational monitoring system combining field data and emerging technologies; Option 2 provides a scaled-down, pragmatic monitoring program focused on baseline conditions and early detection; and Option 3 represents a flagship research initiative aimed at scientific innovation and predictive modelling of ecosystem change

Study Option	Purpose / Scope	Core Design	Key Technologies	Scale of Effort	Main Strengths	Limitations
Option 1: Nested Watershed Study with Remote Sensing, Acoustic Monitoring and eDNA	Comprehensive watershed monitoring framework to detect mechanisms, watershed responses, and cumulative impacts in peatland-dominated landscapes.	Three-tier structure: **Tier A micro-catchments (0.1–10 km^2)** for process studies; **Tier B meso-catchments (10–500 km^2)** for watershed responses; **Tier C large basins (500–20,000+ km^2)** for cumulative signals.	Remote sensing (SAR, optical satellites), eDNA biodiversity monitoring, acoustic sensors, automated water quality stations, IoT sensors, carbon flux monitoring.	High effort, multi-institutional monitoring network.	Strong mechanistic understanding; integrates field data with landscape-scale remote sensing; detects early ecological change and cumulative impacts.	Higher cost and logistical complexity; requires sustained monitoring and technical capacity.
Option 2: Lower-Cost Version (3–5 Years)	Cost-effective baseline and early-warning monitoring program suitable for collaborative government or research funding.	Simplified nested structure: **2–3 Tier A sites**, **3–4 Tier B basins**, and **2 Tier C major basins** using existing gauges.	Basic water-quality sensors, seasonal sampling, limited eDNA surveys, acoustic recorders, open-access satellite data (Sentinel).	Moderate effort and cost.	Practical and feasible in remote areas; leverages existing monitoring infrastructure; suitable for baseline and early change detection.	Less intensive data collection; fewer mechanistic insights and reduced ability to detect subtle ecological processes.
Option 3: High-Innovation Flagship Research Program	Advanced interdisciplinary research initiative integrating environmental science, genomics, AI, and Indigenous governance to detect ecological thresholds.	Same nested watershed framework but expanded with research platforms and modelling.	eDNA/metagenomics, AI-driven remote sensing analysis, methane detection drones, eddy covariance towers, distributed temperature sensing, real-time data dashboards.	Large research program (e.g., SSHRC/NSERC/CIFAR scale).	Breakthrough science potential; integrates hydrology, biodiversity, carbon dynamics, and governance; supports early-warning systems and cumulative-effects modelling.	Requires substantial funding and interdisciplinary coordination; may be difficult to sustain operationally without long-term research funding.

.

Table B.2. Comparison of how the three study options implement the nested watershed concept across the three tiers (A–C). The tiers represent increasing watershed scale and decreasing monitoring intensity from headwater process studies to basin-scale cumulative effects detection. All three options apply the same nested watershed structure: intensive monitoring at small headwaters (Tier A); integration at sub-watershed scale (Tier B); and cumulative signal detection at basin scale (Tier C). The primary difference lies in monitoring intensity, technological sophistication, and research ambition, ranging from a practical baseline program (Option 2) to a comprehensive monitoring system (Option 1) or a highly innovative interdisciplinary research platform (Option 3).

Tier	Watershed Scale and Purpose	Option 1: Full Nested Monitoring	Option 2: Lower-Cost Version	Option 3: High-Innovation Research Program
Tier A – Process Sites	**Micro-catchments (0.1–10 km^2)**. Understand mechanisms in peatlands and headwaters; isolate hydrological and biogeochemical processes.	6–12 intensively instrumented sites. Water table wells, discharge measurements, continuous sensors (temperature, conductivity, turbidity, DO), carbon flux monitoring (CO_2/CH_4), nutrient and metal sampling, event sampling during storms or snowmelt.	2–3 simplified sites. Manual water-table wells, seasonal DOC/nutrient sampling, portable flow measurements, one methane chamber site.	Same small catchment structure but enhanced with advanced technologies such as eddy covariance towers, distributed temperature sensing, drone methane detection, genomic biodiversity monitoring.
Tier B – Watershed Response Sites	**Meso-catchments (10–500 km^2)**. Integrate tributary networks and detect watershed-level responses to disturbance.	4–8 sub-watersheds including reference and development-influence basins. Continuous streamflow and water-quality sensors, seasonal synoptic surveys, eDNA monitoring, remote sensing calibration, acoustic biodiversity monitoring.	3–4 sub-watersheds. One continuous monitoring station per basin, seasonal grab samples, limited eDNA (twice per year), remote sensing using open satellite data.	Same catchment structure but integrated with AI-assisted remote sensing, advanced eDNA/metagenomics analysis, and automated data integration systems.
Tier C – Cumulative Basins	**Major basins (500–20,000+ km^2)**. Detect cumulative effects at policy and management scale.	2–3 major river basins. Strategic sensors at key nodes, long-term gauge enhancement, load estimation for DOC/nutrients/sediment, periodic biological indicators (fish, benthos, eDNA).	2 major basins relying mainly on existing hydrometric gauges. Simple sensors (turbidity, temperature), annual eDNA surveys, basin-scale trend analysis.	Basin-scale modelling and early-warning systems integrating satellite data, real-time monitoring networks, predictive hydrologic–biogeochemical models, and decision-support dashboards.

B4 Integration of New and Emerging Monitoring Technologies

Integrating new and emerging technologies into a nested watershed study offers the opportunity to use intensive field sites (Tier A; micro-catchments) to calibrate technologies, then scale with remote sensing and automated systems at Tier B (meso-catchments) and Tier C (large basins).

Many of the technologies listed here would benefit from ground truthing or other field support by local communities. Indigenous data governance must be embedded early in any monitoring plan.

B.4.1 Remote Sensing

Remote sensing is essential in a vast, road-limited peatland landscape. However, as several interviewees emphasized, remote sensing data cannot be used without ground truthing, adding time and cost to data acquisition.

Hydrology and Connectivity

SAR (Synthetic Aperture Radar) is especially useful in peatlands because it works through clouds (essential in northern Ontario) and is sensitive to water table position and surface moisture. It could be calibrated with water table wells in Tier A sites and could help to scale wetness patterns across Tier B/C basins. It would be used to:

- Map seasonal inundation (spring freshet vs late summer)
- Detect expansion/contraction of wetlands
- Track road-induced hydrologic fragmentation
- Identify altered flow paths near infrastructure

Vegetation and Peatland Condition

Optical Time Series (Sentinel-2, Landsat) have multiple applications within the Assessment Area including:

- NDVI/NDWI for vegetation stress
- Fire scars and recovery trajectories
- Shrub expansion or drying trends
- Vegetation shifts from bog to fen indicators
- Nested use:
    - Validate with ground vegetation plots
    - Detect disturbance signals upstream of water quality changes

Surface Disturbance Detection

Remote sensing tools can be applied to detect changes in surface disturbance, potentially supporting identification of early warning trigger conditions related to:

- Road corridor detection and expansion
- Borrow pits and aggregate extraction footprints
- Sediment plumes in rivers (turbidity proxies)
- Tailings or storage footprint expansion

Thermal Imaging (satellite or drone)

Thermal imaging is especially powerful in identifying subtle hydrologic change before chemistry shifts. Examples include:

- Detecting groundwater inflows (thermal anomalies)
- Identifying altered flow regimes
- Mapping beaver pond dynamics

B.4.2 eDNA (Low-Disturbance Biodiversity Monitoring)

eDNA is exceptionally well suited to remote peatland systems. It avoids the need for repeated electrofishing in remote areas and requires minimal equipment. The logic here would be to conduct intensive sampling at Tier A (micro-catchment) sites, as a basis for interpreting process, with lower frequency sampling at Tier B (meso-catchment) and Tier C (large basin) sites, to detect cumulative shifts across the broader landscape. Biodiversity monitoring may be especially important as an early warning mechanisms for detection of invasive or stress-tolerant species, for example if road corridors increase access/connectivity and/or construction practices introduce new vectors. However, caution is also warranted: eDNA interpretation can be challenging in high-flow peat systems with associated transport issues.

Fish and Aquatic Community Baselines

At Tier B (meso-catchment) outlets:

- 2–4 seasonal samples per year
- Track fish assemblage shifts
- Detect rare or at-risk species
- Monitor colonization after disturbance

Benthic and Microbial Community Signals

- Macroinvertebrate DNA (where reference libraries exist)
- Microbial shifts tied to redox or nutrient change

- Methanogen community tracking in peatlands

B.4.3 Acoustic Monitoring

Acoustic monitoring can support tracking of continuous, non-invasive ecosystem indicators and is already in use in some parts of the region.

Ecoacoustic Biodiversity Monitoring

Autonomous recording units (ARUs) could be deployed at Tier A (micro-catchment) and Tier B (meso-catchment) sites to track bird community composition; amphibians; and insect phenology. Acoustic diversity indices could serve as ecosystem health proxies and support comparison between reference and impacted basins.

Aquatic Acoustic Monitoring

Passive hydrophones could be used to detect fish movement and identify the acoustic signatures of ice breakup or flow regime shifts. Soundscape changes are gaining acceptance as monitors of disturbance[61] and could have future application in the Assessment Area.

B.4.4 Continuous In-Situ Sensor Arrays

Basic and more advanced sensors could be strategically deployed at Tier B (meso-catchment) and Tier C (major basin) outlets to reduce the cost of fly-in sampling programs. In-situ sensor arrays would help to capture event-driven pulses such as occur during spring melt and storms and would also quickly detect water chemistry changes such as those related to dewatering impacts.

Core Sensors

- Temperature
- Conductivity
- Turbidity
- Dissolved oxygen
- pH

Advanced Options

- UV–Vis spectrophotometers (DOC proxy)
- Fluorescence sensors
- Real-time nutrient sensors (where feasible)

---

[61] See for example Arzberger, S., Fairbairn, A., Hemauer, M., Mühlbauer, M., Weissmann, J. and Egerer, M., 2025. The potential of soundscapes as an ecosystem monitoring tool for urban biodiversity. *Journal of Urban Ecology*, *11*(1), p.juaf002.

B.4.5 Greenhouse Gas and Carbon Monitoring Technologies

Given peat carbon importance, the following approaches are recommended; most of these are already in use or have been tested within the Assessment Area.

Eddy Covariance Towers (install at 1–2 flagship sites)

Elyn Humphreys (Carleton University) and others have led eddy-covariance measurements of CO_2 exchange in Hudson Bay Lowlands (HBL) bogs, demonstrating that HBL peatlands can function as annual CO_2 sinks. These towers could be used to track continuous CO_2 and CH_4 flux and validate carbon export models.

Chamber-Based Automated Systems

Automated chamber-based methane detection systems hold promise for monitoring peatland methane hotspots and tracking drying-induced flux shifts[62].

Drone-Based Methane Detection (emerging)

Drone-based methane detection is an emerging technology that allows rapid mapping of methane emissions hotspots[63]. It could be used at intensive carbon sampling sites to inform watershed DOC export modelling.

B.4.6 Hydrologic Monitoring Innovations

Distributed Temperature Sensing (Fibre Optic)

Fibre optic temperature sensors are increasingly used to map groundwater inflows and detect altered hydrologic connectivity, particularly processes at the interface between groundwater and surface water and in the shallow subsurface. Fibre Optic Distributed Temperature Sensors track the temperature of glass fibre continuously over kilometers of armored cable and are therefore well suited for tracking hydrologic changes across large systems[64].

Low-Cost "Internet of Things" [IoT] Sensor Networks

IoT sensor networks are now widely used in watershed management, agriculture, municipal infrastructure and many other applications including hydrologic and water quality monitoring; real-time water-level sensors in rivers and urban drainage networks; and wetland and peatland monitoring using networks of water-table sensors and soil

---

[62] See for example Brown, A.G., Rousseau, N.G., Doskocil, D., O'Neill, C.T., VanMatre, S.G., Kane, J.J., Casey, J.G., Hannigan, M.P. and Coffey, E.R., 2025. Calibration and Validation of an Autonomous, Novel, Low-Cost, Dynamic Flux Chamber for Measuring Landfill Methane Emissions. *Sensors*, *25*(21), p.6613.

[63] See for example Tassielli, G., Cananà, L. and Spalatro, M., 2024. Detection of methane leaks via a drone-based system for sustainable landfills and oil and gas facilities: effect of different variables on the background-noise measurement. *Sustainability*, *16*(17), p.7748.

[64] See for example Briggs, M.A., Rey, D.M., Opatz, C.C., Terry, N.C., Newman, C.P., Gruhn, L.R. and Johnson, C.D., 2025. *Fiber-optic distributed temperature sensing of hydrologic processes—Diverse deployments and new applications by the US Geological Survey* (No. 2025-3006). US Geological Survey.

moisture probes[65]. Within the Assessment Area, IoT sensor networks could incorporate solar-powered loggers with satellite uplink (Iridium, Starlink-type relay), reducing the need for on-site manual sampling. IoT sensor networks also support adaptive sampling triggers and alerts.

Depending on the location and type of sensor, sensors may require winterization and ice-proofing.

B.4.7 Sediment and Geochemistry Tools

Turbidity-to-Load Modelling

Recent advances in sensor technology have resulted in the development of continuous turbidity sensors that can be used to collect turbidity measurements without the need for manual sampling or costly infrastructure. Such measurements could provide early warning of increased turbidity arising from altered erosion regimes, for example at new road crossings, and could be linked directly to load modelling.[66]

Stable Isotopes

Stable isotopes have been used for many years in the detection of trace carbon and nutrient sources[67], and could be used in the Assessment Area to separate peat-derived DOC from mineral contributions

B.4.8 Data Integration Strategy

The systems recommended above could be integrated in the following way:

Tier	Field	Remote	Automated	Purpose
A	Intensive wells, chambers	High-res drone/SAR	Continuous water sensors	Establish mechanistic relationships
B	Outlet sampling + eDNA	SAR inundation mapping	Continuous water quality stations	Validate watershed response
C	Strategic biological surveys	Basin-scale trend analysis	Load estimation models	Use remote sensing to scale to Tier C; integrated into cumulative effects model

[65] See for example Mitchell, H.L., Cox, S.J. and Lewis, H.G., 2024. A Low-Cost Sensor Network for Monitoring Peatland. *Sensors*, *24*(18), p.6019.

[66] See for example Wang, M., Shi, B., Catsamas, S., Kolotelo, P. and McCarthy, D., 2024. A compact, low-cost, and low-power turbidity sensor for continuous in situ stormwater monitoring. *Sensors*, *24*(12), p.3926.

[67] See for example Kuhn, M.A., Varner, R.K., McCalley, C.K., Perryman, C.R., Aurela, M., Burke, S.A., Chanton, J.P., Crill, P.M., DelGreco, J., Deng, J. and Heffernan, L., 2024. Controls on stable methane isotope values in northern peatlands and potential shifts in values under permafrost thaw scenarios. *Journal of Geophysical Research: Biogeosciences*, *129*(7), p.e2023JG007837.

This approach could be especially valuable in the Assessment Area because of the region’s huge size and accessibility challenges. The literature scan and interviews confirm that peatlands can be expected to respond subtly to disturbance before catastrophic shifts, and that hydrologic connectivity is key to these shifts, yet difficult to observe on site. A further concern is that development may be phased, so monitoring must be able to detect early change to support rapid response as climate warming proceeds. The emerging technologies described in this section could help to reduce monitoring costs but also the physical disturbance footprint associated with some older monitoring approaches. By reducing the lag time between impact and detection, they also support Trigger Action Response Planning and rapid response to change.