

A Review of Wetlands on the Landscape

A WHOLE LANDSCAPE APPROACH TO ECOSYSTEM-BASED MANAGEMENT: PART 2

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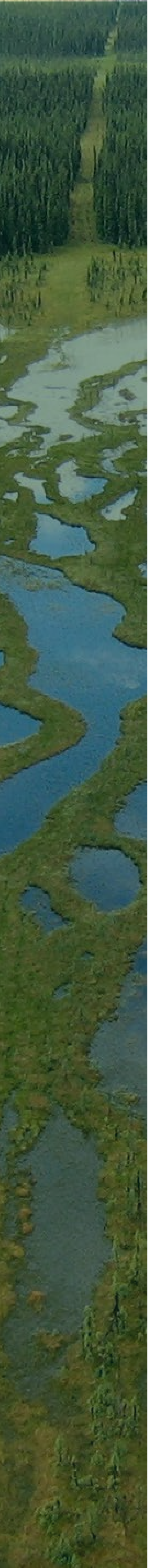

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INTRODUCTION

Project Background

Over its history, the Healthy Landscapes Program (HLP) at fRI Research has developed an understanding of the natural range of variation and landscape patterns of upland forests in Canada's western boreal forest. This has been primarily guided by the membership of the HLP (forest industry and government) and the focus of forest management policy on managing areas with merchantable timber and avoiding non-merchantable areas (e.g., most wetland types). Recent HLP projects have revealed a historic lack of wildfire activity on parts of the landscape not managed for timber, which in turn, has created unnaturally high levels of older seral stages.[2] This discovery, alongside recent extreme fire seasons, highlighted the need to widen the scope of the HLP from an upland forest focus to a whole landscape approach. This more inclusive focus will better align HLP with several elements of ecosystem-based management , recognize the diversity of values, and create opportunities for non-forest sector organizations (e.g., Indigenous communities, non-profits, other government branches) to participate in future HLP projects.

"Recognizing the interconnectedness of all boreal forest ecosystems, the complexity of today's threats such as climate change and biodiversity loss, and the need for diverse perspectives to inform solutions to these threats and to other natural resource management challenges – there is an opportunity for the HLP to broaden its approach and to consider all parts of the landbase, including wetlands." [1]

Wetlands and the Healthy Landscapes Program

Boreal wetlands are abundant, diverse, and provide a wealth of important ecosystem services. However, in the context of forest management they may be referred to as unproductive, non-merchantable, 'passive', or even undesirable parts of the land base. They are often not included as part of the merchantable or 'active' land base managed by forest companies; however, this viewpoint is shifting as our understanding of wetland functions and their interactions with surrounding ecosystems grows. Land managers are recognizing a need for a whole landscape approach to forest management, with integrated management of upland, wetland, and aquatic ecosystems.[2]

Boreal wetlands are abundant in the western boreal forest, making up over 40% of some forest tenure areas. Wetlands form strong hydrological connections with adjacent wetlands, riparian areas, and upland forests. Because of their abundance and connectivity to surrounding ecosystems, boreal wetlands support a multitude of values across the landscape, including:

- Contributing to forest productivity and resiliency;
- Mitigating the effects of upland harvest on waterbodies;
- Influencing wildfire behaviour and pattern; and,
- Mitigating effects of climate change through carbon storage and sequestration.[3]

Healthy boreal wetlands support healthy upland forests and changes in wetland function can impact surrounding ecosystems. For example, wetlands have served as fire breaks, but recent studies show that some wetland types are increasingly susceptible to high-severity fires, increasing fire risk across the landscape.[4,5] Similarly, while complete avoidance when building resource roads is often impossible in the western boreal due to wetland abundance and connections with upland forests. Some forested wetlands can even contain merchantable timber. Knowledge of wetland ecology, hydrology, and relationships with surrounding ecosystems provides valuable information for managing landscapes as wholes, not as pieces, one of the foundations of ecosystem based management.

Objectives

The objectives of the HLP Whole Landscapes project are to:

OBJECTIVE ONE

Develop a working definition of 'whole landscape' for use by the HLP and a high-level landscape classification scheme.

Objective one is assessed in **How does the HLP Define a Whole Landscape.**

OBJECTIVE TWO

Conduct a literature review summarizing the current state of wetland knowledge as it relates to ecosystem-based management topics and create a road map identifying knowledge gaps and potential project and collaboration opportunities for the HLP.

This report addresses **Objective Two,** and is complimentary to **"How does the HLP Define a Whole Landscape"**. Wetlands are not the only 'other' component of a whole landscape, in Canada's western boreal forest, but wetlands make up a significant portion of the non-upland area and are critical to the functioning of upland forests. Wetlands cover over 1 million km^2, constituting more than 35% of the western boreal forest land base.[6] They support ecosystem functions that provide carbon storage, water regulation, habitat, and many other ecological, social, and economic services.[7] For these reasons, wetlands are the focus of Objective Two. A similar review could be applied to other ecosystem types (e.g., grasslands, montane, etc.).

The overarching purpose of **Objective Two** is to summarize current knowledge and research, available resources, key researchers and organizations, and knowledge gaps in key wetland related topic areas relevant to the HLP with the goals of:

- Providing an overview and introduction to boreal wetlands for HLP members;
- Identifying areas of intersection between wetland topics and the HLP;
- Summarizing key wetland knowledge gaps relevant to the HLP; and,
- Developing a roadmap identifying opportunities for future research.

To achieve these goals, we conducted a literature review presented as a series of topic-based factsheets. The topics for the factsheets were chosen based on the priority needs and interests of the HLP. The first section builds the foundational understanding of wetland ecosystem function, values, and connections on the landscape. The second section explores key natural disturbances affecting boreal wetland ecosystems. The third section highlights key effects of anthropogenic activities on boreal wetlands that need to be considered when conducting ecosystem based management across the whole landscape. Factsheets can be read individually or collectively and are organized into three sections (Table 1).

Each section starts with an introduction and includes several factsheets on topics that fit under the theme. Individual factsheets consist of an introduction, relevance to the HLP, summary of the topic, and key resources. At the end of each section we have summarized knowledge gaps organized by factsheet topic. At the end of the report, we provide a road map for the HLP, identifying priority knowledge gaps along with a list of wetland researchers and organizations. This review enhances our understanding of wetland importance, ecological function, and interconnectedness within the boreal landscape. In summarizing and presenting the information in an accessible manner, this project will support informed decision-making, guide future HLP project initiatives and promote a whole landscape approach to ecosystem-based management.

Table 1. Section themes and factsheet topics.

Wetlands on the Landscape	1	*Wetland Values*
	2	*Wetland Connectivity*
	3	*Wetland Classification*
	4	*Wetland Inventories*
	5	*Wetland Hydrology*
	6	*Wetland Soil Carbon*
	7	*Wetlands and Climate Change*
Natural Disturbance	8	*Wetland Fire Behaviour*
	9	*Post-Fire Succesional Dynamics*
	10	*Indigenous Fire Stewardship*
	11	*Managing Wetlands for Fire Risk*
	12	*Wetlands and Beavers*
Anthropogenic Disturbance	13	*Wetland Resource Roads*
	14	*Forest Harvest*
	15	*Cummulative Effects*

1. Ducks Unlimited Canada & fRI Research. (2024). A Whole Landscape Approach to Ecosystem-Based Management Part 1: How does the Healthy Landscape Program Define a Landscape. Ducks Unlimited Canada.
2. Anderson, R. L., Foster, D. R., & Motzkin, G. (2003). Integrating lateral expansion into models of peatland development in temperate New England. Journal of Ecology, 91(1), 68–76. https://doi.org/10.1046/j.1365-2745.2003.00740.x
3. Forest Management and Wetland Stewardship Initiative (FMWSI). 2018a. Guiding Principles for Wetland Stewardship and Forest Management Technical Report. Edmonton, (AB): Ducks Unlimited Canada.
4. Gingras, B., Slattery, S., Smith, K., & Darveau, M. (2016). Boreal Wetlands of Canada and the United States of America. In The Wetland Book (pp. 1–23). Springer Netherlands. https://doi.org/10.1007/978-94-007-6173-5_9-1
5. Hokanson, K. J., Lukenbach, M. C., Devito, K. J., Kettridge, N., Petrone, R. M., & Waddington, J. M. (2015). Groundwater connectivity controls peat burn severity in the Boreal Plains. Ecohydrology, 9(4), 574–584. https://doi.org/10.1002/eco.1657
6. Prairie Habitat Joint Venture (PHJV). 2021. PHJV Implementation Plan 2021-2025L The Western Boreal Forest. Produced by Environment and Climate Change Canada (ECCC), Ducks Unlimited Canada (DUC) and Members of the PHJV Science Committee.
7. Wilkinson, S. L., Moore, P. A., Thompson, D. K., Wotton, B. M., Hvenegaard, S., Schroeder, D., & Waddington, J. M. (2018). The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. Canadian Journal of Forest Research, 48(12), 1433–1440. https://doi.org/10.1139/cjfr-2018-0217

WETLANDS ON THE LANDSCAPE

More than two-thirds of Canada's western boreal forest is covered by aquatic ecosystems, including wetlands, lakes, rivers, and streams. Boreal wetlands are diverse, complex, and highly interconnected and contain a wealth of ecological, social, and economic benefits alongside growing industry operations.

While important, wetlands are often poorly understood leading to difficulties or surprises in managing. For example, some boreal wetland types, such as treed organic wetlands, can be mistaken for uplands, particularly during dry periods. If a dry organic wetland is the site of road construction and the design and construction assumes dry, upland conditions, there is a high likelihood that during the next wet season or year, the road would experience problems ranging from flooding to washouts. These problems could likely have been avoided with a better baseline understanding of wetlands. Sometimes information about wetland presence and functions is not readily available, sometimes there is gap in training the pracitioners or decision-makers.

Topics in this section:

1. Wetland Values
2. Wetland Connectivity
3. Wetland Classification
4. Wetland Inventories
5. Wetland Hydrology
6. Wetland Soil Carbon
7. Wetlands and Climate Change

Adopting a whole landscape approach to ecosystem-based management starts with understanding all parts of the landscape. The first step is to fill knowledge gaps relating to non-managed forests so that this information can be incorporated into future Healthy Landscapes Program projects and program activities.

Section One, Wetlands on the Landscape, summarizes the current state of western boreal forest wetland knowledge including wetland values, presence (i.e. classification and inventories), fuctions, and interconnectivity with upland forests. While all boreal wetland types are important and addressed in Section One, organic wetlands feature heavily as they are abundant, complex, and highly connected to surrounding ecosystems, with a large influence across the western boreal fores.

WETLANDS ON THE LANDSCAPE:

Wetland Values

Wetlands in the western boreal forest provide many ecosystem services, ranging from providing habitat for plant and animal species, to regulating surface and groundwater storage and flow, to serving as sites for recreation. A whole landscape approach to ecosystem-based management requires the recognition of the values and services provided by wetlands, even though they may not provide obvious and immediate economic benefits.

Ecosystem services provided by wetlands can be grouped into four categories: [1]

Cultural Services
Non-material benefits that ecosystems provide to humans. These services encompass the intangible aspects of nature that enrich human lives, enhance well-being, and foster cultural identity and traditions.

Regulating Services
Ecological processes and functions that help maintain the balance and stability of ecosystems by regulating important environmental factors.

Provisioning Services
Direct benefits that humans obtain from ecosystems in the form of goods and resources necessary for survival and well-being.

Supporting Services
Ecological processes and functions that are essential for the maintenance of ecosystems and the production of all other ecosystem services.

Table 1. Boreal wetland ecosystem services.[10]

Regulating Services	• Climate regulation • Water regulation • Water purification and treatment • Erosion protection	• Influencing rainfall, temperature, and greenhouse gas exchanges. • Maintaining evapotranspiration during dry periods.[2,3] • Storing more carbon than forests (organic wetlands), but potentially emitting methane, especially if disturbed.[4,5] • Regulating local and regional water flow by storing and moving surface and groundwater. • Storing and contributing water during droughts and floods.[6] • Controlling erosion and mitigating runoff, especially in timber harvest areas.[7,8,9]
Provisioning Services	• Fibre and fuel energy • Food • Fresh water • Medicines	• Supplying fresh water and replenishing groundwater sources for domestic and industrial use. • Providing wild game and food resources. • Providing fuel wood and commercial wood fiber. • Supporting fur-bearer resources for trappers. • Providing habitat for economically important pollinators and medicinal plants.[1]
Cultural Services	• Recreational and aesthetic • Spiritual and inspirational • Educational • Cultural	• Wetlands are important ecosystems for Indigenous Peoples, serving as reliable travel corridors, providing areas for hunting, and offering goods for food, shelter, and medicine. • Canadians from diverse backgrounds derive spiritual, inspirational, and recreational benefits from wetlands, including activities like canoeing, hunting, hiking, fishing, trapping, and birdwatching.[1]

Table 1 continued. Boreal wetland ecosystem services.[10]

Supporting Services	• Biodiversity • Soil formation • Nutrient Cycling	Biodiversity: • Providing habitat for numerous plant and animal species. • Indirectly influencing ecosystem function and resilience.[11] • Supporting breeding waterfowl, with approximately 26 million waterfowl utilizing North America's boreal wetlands annually.[1,12] • Providing habitat for unique (e.g., the bog pitcher plant is wetland specialist) and at risk (e.g., boreal woodland caribou rely significantly on wetland habitat) species.[13] Water Quality: • Help maintain water quality through filtration and nutrient cycling. • Pollutants, sediment, or nutrients can compromise wetland water quality and impact species composition. • Organic wetland water quality influences surrounding areas, with alterations potentially affecting pH levels and nutrient distribution.[14,15,16,17] Soil Integrity: • Wetland soils, especially saturated and organic soils, are sensitive to disturbances and play a crucial role in chemical transformations and storage for wetland plants.[18] • Activities in wetlands can affect soil properties such as bulk density, porosity, hydraulic conductivity, and nutrient availability.[18] Carbon: • Wetlands are key players in the global carbon cycle due to the large amounts of organic carbon they store in vegetation and soils. • Wetland soil carbon stocks are influenced by hydrology, which affects carbon sequestration and release.[19] • Alterations to wetland hydrology, such as flooding, can significantly impact methane (CH_4) emissions due to changes in anaerobic (wet) processes.[19]

Few provisioning services have a measurable market value that is tracked, making it challenging to assign a dollar value to these services. Nonetheless, the estimated monetary value of ecosystem services provided by wetlands globally is approximately $47.4 trillion annually.[20] However, this figure only includes the economic benefits that can be quantified, possibly neglecting benefits that are harder to quantify such as cultural heritage and water security. Monetary valuation approaches represent just one aspect of measuring the overall benefits that wetlands provide.

Indigenous Wetland Values

Identifying and defining wetland values has historically focused on western knowledge systems, often with an emphasis on economic value. A whole landscape approach needs to bring together western and Indigenous wetland values. "Muskeg", a common term for wetlands in the western boreal forest, is derived from Cree and Ojibway languages. Wetlands hold profound cultural significance for Indigenous Peoples, reflecting a deep interconnection between land, language, and traditional knowledge. Indigenous cultures across North America encode their understanding of ecosystems and habitats within their languages, revealing nuanced ecological insights that often differ from Western scientific perspectives.[21]

In Indigenous worldviews, land is not merely defined by an ecologically distinct space or static representation on a map, but rather as a place inseparable from the people.[21,22] These places maintain a habitat for living and fostering complex social and spiritual relationships.[21] Essentially, they are described as vibrant societies or a network of interconnected relationships.

Wetlands are rich in biodiversity, ranging from sedges and mosses to shrubs and berries.[23] The intricate relationship between wetlands and Indigenous terms for "wet places" corresponds to ecological vegetation types.[21]

Wetlands provide essential medicinal plants, plant foods, and animal resources crucial for Indigenous livelihoods.[23] Shrubby swamps, for instance, may be associated to specific seasonal hunting grounds, such as fall and winter moose habitats, while small lakes and ponds supports summer moose habitat.[21,23,24]

Vegetation, geographic features, and seasons influences travel routes for accessing potential resources. Viewing these connections between plants and landscape from an ethnoecological perspective grants insight into the fundamental relationships of Indigenous peoples to their homelands.[23]

Recognizing the insights derived from Indigenous knowledge of wetlands not only enhances the cultural relationship with the land but also contributes to sustainable land management practices, thereby fostering long-term sustainability and resilience.[23] Moreover, preserving linguistic diversity and cultural heritage enriches understanding of historical and contemporary relationships with the land.[21] Valuing Indigenous knowledge allows for a deeper appreciation of the interconnectedness of the landscape and promotes holistic approaches to wetland stewardship and management.[21,23]

Resources:

- Gingras, B., Slattery, S., Smith, K., & Darveau, M. (2016). Boreal Wetlands of Canada and the United States of America. In The Wetland Book (pp. 1–23). Springer Netherlands. https://doi.org/10.1007/978-94-007-6173-5_9-1
- Millennium Ecosystem Assessment (Program). (2005). Ecosystems and human well-being : wetlands and water synthesis : a report of the Millennium Ecosystem Assessment. World Resources Institute.
- Davidson, N. C., Van Dam, A. A., Finlayson, C. M., & McInnes, R. J. (2019). Worth of wetlands: Revised global monetary values of coastal and inland wetland ecosystem services. Marine and Freshwater Research, 70(8). https://doi.org/10.1071/MF1839
- Johnson, L. M. (2011) Trail of story, traveller's path: reflections on ethnoecology and landscape. Choice Reviews Online, 48(08). https://doi.org/10.5860/choice.48-4559
- Johnson, L. M. (2013). Plants, places, and the storied landscape: looking at First Nations perspectives on plants and land. BC Studies, (179), 85. https://link.gale.com/apps/doc/A359615153/E?u=anon~d05e1efe&sid=googleScholar&xid=cafea3c5
- Johnson, L. M. (2010). Visions of the land: Kaska ethnoecology, "kinds of place," and "cultural landscape." In Landscape Ethnoecology: Concepts of Biotic and Physical Space (Vol. 9).

1. Gingras, B., Slattery, S., Smith, K., & Darveau, M. (2016). Boreal wetlands of Canada and the United States of America. In The Wetland Book (pp. 1–23). Springer Netherlands. https://doi.org/10.1007/978-94-007-6173-5_9-1
2. Rouse, W. R., Oswald, C. M., Binyamin, J., Blanken, P. D., Schertzer, W. M., & Spence, C. (2003). Interannual and seasonal variability of the surface energy balance and temperature of central Great Slave Lake. Journal of Hydrometeorology.
3. Van der Kamp, G., & Marsh, P. (2004). Climate variability and change: Wetlands. In Threats to water availability in Canada (Chapter 13, NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1, pp. 101–106). National Water Research Institute.
4. Henschel, C., & Gray, T. (2007). Forest carbon sequestration and avoided emissions. www.ivey.org
International Peatland Society. (2019). Peatlands and climate. https://peatlands.org/peatlands/peatlands-and-climate/
5. Spence, C., Guan, X. J., & Phillips, R. (2011). The hydrological functions of a boreal wetland. Wetlands, 31(1), 75–85. https://doi.org/10.1007/s13157-010-0123-x
6. Devito, K. J., Hokanson, K. J., Moore, P. A., Kettridge, N., Anderson, A. E., Chasmer, L., Hopkinson, C., Lukenbach, M. C., Mendoza, C. A., Morissette, J., Peters, D. L., Petrone, R. M., Silins, U., Smerdon, B., & Waddington, J. M. (2017). Landscape controls on long-term runoff in subhumid heterogeneous Boreal Plains catchments. Hydrological Processes, 31(15), 2737–2751. https://doi.org/10.1002/hyp.11213
7. Donnelly, J. P., Naugle, D. E., Hagen, C. A., & Maestas, J. D. (2016). Public lands and private waters: scarce mesic resources structure land tenure and sage-grouse distributions. Ecosphere, 7(1). https://doi.org/10.1002/ecs2.1208
8. Rothwell, R., Hillman, G., & Pomeroy, J. W. (2016). Marmot creek experimental watershed study. The Forestry Chronicle, 92, 32.
9. Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. Environmental Reviews, 23(1), 78–131. National Research Council of Canada. https://doi.org/10.1139/er-2014-0063
10. Elmqvist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, J., Walker, B., & Norberg, J. (2003). Response diversity, ecosystem change, and resilience. Frontiers in Ecology and the Environment, 1(9), 488–494. www.frontiersinecology.org
11. U.S. Fish & Wildlife Service. (2024). Waterfowl population status, 2024. 2024 Waterfowl Breeding Population and Habitat Survey. https://www.fws.gov/sites/default/files/documents/waterfowl-population-status-report-2022.pdf
12. Smith, K. B., Smith, C. E., Forest, S. F., & Richard, A. J. (2007). A field guide to the wetlands of the Boreal Plains EcoZone of Canada.
Ferone, J. M., & Devito, K. J. (2004). Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. Journal of Hydrology, 292(1–4). https://doi.org/10.1016/j.jhydrol.2003.12.032
13. Creed, I. F., Beall, F. D., Clair, T. A., Dillon, P. J., & Hesslein, R. H. (2008). Predicting export of dissolved organic carbon from forested catchments in glaciated landscapes with shallow soils. Global Biogeochemical Cycles, 22(4). https://doi.org/10.1029/2008GB003294
14. Mertens, A. (2018). Spatial variability and controls on surface water chemistry and quality in a heterogeneous landscape: The western boreal forest. https://doi.org/10.7939/R3Q52FV4C
15. Halsey, L. A., Vitt, D. H., & Trew, D. O. (1997). Influence of peatlands on the acidity of lakes in northeastern Alberta, Canada. Water, Air, and Soil Pollution, 96, 17–38.
16. Mitsch, W. J., & Gosselink, J. G. (2015). Wetlands (5th ed.). Wiley.
17. Turetsky, M. R., Kotowska, A., Bubier, J., Dise, N. B., Crill, P., Hornibrook, E. R., Minkkinen, K., Moore, T. R., Myers-Smith, I. H., Nykänen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E., Waddington, J. M., White, J. R., Wickland, K. P., & Wilmking, M. (2014). A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. Global Change Biology, 20(7), 2183–2197. https://doi.org/10.1111/gcb.12580
18. Davidson, N. C., Van Dam, A. A., Finlayson, C. M., & McInnes, R. J. (2019). Worth of wetlands: Revised global monetary values of coastal and inland wetland ecosystem services. Marine and Freshwater Research, 70(8). https://doi.org/10.1071/MF18391
19. Johnson, L. M. (2011). Trail of story, traveller's path: Reflections on ethnoecology and landscape. Choice Reviews Online, 48(08). https://doi.org/10.5860/choice.48-4559
20. Casey, E. S. (1996). How to get from space to place in a fairly short stretch of time: Phenomenological prolegomena. In Sense of place.
21. Johnson, L. M. (2013). Plants, places, and the storied landscape: Looking at First Nations perspectives on plants and land. BC Studies, 179, 85. https://link.gale.com/apps/doc/A359615153/AONE?u=anon~d05e1efe&sid=googleScholar&xid=cafea3c5
22. Johnson, L. M. (2010). Visions of the land: Kaska ethnoecology, "kinds of place," and "cultural landscape." In Landscape ethnoecology: Concepts of biotic and physical space (Vol. 9).

WETLANDS ON THE LANDSCAPE:
Wetland Connectivity

The western boreal forest is a hydrological mosaic of lakes, streams, and wetlands interwoven within upland forests. Wetlands are an essential part of the boreal forest, **covering over 1 million km^2, or more than 35% of the land base.**[1] Within the boreal forest are over 200 million acres of freshwater resources, accounting for approximately 20% of the world's freshwater resources stored in lakes, reservoirs, soils, and groundwater.[2]

Functioning wetlands benefit upland forests by contributing to forest productivity and resiliency, mitigating the effects of upland harvest on water bodies, influencing wildfire behaviour and patterns, and mitigating the effects of climate change through carbon storage and sequestration. Sustainable forest management can support healthy wetland ecosystems, and healthy wetlands are crucial to sustaining productive upland forests. Due to the interconnectedness between wetlands and uplands, knowing how each system influences and interacts with the other is essential as industry activities may influence wetland hydrology with potentially far-reaching effects on connected wetlands and uplands. Understanding the primary factors influencing water movement can provide valuable information for a whole landscape approach to ecosystem-based management

Hydrological Connectivity between Wetlands and Uplands

Wetlands in the western boreal forest form highly interconnected systems with the ability to **transport significant amounts of water across the landscape**. Wetland hydrologic connectivity describes how wetlands facilitate the movement of surface and groundwater throughout the landscape. Wetlands can be hydrologically connected to other wetlands, creating **wetland complexes**, but can also be connected to uplands. Because of this connectivity, **wetlands act as important water sources during dry periods, and can buffer and slowly move large amounts of water during wet period, mitigating flood events**.[3]

Wetland hydrology influences uplands in three key ways:

a. **Discharging water to downstream ecosystems:** when the water table is high and the storage capacity of the wetland is full, wetlands will generate runoff with surplus water that will flow into downstream ecosystems, such as streams, lakes, or other open water wetlands.

b. **Groundwater recharge:** During dry periods (both seasonally and annually) wetlands will transmit water to uplands and other connected open water wetlands.

c. **Water storage:** During prolonged dry periods, wetlands will no longer transmit water, and will instead store water to maintain wetland processes.[4]

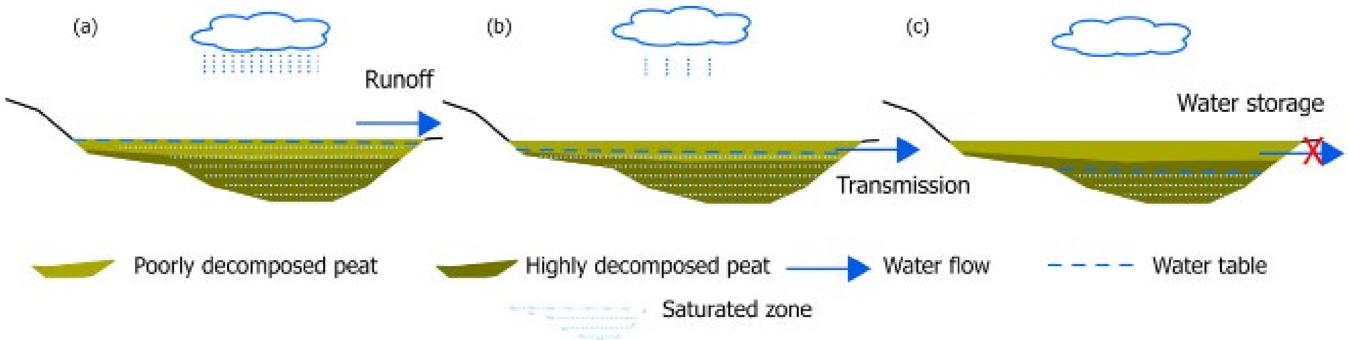

Figure 1. Model showing wetland function of a organic wetland system with respect to water table and peat decomposition degree, from Volik et al. (2023).

Upland forests and open water bodies act as sinks, **while vegetated wetlands with little or no standing water act as sources** that can contribute to increased forest productivity in upland habitats that may otherwise face water deficits.[3] This relationship can increase upland forest productivity, influencing vegetation cover, growth, and yield.[3]

Different wetland classes (*Factsheet #3*) play different roles in water distribution. For example, fens, marshes, and shallow open waters can have surface inflow and outflow points which contribute water to wetland complexes, influencing water distribution on the landscape.[6] Some fens and bogs also move groundwater through their soil profile instead of surface inflow and outflow points.[6] Therefore, understanding **wetland classification** is critical for understanding the potential hydrologic connectivity of a specific wetland and for effective wetland management.

HYDROLOGICAL HOTSPOTS

Water table fluctuations can vary across a single wetland or wetland complex, resulting in different parts of the wetland or complex contributing in different ways to landscape hydrological dynamics. Central and deeper areas in a wetland are typically less hydrologically dynamic than the edges and transition zones. This stability is important in maintaining wetland function during dry periods. Areas that experience more dynamic water table fluctuations are considered hydrological hot spots, as hydrological and biogeochemical processes are heightened in these areas.[4] Hotspots are typically the wetland's edges or transition zones, and are often classified as swamps. Despite being important hydrological and biogeochemical hotspots, swamps are the least understood of the five wetland classes.[7]

Forests regulate adjacent ecosystems' micro climatic and hydrologic conditions, including light, wind, temperature, and moisture conditions.[8] Given the landscape mosaic of upland forests and wetlands prevalent across the western boreal forest, upland forest disturbance can affect adjacent or nearby wetland ecosystems.

Wetlands can also play an important role in mitigating the effects of upland forest disturbance. Wetlands are resilient ecosystems that have the ability to adapt to both disturbance and climate related stressors.[9] For example, as documented in the Forest Watershed and Riparian Disturbance Project in west-central Alberta, intact wetlands can mitigate the effects of forest harvest on water yield and quality by reducing runoff and contributing positively to recovery.[10] However, this mitigating role and resiliency may be dependent on climatic conditions and wetland abundance.

Wetland loss can affect wetland upland forest water quantity and quality in several ways:

- Reduce overall storage capacity of wetlands at a landscape scale, which can result in greater flow events, increased soil erosion, and flooding during wet periods.
- Diminish the ability of wetlands to support upland forests during dry periods.
- Reduce water quality as nutrients, such as nitrogen, phosphorous and dissolved organic carbon, that are typically filtered and stored by wetlands are now mobilized into the watershed.[2]

A wetland's potential to mitigate the effects of climate change (e.g., flooding, drought, fire) on adjacent upland systems is itself dependent on climactic conditions. This includes both short-term climate variation and long-term climate change (*Factsheet #7*). During wet or dry periods, there may be a limit to the mitigation potential of wetlands. For example, during dry periods, wetlands will only release water to surrounding forests to a certain extent to preserve the wetland's functions.[4]

The important relationships between wetlands and uplands can be impacted by both climate and land use changes. Understanding the connections and the effects of anthropogenic disturbances (***Section Two***) and natural disturbances (***Section Three***) on these connections is needed for a whole landscape approach to ecosystem based management. Activities that take place in upland forests can impact wetlands and vice versa.

Resources

- Åhlén, I., Thorslund, J., Hambäck, P., Destouni, G., & Jarsjö, J. (2022). Wetland position in the landscape: Impact on water storage and flood buffering. Ecohydrology. https://doi.org/10.1002/eco.2458.
- Department of the Environment and Energy. (2016). Wetlands and changes in water flows. Commonwealth of Australia. https://www.dcceew.gov.au/water/wetlands/publications/factsheet-wetlands-water-changes
- Devito, K., Mendoza, C., and Qualizza, C. (2012). Conceptualizing water movement in the Boreal Plains. Implications for watershed reconstruction. Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research Group. 164p.
- Ducks Unlimited Canada. (March 29, 2019). Scott Ketcheson- Towards Understanding the Influence of Headwater Catchments on Water Availability in the Athabasca River Basin. From Wetland Knowledge Exchange. Vimeo [webinar]. https://vimeo.com/327373987. (not sure how to cite this one properly)
- Leibowitz, S. G., Wigington, P. J., Jr, Schofield, K. A., Alexander, L. C., Vanderhoof, M. K., & Golden, H. E. (2018). CONNECTIVITY OF STREAMS AND WETLANDS TO DOWNSTREAM WATERS: AN INTEGRATED SYSTEMS FRAMEWORK. Journal of the American Water Resources Association, 54(2), 298–322. https://doi.org/10.1111/1752-1688.12631
- Price, J. S., McCarter, C. P. R., & Quinton, W. L. (2023). Groundwater in peat and peatlands. The Groundwater Project.
- Rittenhouse, T.A., Peterman, W.E. (2018). Connectivity of Wetlands. In: Finlayson, C.M., et al. The Wetland Book. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-9659-3_54.
- Volik, O., Petrone, R., Price, J. (2024). Wetlands as integral parts of surface water–groundwater interactions in the Athabasca Oil Sands Area: Review and synthesis. Environmental Reviews. 32(2): 145-172. https://doi.org/10.1139/er-2023-0064.
- Wu, X., Ma, T. & Wang, Y. (2020). Surface Water and Groundwater Interactions in Wetlands. J. Earth Sci. 31, 1016–1028. https://doi.org/10.1007/s12583-020-1333-7.

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1. Prairie Habitat Joint Venture (PHJV). 2021. PHJV Implementation Plan 2021-2025L The Western Boreal Forest. Produced by Environment and Climate Change Canada (ECCC), Ducks Unlimited Canada (DUC) and Members of the PHJV Science Committee
2. Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. Environmental Reviews (23)1, 78–131.doi.org/10.1139/er-2014-0063
3. Forest Management and Wetland Stewardship Initiative (FMWSI). 2018a. Guiding Principles for Wetland Stewardship and Forest Management Technical Report. Edmonton, (AB): Ducks Unlimited Canada.
4. Volik, O., Petrone, R., & Price, J. (2023). Wetlands as integral parts of surface water–groundwater interactions in the athabasca oil sands area: Review and synthesis. Environmental Reviews, 32(2), 145–172. https://doi.org/10.1139/er-2023-0064
5. Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015) Hydrological feedbacks in northern peatlands. (8)1, 113-127. Ecohydrology. 10.1002/eco.1493
6. Labadz, J., Allott, T., Evans, M., Butcher, D., Billett, M., Stainer, S., Yallop, A., Jones, P., Innerdale, M., Harmon, N., Maher, K., Bradbury, R., Mount, D., Brien, H. O., & Hart, R. (2010). Peatland Hydrology
7. Davidson, S. J., Dazé, E., Byun, E., Hiler, D., Kangur, M., Talbot, J., Finkelstein, S. A., & Strack, M. (2022). The unrecognized importance of carbon stocks and fluxes from swamps in Canada and the USA. Environmental Research Letters, 17(5), 053003. https://doi.org/10.1088/1748-9326/ac63d5
8. Plach, J. M., Petrone, R. M., Waddington, J. M., Kettridge, N., & Devito, K. J. (2016). Hydroclimatic influences on Peatland Co2 Exchange following upland forest harvesting on the Boreal Plains. Ecohydrology, 9(8), 1590–1603. https://doi.org/10.1002/eco.1750
9. Stralberg, D., Arseneault, D., Baltzer, J. L., Barber, Q. E., Bayne, E. M., Boulanger, Y., Brown, C. D., Cooke, H. A., Devito, K., Edwards, J., Estevo, C. A., Flynn, N., Frelich, L. E., Hogg, E. H., Johnston, M., Logan, T., Matsuoka, S. M., Moore, P., Morelli, T. L., … Whitman, E. (2020). Climate-change refugia in Boreal North America: What, where, and for how long? Frontiers in Ecology and the Environment, 18(5), 261–270. https://doi.org/10.1002/fee.2188
10. McEachern, P. 2016. Forest Watershed and Riparian Disturbance Project (FORWARD). The Forestry Chronicle. 92(1): 29-31

Healthy Landscapes Program
FACT SHEET #3

WETLANDS ON THE LANDSCAPE:
Wetland Classification

Wetlands are diverse, complex, highly interconnected systems. A whole landscape approach to ecosystem-based management in the western boreal forest requires understanding all parts of the landscape, including wetlands. Understanding what type of wetlands are present is the first step to conserving, managing, and restoring wetlands and their associated values. There is no single, legally recognized definition of the term 'wetland' that is used consistently across municipal, provincial, and federal jurisdictions in Canada. However, the Canadian Wetland Classification System[1] definition is widely used and the most applicable when working across multiple jurisdictions:

> ***"... land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation, and various kinds of biological activity which are adapted to a wet environment..."***

Canadian Wetland Classification

The Canadian Wetland Classification System is a standardized system that describes wetland characteristics and can be applied across all Canadian jurisdictions. Some provinces and territories have developed their own classification systems (e.g. the Alberta Wetland Classification System), but this is not consistent across the country. The Canadian Wetland Classification System divides wetlands into two categories: ***Organic Wetlands*** and ***Mineral Wetlands***. Wetlands can be isolated or form intricate networks that stretch across the landscape. These connected systems, called wetland complexes, are especially prevalent in the western boreal forest.

ORGANIC WETLANDS

Organic wetlands are often referred to as peatlands or muskeg. Organic wetlands are peat-forming wetlands with peat layers *greater than 40cm*. This includes:

FEN

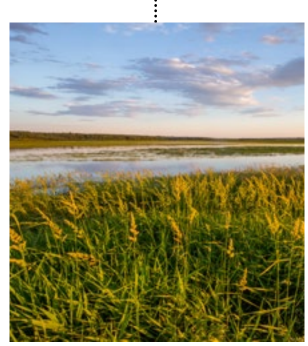
BOG

MINERAL WETLANDS

Mineral wetlands are wetlands that are non-peat forming and have peat layers *less than 40cm*, although some swamps occasionally have peat deposits greater than 40cm and are referred to as peat swamps. This includes:

SWAMP

MARSH



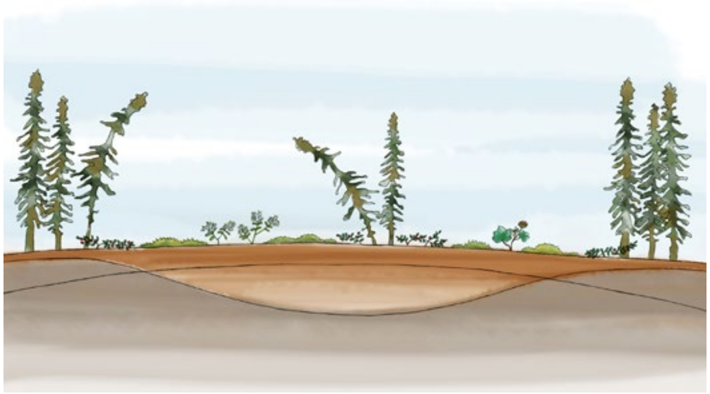
SHALLOW OPEN WATER

Organic Wetlands

Organic wetlands, often referred to as peatlands, are characterized by the presence of poorly decomposed organic soil deposits, called peat, that are typically greater than 40 centimeters in depth. These thick layers of organic soils often disguise the large amounts of water stored within the wetlands soils. Stable water tables and cooler temperatures in organic wetlands result in slow decomposition and the accumulation of carbon rich peat. Due to their thick layers of soils, organic wetlands can host plant communities such as shrubs and trees, which to the untrained eye can make them trickier to identify as wetlands. Vegetation in organic wetlands is often water-loving or has stunted growth, both of which are indicators of healthy wetland function.

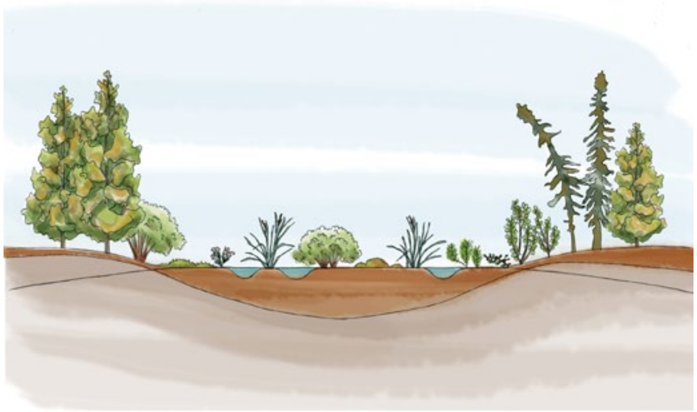
Bogs

- Isolated from groundwater and receive water through precipitation.
- Minimal water movement, rarely producing surface run-off. However, during wet periods bogs have the potential to move water and act as important water sources to adjacent wetlands and uplands.
- Nutrient poor due to their disconnected nature, resulting in highly acidic conditions and low, but unique, plant diversity.



Fens

- Receive water through a combination of precipitation, surface runoff, and groundwater sources.
- Gradual to moderate water movement, characterized by the presence of slow-moving or meandering channels. Able to move large amounts of water during wet periods and can act as important water sources to adjacent wetlands and uplands.
- Nutrient rich due to diverse water inputs, less acidic than bogs, with high plant diversity.



ORGANIC WETLANDS AND SOIL CARBON:

While only covering 3-5% of the earth's terrestrial surface, 30% of the earth's soil carbon pool is stored in organic wetlands (peatlands) globally.[3] In North America, 85% of soil carbon is stored in peatlands, primarily in Canada, which contains one-third of the world's carbon-rich peatlands.[4,5] Peatland soil carbon stocks exceed soil carbon in forest soils and agricultural soils combined. In the western boreal forest, approximately 60% of wetlands are peatlands, making these systems extremely important to conserve, manage, and restore.[2]

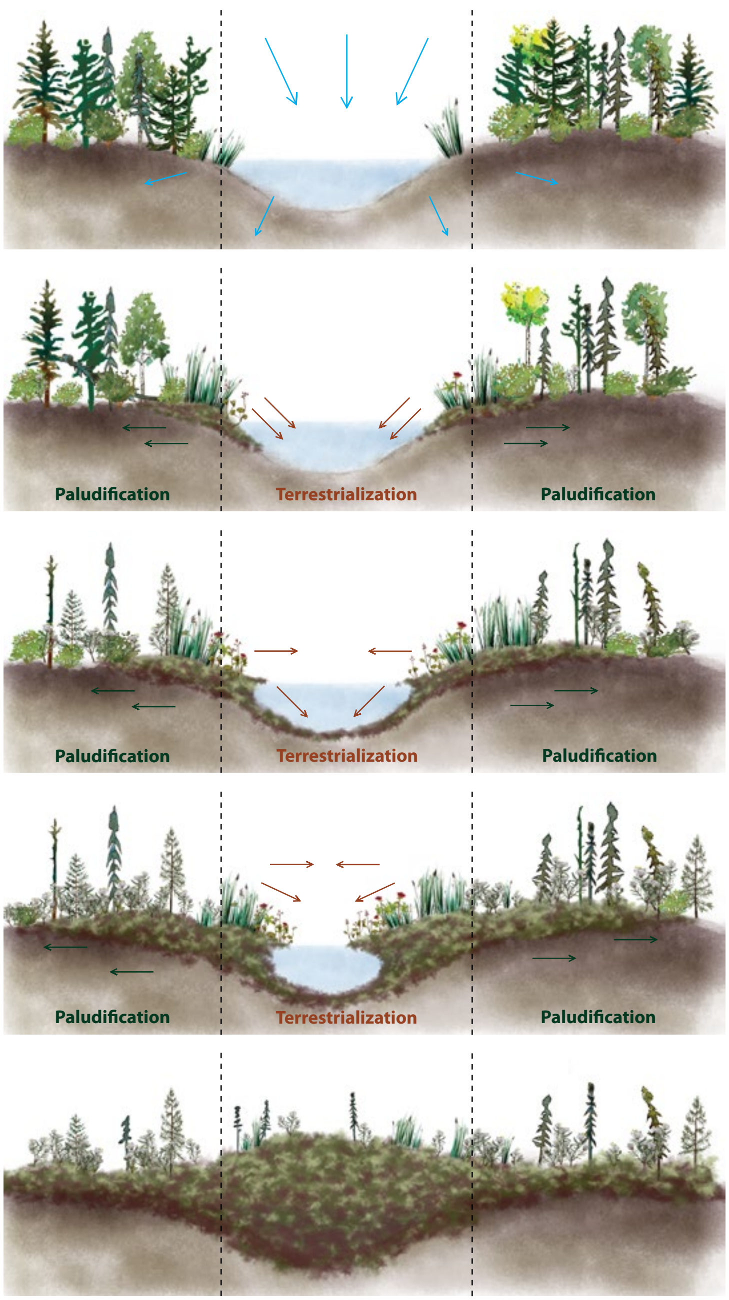
Organic Wetland Formation

Despite the relatively dry climatic conditions in the western boreal forest, up to **40% of the area is wetland**, predominantly organic wetlands. Organic wetland formation requires a **positive water balance** and **a stable water table** to establish *Sphagnum* mosses and enable peat accumulation, triggering one of two peatland formation processes:[3]

- **Terrestrialization:** The gradual filling of a shallow lake from the surface, with vegetation developing from the edges toward the middle.[1]
- **Paludification:** Wetland vegetation blankets over terrestrial ecosystems and mineral soils, typically triggered by waterlogged soils due to natural or anthropogenic disturbance.[4]

Organic wetlands are sucessional ecosystems, meaning, that they transition from one form to another overtime through terrestrialization and paludification processes. As demonstrated in Figure 1, wetlands can transition from hydrologically connected, wet and open systems, such as fens, to hydrologically disconnected, dry, treed systems such as bogs.

Stages of Organic Wetland Formation



Water from rainfall, runoff, groundwater etc. is collected and retained in depressions. Mineral soils adjacent to these depressions become saturated.

Decaying organic matter begins to accumulate near the margins of the open water, and peat mosses begin forming in this area of high saturation. Less water-tolerant species such as white spruce *(Picea glauca)* begin to die back.

Because of the anoxic conditions in the water, organic matter continues to accumulate faster than it can decompose. As *Sphagnum* mosses spread, they further retain ground saturation and lower the pH, aiding in peat accumulation.

As the moss layer raises above the saturated ground layer, ericaceaous shrubs as Labrador tea *(Rhododendron Groenlandicum)* and tamarack *(Picea glauca)* propagate in the hummocks, while water-loving plants form in the hollows.

Peat continues to accumulate over time, and may eventually form hydrologically disconnected or domed bogs. Trees growing in these areas are heavily stunted, and almost exclusively black spruce *(Picea mariana)*.

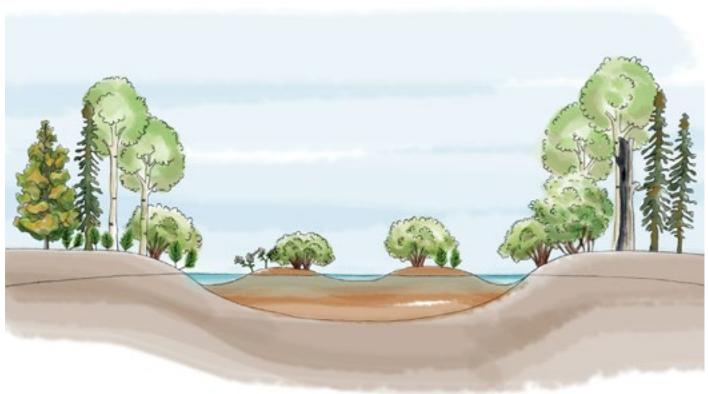
Figure 1. Comparison of the terrestrialization and paludification processes of peatland formation.

Mineral Wetlands

Mineral wetlands typically have shallow organic soil deposits that are less than 40 centimeters, and underlain by mineral sand, silt, and clay. Water table fluctuations, warmer temperatures, or vegetation properties lead to higher decomposition rates, allowing vegetation litter to become incorporated into the mineral soil horizon or forming a highly decomposed, thin layer of organic soil.[1,4] These wetlands support water loving and aquatic vegetation, and when trees and shrubs are present, they experience more vigorous growth than in organic wetlands due to more dynamic water tables throughout growing season. Mineral wetlands that have surface water present year-round differ from ponds and lakes in that their average depth throughout a growing season is 2 meters or less. In the western boreal forest, it is often that you find these systems along the edges of lakes and ponds, and even in transition areas between upland forests and organic wetlands.

Swamp

- Receive water through a combination of precipitation, surface runoff, and groundwater sources.
- Water movement can vary depending on swamp type and landscape position. They are commonly recognized as shoreline/riparian areas of rivers and lakes, experiencing dynamic water levels over the season.
- Highly diverse wetlands that are sometimes referred to as lowland forests, forested wetlands, and shrub swamps.
- Occasionally, have deeper organic soil deposits that are greater than 40 centimeters.

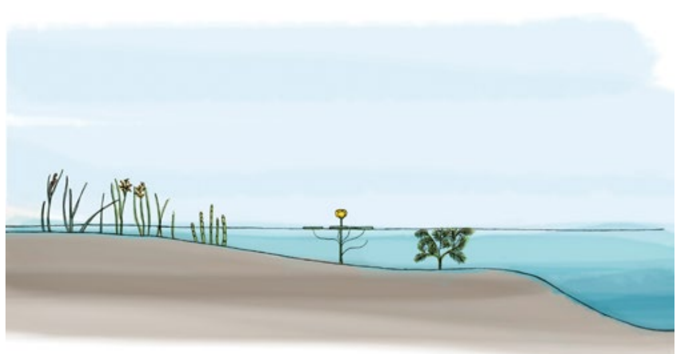


Marsh

- Receive water through a combination of precipitation, streams, and groundwater sources.
- Water levels in marshes fluctuate seasonally and are often transition zones between open water and shorelines.
- Dry out periodically, exposing soils to oxygen and resulting in a nutrient rich soil substrate.
- Supports the germination of water tolerant emergent plants (e.g., sedges, grasses, rushes, reeds, and cattail).

Shallow Open Water

- Receive water through a combination of precipitation, streams, and groundwater sources.
- Generally permanently flooded but water levels may fluctuate seasonally, resulting in exposed mudflats.
- Water depth is less than 2 meters with pond-lily or submerged aquatic vegetation.



Resources

Classification Systems:

- National Wetlands Working Group 1997
- Wetland Classification of the Boreal Plains (Enhanced Wetland Classification)
- Alberta Wetland Classification System

Field Guides:

- Alberta Wetland Classification Field Guide
- Wetlands of British Columbia: A Guide to Identification
- Wetland Plants of British Columbia: Field Guide to Indicator Species for Wetland Classification
- Manitoba Prairie Wetland Classification Guide
- Field Guide to the Ecosites of Saskatchewan's provincial forests. Saskatchewan Ministry of Environment, Forest Service. Prince Albert, Saskatchewan. 343 pp

Trainings:

- Aquality Enviromental Consulting - Alberta Wetlands: From Classification to Policy
- Tannas Conservation Services Ltd. Wetland Course
- Ducks Unlimited Canada - Wetlands 101: Boreal Wetland Classification and Identification
- University of Alberta - Wetland Deliniation, Classification and Assessment
- University of British Columbia - Fundamentals of Wetland Delineation and Assessment

1. National Wetlands Working Group. (1997). The Canadian Wetland Classification System, second edition. Wetland Research Centre, University of Waterloo, Waterloo, Ontario. https://nawcc.wetlandnetwork.ca/Wetland%20Classification%201997.pdf
2. Fissore, C., Giardina, C. P., Swanston, C. W. & King, G. (2009). Variable Temperature Sensitivity of Soil Organic Carbon in North American Forests. Global Change Biology, 15(9). https://www.researchgate.net/publication/44929892_Variable_Temperature_Sensitivity_of_Soil_Organic_Carbon_in_North_American_Forests
(Zoltai and Martikainen, 1996)
3. Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. In Environmental Reviews (Vol. 23, Issue 1, pp. 78–131). National Research Council of Canada. https://doi.org/10.1139/er-2014-0063
4. Lavoie, M., Paré, D., Fenton, N., Groot, A., & Taylor, K. (2005). Paludification and management of forested peatlands in Canada: A literature review. In Environmental Reviews (Vol. 13, Issue 2, pp. 21–50). https://doi.org/10.1139/a05-006

Healthy Landscapes Program
FACT SHEET #4

WETLANDS ON THE LANDSCAPE:

Wetland Inventories

Wetland inventories refer to the systematic processes of identifying, documenting, and categorizing wetlands within a geographic area. Wetland inventories support ecosystem-based management by providing infomation about where wetlands are (wetland inventory) and what what type of wetlands are present (wetland classification). Wetland inventories are an important tool for managing the whole landscape as they can inform industry planning and practices, wetland policy implementation, land use planning, species monitoring, and research.

Wetland inventories may be conducted at various scales, from local to regional or national levels. Inventories and their associated maps are a comprehensive tool, consolidating, assessing, and validating a wide range of remote sensing data to create detailed, large-scale representations of boreal landscapes. Wetland inventories require an underlying classification system, this can be as simple as wetlands vs. uplands, the five major wetland classes found in most Canadian Wetland Classification Systems (***Factsheet #3***), or more detailed categories that align with regional classification systems (e.g., Ducks Unlimited Canada's Enhanced Wetland Classification System, the Alberta Wetland Classification System). Wetland inventories typically involve collecting data on the location, size, type, and ecological characteristics of wetlands, as well as their functions and values.

Various techniques are used to develop a wetland inventory, such as:

Remote Sensing:

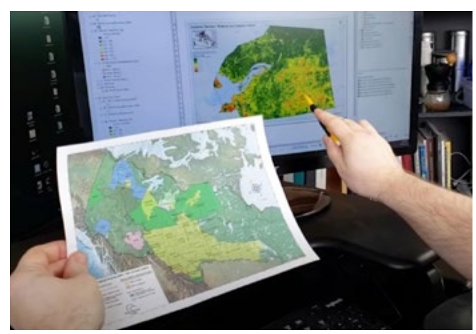
Utilizing satellite imagery, aerial photography, light detection and ranging (LiDAR) to identify and delineate wetland areas based on spectral characteristics, vegetation patterns, and hydrological features.

Field Surveys:

Conducting on-site surveys to validate remote sensing outputs by collecting data on wetland type, vegetation structures, soil characteristics, and hydrological conditions.

Geographic Information System (GIS) Analysis:

Using GIS software to digitize, manage, integrate, analyze, and visualize spatial data related to wetlands.



There are numerous wetland inventories covering different parts of the western boreal forest, but the two described in this factsheet, the Enhanced Wetland Classification Inventory and the Canadian Wetland Inventory, cover significant geographic areas and span beyond a single jurisdiction. They are also not wholly independent, the Canadian Wetland Iventory is a compilation of inventories that meet a certain standard. In boreal Canada, the Enhanced Wetland Classification Inventory is the main component of the Canadian Wetland Inventory.

Enhanced Wetland Classification System Inventory

Ducks Unlimited Canada (DUC) has created detailed and accurate wetland maps for large areas of the western boreal forest (Figure 1). To date, nearly 146 million hectares (approximately 25% of the western boreal forest) have been mapped; of this, 98 million hectares have been mapped to DUC's Enhanced Wetland Classification (EWC) standards. These standards align with the five major wetland classes described in ***Factsheet #3*** (bog, fen, swamp, marsh, and shallow open water).

The EWC inventory is based on multi-source and multi-temporal Earth observation datasets (i.e., optical, radar and topographic information). Reference data including helicopter-based vegetation surveys and high-resolution photo-interpretation are used to train and test the machine learning models. The result is a 10 or 30-metre raster dataset detailing up to 19 wetland classes, conforming with both the Alberta and Canadian Wetland.

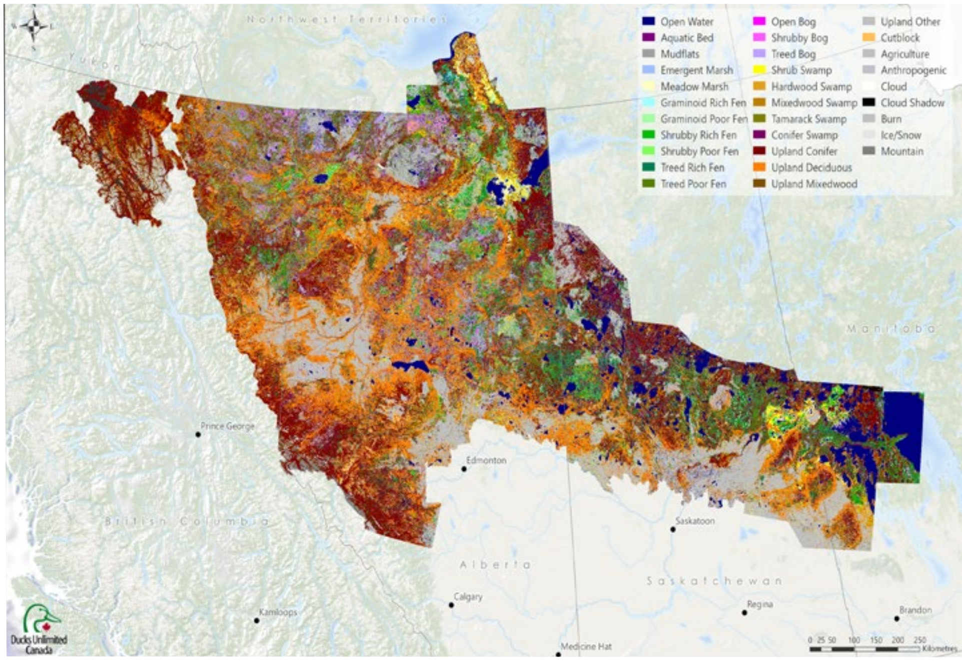


Figure 1. Ducks Unlimited Canada Enhanced Wetland Inventory map.

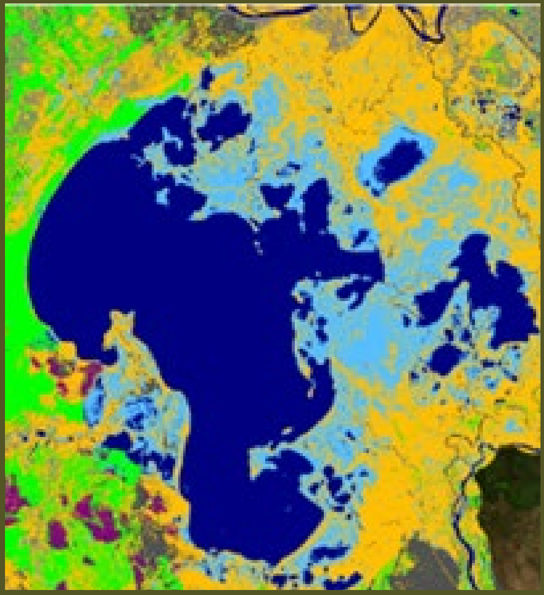
Mapping Canada's wetlands requires collaborative effort.

DUC has partnered with governments, Indigenous communities, and industries to map approximately 25% of the western boreal forest. Inventories are funded and completed on a project basis. Inventory renewal and detailed data availability is dependent on project funding, partners, and priority areas.

INFERRED PRODUCTS OF WETLAND MAPPING:

Wetland mapping can be used as a baseline for inferred products and further analyses.[2] Examples include:

- Water flow characteristics, soil moisture content, nutrient status;
- Biodiversity habitat assessments;
- Species modelling (e.g., waterfowl, caribou, bison);
- Wetland subsurface carbon storage modelling;
- Spatial prioritization for conservation planning; and
- Measuring the performance of policies and protocols towards landscape sustainability objectives.



Canadian Wetland Inventory

The Canadian Wetland Inventory was established in 2002 through collaboration between DUC, Environment Canada, the Canadian Space Agency, and the North American Wetlands Conservation Council.[1] Its primary objective is to provide a national framework for mapping wetlands, fostering consistent interpretations through a common data structure and classification system. This classification system aligns with the five major wetland classes described in ***Factsheet #3***.

A key outcome of these efforts was the development of an interactive Canadian Wetland Inventory Progress Map, displaying wetlands across Canada. This tool is a valuable resource for assessing prospective wetland loss, degradation, and restoration. The interactive map exhibits Canadian Wetland Inventory-compatible wetland inventory areas, both in progress and completed, throughout Canada. Compiled with the aim of making wetland information easily accessible, it adheres to diverse data use agreements, and catering to a broad range of users.

Currently, the Canadian Wildlife Services of Environment and Climate Change Canada is leading a new collaborative effort to compile a comprehensive publicly available Canadian National Wetlands Inventory.

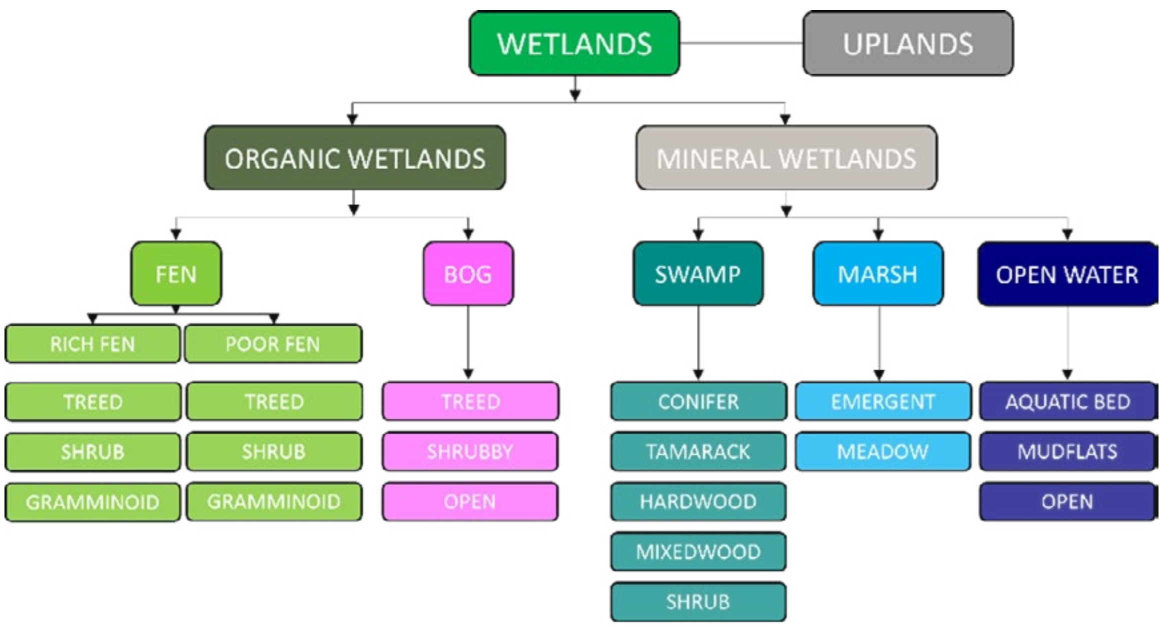


Figure 2. Ducks Unlimited Canada's Enhanced Wetland Classification System aligns with the Canadian Wetland Inventory at the five major class level.

Resources:

- Canadian Wetland Inventory Data Model
- Canadian Wetland Inventory Progress Map
- Canadian National Wetlands Inventory
- Alberta Biodiversity Monitoring Institute Wetland Inventory
- British Columbia Wetland Atlas
- Mahdianpari, M., Brisco, B., Granger, J., Mohammadimanesh, F., Salehi, B., Homayouni, S., & Bourgeau-Chavez, L. (2021). The third generation of pan-canadian wetland map at 10 m resolution using multi-source earth observation data on cloud computing platform. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 14. https://doi.org/10.1109/JSTARS.2021.3105645
- Merchant, M. A., Warren, R. K., Edwards, R., & Kenyon, J. K. (2019). An object-based assessment of multi-wavelength SAR, optical imagery and topographical datasets for operational wetland mapping in boreal Yukon, Canada. Canadian Journal of Remote Sensing, 45(3-4), 308-332.
- Merchant, M., Haas, C., Schroder, J., Warren, R., & Edwards, R. (2020). High-latitude wetland mapping using multidate and multisensor Earth observation data: a case study in the Northwest Territories. Journal of Applied Remote Sensing, 14(3), 034511-034511.

1. Ducks Unlimited Canada. (2022, July 22). Canadian Wetland Inventory — Ducks Unlimited Canada. https://www.ducks.ca/initiatives/canadian-wetland-inventory/
2. Ducks Unlimited Canada enhanced Wetland classification and mapping. (2021, May 7). Canadian Conservation and Land Management (CCLM) Knowledge Network. https://www.cclmportal.ca/resource/ducks-unlimited-canada-enhanced-wetland-classification-and-mapping
3. Ducks Unlimited Canada. (2023, March 9). Boreal Wetland inventory - Ducks Unlimited Canada National Boreal Program. Ducks Unlimited Canada National Boreal Program. https://boreal.ducks.ca/boreal-wetland-inventory/

Healthy Landscapes Program
FACT SHEET #5

WETLANDS ON THE LANDSCAPE:
Wetland Hydrology

Wetland hydrology refers to the distribution, movement, and management of water in wetlands. It is the most critical determinant of a wetland's structure and role within a watershed. Wetlands are in part defined by the presence of water (*Factsheet #3*) and wetland hydrology influences water quality, connects adjacent ecosystems, and transports water between across the landscape (***Factsheet #2***). Because of these connections, understanding wetland hydrology at local and regional scales is crucial for a whole landscape approach to ecosystem-based management.

Wetland Ecohydrology

Wetland hydrology has a strong relationship with wetland ecology (i.e. living things and their interactions with each other and with their physical surroundings). This relationship is called ecohydrology and can determine:

- **Vegetation Composition:** moisture regimes influence the types of plants that grow in a wetland, and how fast they grow.[1] Wetland plants can also impact water movement. For example, *Sphagnum* moss can move water vertically though a wetland.
- **Water Storage:** different wetland types have the potential to store different quantities of water based on the plant species present.[1]
- **Accumulation of Organic Material:** organic wetlands accumulate greater amounts of organic material compared to mineral wetlands due to their ecohydrological regime.[1]
- **Nutrient Cycling and Availability:** different wetland types are more nutrient rich than others based on water inputs, which can in turn influence plant diversity.[1,2] Plants can also influence the wetland water quality, for example, *Sphagnum* moss can acidify water chemistry.

Controls on Wetland Hydrology

The western boreal forest is characterized by a sub-humid, relatively dry climate and diverse soil properties, creating a favorable environment for forest ecosystems that store large amounts of water. Wetlands are often associated with low lying areas, but in the western boreal forest, wetlands often form on relatively flat areas due to deep organic soil deposits. This results in a landscape featuring a mosaic of wetlands and uplands.

A water balance is the hydrology accounting system and can be used to understand how water moves and is stored in wetlands. The water balance (Figure 1) takes into account inputs, including precipitation (P), groundwater (G_{in}), and surface inflow (S_{in}) and outputs including evapotranspiration (ET), groundwater (G_{out}), and surface outflow (S_{out}).

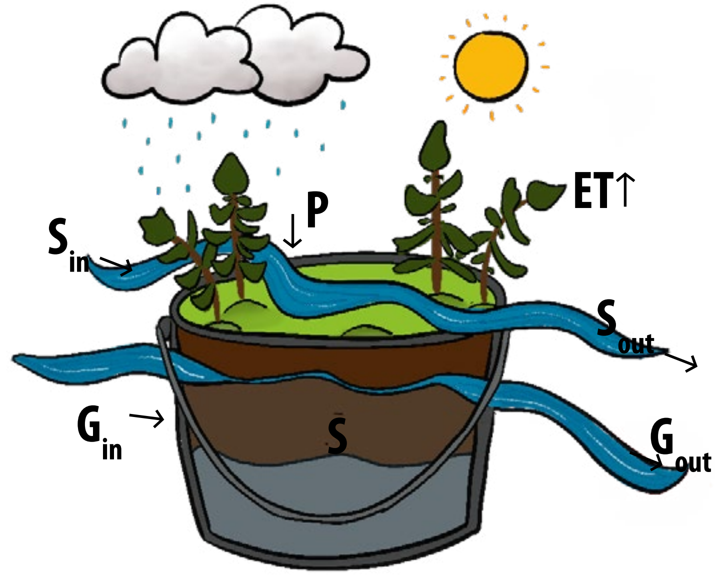


Figure 1. A wetland water balance can be described using a bucket analogy. S, represents the bucket and how much water the wetland stores, P, G_{in} and S_{in} represent inputs into a wetland, and ET, G_{out}, and S_{out} represent outputs from a wetland.

The main drivers of wetland hydrology, funtion and formation in the western boreal forest are:

1. Climate

The western boreal forest operates at a moisture deficit, where evapotranspiration exceeds precipitation.[3] Seventy percent of precipitation occurs during the growing season (May to September), resulting in significant amounts of water lost to evaporation. Most water is accumulated from rain and snowfall in the non-growing season (October to May) due to lower evapotranspiration rates from dormant vegetation.[3] This moisture deficit creates greater drought potential in the region.[4]

The amount of water a wetland stores, receives, and releases varies throughout the growing season (May to October). We refer to these temporal patterns of wet and dry periods as a **wetland hydroperiod**. Monitoring wetland hydrology can provide information about:

- **Duration of Inundation:** How long a wetland remains flooded or saturated with water. Some wetlands may have a permanent water presence, while others might experience seasonal flooding or periodic inundation.
- **Frequency of Flooding:** Some wetlands might flood annually during the rainy season, while others might only flood once every few years during major storm events.
- **Seasonality:** The wetland hydroperiod can be highly seasonal, with distinct wet and dry periods throughout the year. The timing and duration of wet and dry phases can influence the types of plant and animal species.
- **Variability:** Climate variability, precipitation patterns, water management, and land use change can cause year-to-year varibility in a wetland's hydroperiod.

2. Surficial Geology

The subsurface geology of wetlands influences how soils and sediment have layered (e.g. mineral or organic) and defines the potential storage, groundwater flow, and runoff processes.[3,5]

3. Topography and Drainage Networks

Topography has little influence on wetland development in the western boreal forest.[3,6] Wetlands tend to form in flat, gently undulating, to hummocky areas and are often associated with riverine systems. This topography creates drainage network that is not well-defined, trapping water and allowing for the formation of wetland complexes. Surficial topography greatly influences groundwater flow and functions as groundwater recharge.

4. Soil Type and Depth

Soil type and moisture regimes determine how much water can be stored within wetlands. Soils with higher clay content tend to retain more water compared to sandy soils. Organic wetlands, or peat, have the ability to store large amounts of water, resulting in high water tables and the establishment of water tolerant vegetation such as *Sphagnum* moss and black spruce. Soil depth influences wetland hydrology by affecting water infiltration and retention. Deeper soils may retain more water and allow water to remains in the wetland for a longer period of time.

Water Flow Pathways

How water flows in and out of wetlands depends on **wetland type.** Water can flow in and out of wetlands, particularly in organic wetlands, as surface water, sub-surface water, or groundwater. The movement, quantity, and speed of water through organic wetlands depends on:

- **Porosity:** pore space in soil that can be occupied by water or air. For example, increased peat porosity results in faster water movement through the peat profile.
- **Peat Composition:** Peat can be composed of decomposed mosses, sedges, or woody material, depending on peatland type. Different types of peat result in different levels of conductivity.
- **Decomposition:** Less decomposed soils have greater conductivity due to higher porosity (more/ bigger gaps between solids), while more decomposed soils have reduced conductivity due to lower porosity (fewer/ smaller gaps between solids).

In the western boreal forest, groundwater flow governs the flow dynamics, as surface runoff is less common due to the limited amounts of excess water.[3] In organic wetlands, surface runoff occurs as a result of influxes of water input into the system (i.e. increased precipitation) and periods of **high-water tables**.[5] Whether there is a surplus of water that can move around the landscape is dependent on groundwater storage capacity at different times of the year. For instance, if a wetland's storage is full, a slight rainfall may produce a more significant response, resulting in increased runoff. However, a significant rainfall event may not produce a large response if a wetland's storage is low.

NOT ALL PEAT IS THE SAME:

Not all peat is *Sphagnum*-dominated. Peat forms due to high water tables, low soil temperatures, and slow decomposition of plant materials.[7] While *Sphagnum* moss is a dominant moss species found in peatlands, some peatlands can have sedge peat, woody peat, or mossy peat. The peat type is dependent on the vegetation communities present and can influence a peatland's hydrologic regime, such as the pH and water conductivity. Peat with high *Sphagnum* content usually has a lower pH than woody peat, and woody peat has lower water conductivity than mossy peat.

Resources:

- Price, J. S., Sutton, O. F., McCarter, C. P. R., Quinton, W. L., Waddington, J. M., Whittington, P. N., … Petrone, R. M. (2023). Advances in wetland hydrology: the Canadian contribution over 75 years. Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques, 48(4), 379–427. https://doi.org/10.1080/07011784.2023.2269137
- Devito, K., Mendoza, C., & Qualizza, C. (2012). Conceptualizing water movement in the Boreal Plains. Implications for watershed reconstruction.
- Price, J. S., McCarter, C. P. R., & Quinton, W. L. (2023). Groundwater in Peat and Peatlands. In Groundwater in Peat and Peatlands. https://doi.org/10.21083/978-1-77470-015-0
- Lavoie, M., Paré, D., Fenton, N., Groot, A., & Taylor, K. (2005). Paludification and management of forested peatlands in Canada: A literature review. In Environmental Reviews (Vol. 13, Issue 2, pp. 21–50). https://doi.org/10.1139/a05-006
- Mitsch, W. J., & Gosselink, J. G. (2015). Wetlands (5th ed.). Wiley.

- Lavoie, M., Paré, D., Fenton, N., Groot, A., & Taylor, K. (2005). Paludification and management of forested peatlands in Canada: A literature review. In Environmental Reviews (Vol. 13, Issue 2, pp. 21–50). https://doi.org/10.1139/a05-006
- Mitsch, W. J., & Gosselink, J. G. (2015). Wetlands (5th ed.). Wiley.

1. Mitsch, W. J., & Gosselink, J. G. (2015). Wetlands (5th ed.). Wiley.
2. Devito, K. and C. Mendoza. 2006. Maintenance and dynamics of natural wetlands in western boreal forest: Synthesis of current understanding from the Utikuma Research Study Area. Cumulative Environmental Management Association. Alberta, Canada. Pg. 84.
3. Devito, K., Mendoza, C., & Qualizza, C. (2012). Conceptualizing water movement in the Boreal Plains. Implications for watershed reconstruction.
4. Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. In Environmental Reviews (Vol. 23, Issue 1, pp. 78–131). National Research Council of Canada. https://doi.org/10.1139/er-2014-0063
5. Willier, C. (2017). Changes in peatland plant community composition and stand structure due to road induced flooding and desiccation.
6. Anderson, R. L., Foster, D. R., & Motzkin, G. (2003). Integrating lateral expansion into models of peatland development in temperate New England. Journal of Ecology, 91(1), 68–76. https://doi.org/10.1046/j.1365-2745.2003.00740.x
7. Thompson, D. K., & Waddington, J. M. (2008). Sphagnum under pressure: towards an ecohydrological approach to examining Sphagnum productivity . Ecohydrology, 1(4), 299–308. https://doi.org/10.1002/eco.31

WETLANDS ON THE LANDSCAPE

Wetland Soil Carbon

Wetlands are vital to the global carbon cycle, serving as significant reservoirs of organic carbon by extracting it from the atmosphere and storing it in their soils and vegetation.

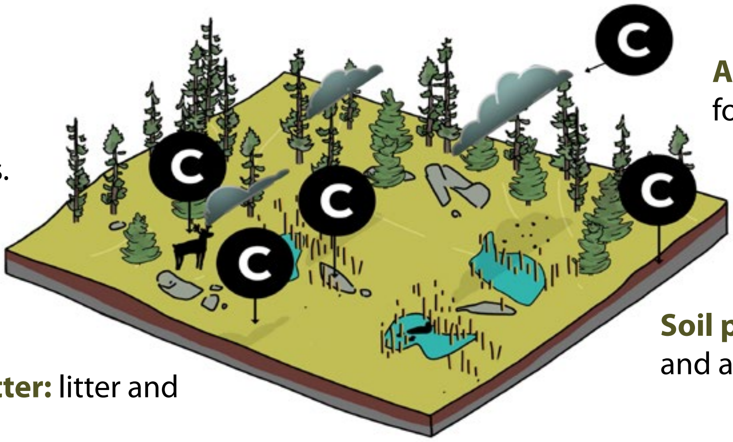
Organic wetlands are one of the most carbon-dense ecosystems globally, covering **only 3% of the Earth's surface yet storing approximately one-third of the global soil carbon stock.**[1] Canada alone contains 25% of global organic wetlands, storing approximately 150 billion tonnes of land-based carbon.[2] However, carbon storage can be affected by natural and anthropogenic disturbances, such as wildfires, forest harvest, and linear disturbances. As government policy, industry certification, and consumer preferences increasingly emphasize carbon accounting and management, understanding the role of wetlands in carbon storage becomes essential in a whole landscape approach to ecosystem-based management.

What is Carbon?

Carbon, a naturally occurring element, serves as a fundamental constituent of all organic compounds and is prevalent in:

Living biomass: animals, vegetation, including roots.

Atmosphere: gaseous forms of carbon.



Dead organic matter: litter and debris.

Soil pools: decomposed plant and animal materials.

Canada's wetlands store more carbon than upland forests, despite upland forests covering a larger land area.[3] This is because wetlands sequester most of the carbon below ground in their soils, with approximately 98.5% of organic wetland carbon stored in soils rather than above ground vegetation.

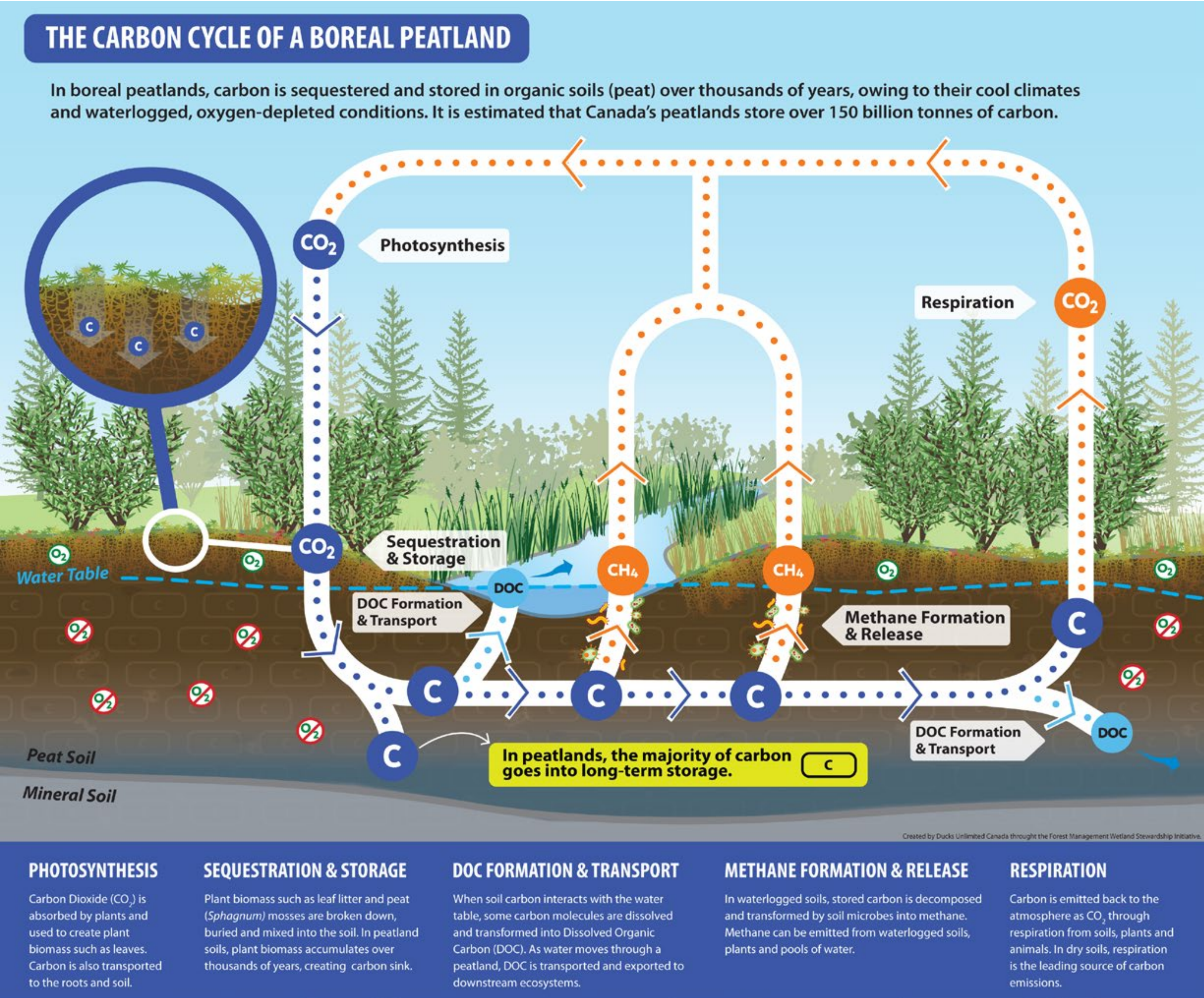
Carbon Sequestration

Wetlands extract significant amounts of carbon dioxide from the atmosphere and store it in the soil through a process called **sequestration**. Wetland ecosystems sequester carbon dioxide through photosynthesis, transforming it into live plant biomass.[4] Carbon is integrated into soil through the incorporation of live biomass, including roots and plant litter, while soil fauna, such as fungi and microbes, further enhance soil organic carbon through their biological activities.[5,6] In organic wetlands, thick layers of dead plants build up over thousands of years under wet conditions, forming deep, carbon-rich, organic soil deposits, known as peat.

Carbon Accumulation

Carbon accumulation occurs over **thousands of years** and is largely influenced by wetland hydrology which governs gas diffusion rates, oxygen levels, nutrient dynamics, and vegetation composition.[7] In organic wetlands, the vast majority (greater than 98%) of the carbon that is sequestered is stored in the organic soil as peat.[8]

Figure 1. Boreal organic wetland (peatland) carbon cycle.[9]



Carbon Loss

Despite their role as carbon sinks, organic wetlands are susceptible to emitting significant amounts of carbon in response to climate and land use changes.[10] **With anticipated increases in the frequency, extent, and intensity of disturbances in the western boreal forest, organic wetlands ability to act as carbon sinks may be constrained, with some wetlands potentially transitioning into carbon sources**.

Carbon can be lost from a wetland through:

- **Dry Condition Respiration:** Under dry conditions, soils become oxygenated and decomposition increases resulting in the release of carbon into the atmosphere. When wetlands dry out or are drained, they can release massive amounts of carbon dioxide ($C0_2$) into the atmosphere.

- **Wet Condition Respiration:** Under wet conditions, decomposition slows and carbon accumulates, but soil microbes still transform soil carbon into methane (CH_4), which can be released through standing water in wetlands. When wetlands are poorly managed or flooded, massive amounts of methane can be released into the atmosphere.

- **Water Movement:** As carbon interacts with the water table, it can be transformed into dissolved organic carbon and can be transported out of the system dissolved in surface and ground water.

- **Wildfire:** Organic wetlands, especially treed wetlands, have the potential for crown fires and for below ground fires though smouldering, releasing significant amounts of carbon. Learn more about peatland fire in ***Factsheet #8***.

Changes to a wetland's hydrology, through both natural and anthropogenic disturbances, can significantly impact a wetland's carbon emissions, and therefore, maintaining the natural hydrology of wetlands, can minimize carbon losses.[11,12] For example, road construction that blocks the natural flow of water can result in one side of the road drying out and flooding on the other side of the road. The dry side will experience greater decomposition rates, resulting in carbon release, and the flooded side is likely to experience greater amounts of methane release. The dry side will also become more susceptible to wildfire ignition and burning, resulting in further carbon loss. A range of anthropogenic activities can result in drying (e.g., drainage for peat harvest) or flooding (e.g., hydro dams) and are furthered explored in ***Factsheet #15***.

Figure 2. Soil organic carbon in Boreal Plains wetlands.

BOREAL WETLAND SOIL CARBON MAPPING

While estimates of carbon storage are readily available for managed forests, comprehensive assessments for boreal wetlands are often lacking or incomplete. To bridge this gap, Ducks Unlimited Canada (DUC) developed a first-generation map of wetland soil organic carbon for the boreal plains ecozone.

This was achieved by aggregating wetland soil organic carbon densities across various wetland classes and integrating them into DUC's Enhanced Wetland Classification maps.

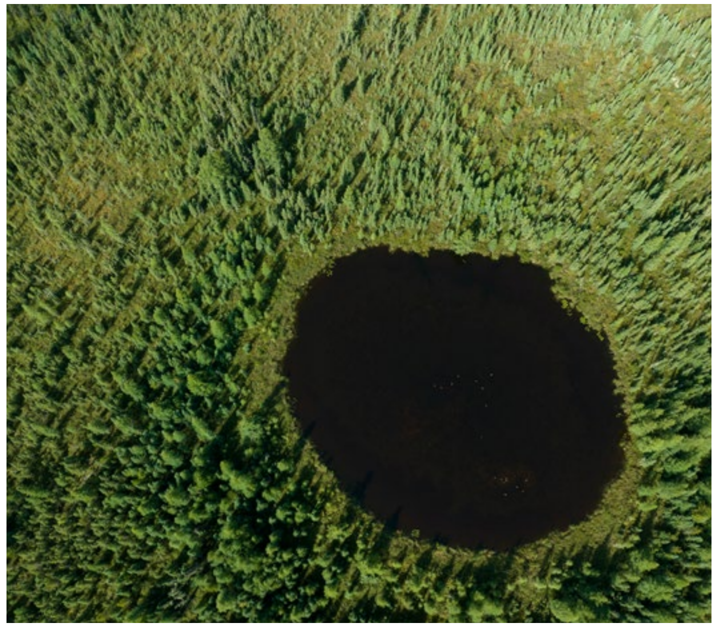
Resources:

- Bona, K. A., Shaw, C., Thompson, D. K., Hararuk, O., Webster, K., Zhang, G., Voicu, M., & Kurz, W. A. (2020). The Canadian model for peatlands (CaMP): A peatland carbon model for national greenhouse gas reporting. Ecological Modelling, 431. https://doi.org/10.1016/j.ecolmodel.2020.109164
- LeBlanc, P., Guindon, J., Morissette, J., Smith, C., Badiou, P., Coote, J., Whittington, P., Yates, T., and M. Johnston. (2017). Protocol for Wetland Carbon Sampling and Data Analysis. Prepared for Sustainable Forestry Initiative, Conservation Grants Program.
- Can-Peat Projects
- Wetlands: A Powerful Carbon Sink video
- WWF Interactive Carbon Map
- Peatlands and Carbon Video Series

1. Wilkinson, S. L., Andersen, R., Moore, P. A., Davidson, S. J., Granath, G., & Waddington, J. M. (2023). Wildfire and degradation accelerate northern peatland carbon release. Nature Climate Change, 13(5), 456–461. https://doi.org/10.1038/s41558-023-01657-w
2. Ducks Unlimited Canada, 2024, Peatlands in Canada: Terrestrial Carbon Hotspots. https://www.youtube.com/watch?v=lvAuGlWDXbk&list=PLd_mIqAjZSTANACrWtvf_LBScgoJDU1yE&index=1
3. Henschel, C., & Gray, T. (2007). Forest Carbon sequestration and avoided emissions. www.ivey.org
4. Schlesinger, W. H. (1997). Biogeochemistry: an analysis of global change.
5. Jackson, R. B., Canadell, J., Ehleringer, J. R., Mooney, H. A., Sala, O. E., & Schulze, E. D. (1996). A global analysis of root distributions for terrestrial biomes. In Oecologia (Vol. 108, Issue 3). https://doi.org/10.1007/BF00333714
6. De Vries, W. I. M., Reinds, G. J., Gundersen, P. E. R., & Sterba, H. (2006). The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Global Change Biology, 12(7), 1151-1173.
7. Gallego-Sala, A. V., Charman, D. J., Brewer, S., Page, S. E., Prentice, I. C., Friedlingstein, P., ... & Zhao, Y. (2018). Latitudinal limits to the predicted increase of the peatland carbon sink with warming. Nature climate change, 8(10), 907-913.
8. Gorham E. 1991. Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. Ecological Applications. 1(2):182-195.
9. Forest Management and Wetland Stewardship Initiative. (May 2023). Summary Report: The Effects of Forest Management Practices on Boreal Soil Carbon Storage.
10. Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., Roulet, N., Rydin, H., & Schaepman-Strub, G. (2008). Peatlands and the carbon cycle: From local processes to global implications - A synthesis. Biogeosciences, 5(5). https://doi.org/10.5194/bg-5-1475-2008
11. Mitsch, W. J., & Gosselink, J. G. (2015). Wetlands (5th ed.). Wiley.
12. Turetsky, M.R., B. Benscoter, S. Page, G. Rein, G.R. van der Werf, A. Watts. 2014. Global vulnerability of peatlands to fire and permafrost loss. Nature Geoscience 8: 11-14.

WETLANDS ON THE LANDSCAPE

Wetlands and Climate Change



Climate change refers to long-term changes in average temperatures and weather patterns, typically occurring over decades or more.[1] This phenomenon is distinct from climate variability, which encompasses all variations in climate that last longer than individual weather events but are shorter than multi-decade trends.[2] Research consistently shows that the current rate of climate warming is significantly accelerated by human activities.

Boreal ecosystems help control weather and climate directly through plant transpiration and sunlight reflection and indirectly by storing carbon and contributing fresh water to oceans. Intact wetlands play important roles in climate change mitigation and adaptation, from helping to buffer upland forests from impacts (e.g., by storing water during dry periods, serving as fire breaks) to storing large amounts of subsurface carbon (***Factsheet #6***).[3] However, climate change has the potential to alter wetland abundance and distribution across the western boreal, in turn affecting wetland functions and values (***Factsheet #1***). Understanding the cumulative effects of climate change and land use change is needed to take a whole landscape approach to ecosystem-based management.

Effects of Climate Change on Boreal Wetlands

Impacts to Water Resources

Many wetlands have variable water tables, which can change seasonally or annually depending on precipitation patterns. This variability makes it difficult to measure and predict long-term trends in wetting or drying. Overall, the boreal is expected to become drier due to increases in temperature and evaporation, which may impact wetland abundance. However, the western boreal is dominated by organic wetlands, which when undisturbed, are resistant to water loss through evaporation and may therefore persist even in a drying climate.[4] Due to their ability to adapt to climate change, managing these wetlands on the landscape is critical. For more information on water and wetlands, see ***Factsheet #3*** and ***Factsheet #4***.

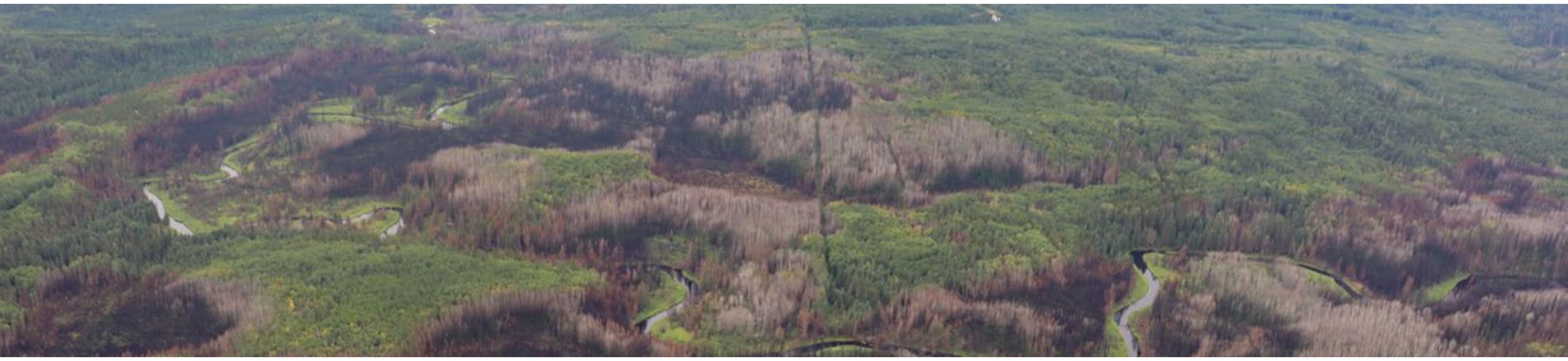
Impacts to Forest Transitions

Boreal wetlands are highly interconnected with upland forests (***Factsheet #2***) and climate change is expected to impact wetlands, upland forests and these connections. Upland western boreal forests are expected to face hotter and drier conditions, increased pressure from pests and diseases, and more frequent wildfires.[5] These factors are predicted to result in the loss of white spruce in upland forests and an expansion of grassland areas in the region.[6] This transition is expected to occur unevenly driven by events that cause the death of mature trees, such as fire, drought, heat stress and flooding.[7]

Impacts to Wildfire Vulnerability

In the western boreal forest, wetlands play an important role in regulating fire on the landscape. Kuntzemann et al. (2023) found that the presence of wetlands significantly decreased the likelihood of adjacent uplands burning during wildfire events. This effect was most pronounced with marshes, but having treed organic wetlands like fens, swamps, and bogs on a landscape also decreased the likelihood of uplands burning compared with landscapes with only uplands.

The wetter the wetland, the more effectively it acts as a fire break. However, disturbing wetland hydrology can lead to drying, making wetlands —especially treed organic wetlands —more vulnerable to burning.[9] Wetlands and wildfire are further explored in ***Factsheet #13*** and ***Factsheet #14***.



Impacts to Permafrost

Climate change is expected to reduce the depth and extent of permafrost globally. As permafrost only occurs in the northern portion of the western boreal forest, the northernly receding of permafrost could lead to a complete loss of permafrost from the western boreal. Permafrost thaw in organic wetlands has been shown to increase the hydrological connectivity of the landscape. This can result in:

- Drained water, previously locked away as ice, into rivers and streams;
- Wetland drying;
- Increased downstream runoff and flooding;
- Altered water quality;
- Altered habitat conditions;
- Increased decomposition; and,
- Increased greenhouse gas emissions.[10]

BOREAL WETLANDS AND THE GLOBAL CARBON CYCLE

Boreal organic wetland are one of the worlds largest organic carbon stores. In Canada, 150 billion tones of carbon is stored in organic wetland soils. These wetlands play an important role in climate change because of their capacity to remove and sequester greenhouse gases, such as methane and carbon dioxide, from the atmosphere, and store carbon in their above- and below-ground biomass. The role of wetlands in the global carbon cycle is explained in ***Factsheet #6***.

Impacts to Habitat and Biodiversity

Climate change is expected to impact the habitat and biodiversity of boreal wetlands. Rising temperatures and increased drought stress may weaken wetland health, making plants and animals more vulnerable to pests and diseases and causing biodiversity loss.

As climate change alters the temperature and moisture conditions of wetlands, their suitability as habitat may be affected, leading to shifts in vegetation composition and shrinking or northward movement of animal ranges. Species who cannot adapt fast enough could be at risk of extirpation or extinction.

Interacting effects of Climate Change and Anthropogenic Disturbance

Boreal wetlands are highly sensitive to disturbances that affect their hydrology (***Factsheet #5***), and the impacts of climate change may exacerbate these vulnerabilities. There is a lack of studies on the cumulative effects of climate change and anthropogenic disturbance on wetlands. However, anticipated climatic changes, such as increased temperatures, higher evaporation rates, and altered precipitation patterns, could interact with anthropogenic disturbances and potentially amplify the effect of each on wetlands.

Organic wetlands, for example, may persist in climates that over time become too dry for their natural establishment, making them especially susceptible to disturbance and challenging to restore if disturbed.[11] For more information on wetlands and anthropogenic disturbances, refer to ***Section 3***.

Boreal Wetlands in Climate Adaptation and Mitigation Strategies

Intact wetlands provide numerous ecosystem services that support climate change adaptation and mitigation, such as protection from flooding and drought, carbon capture and storage, and wildfire mitigation. Wetland conservation, management, and restoration are needed to support wetlands in continuing to provide climate adaptation and mitigation benefits to society.

A whole landscape approach to ecosystem-based management in a changing climate requires understanding where wetlands are located today (***Factsheet #3***) and how their abundance and distribution will change in the future. The Boreal Climate Change Modelling Study (currently underway, 2023 - 2026) is modelling future wetland abundance and distribution across Canada's western boreal forest. This study is engaging diverse groups affected by wetlands and climate change to understand how the results can be tailored and applied to support climate change adaptation and mitigation efforts.

Resources

- Boreal Wetlands and Climate Change
- Boreal Climate Change Modelling Study
- Predicting Wetland Change in the Prairies
- From Impacts to Adaptation: Canada in a Changing Climate
- Northern Peatlands in Canada Story Map

1. Connors, S., Berger, S., Péan, C., Bala, G., Caud, N., Chen, D., Edwards, T., Fuzzi, S., Yew Gan, T., Gomis, M., Hawkins, E., Jones, R., Kopp, R., Leitzell, K., Lonnoy, E., Maraun, D., Masson-Delmotte, V., Maycock, T., Pirani, A., … Zha, P. (2021). Summary for all climate change 2021. The Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/outreach/IPCC_AR6_WGI_SummaryForAll.pdf
2. NOAA. (2018, July). Climate variability vs. climate change. US Department of Commerce National Oceanic and Atmospheric Administration. https://www.weather.gov/media/climateservices/VariabilityAndChange.pdf
3. Ducks Unlimited Canada. (2017). Boreal wetlands and Climate Change. Key Findings for Developing Alberta's Climate Change Adaptation Strategy. https://abnawmp.ca/wp-content/uploads/2020/09/Boreal-Science-Summary-Final_web.pdf
4. Thompson, C., Mendoza, C. A., & Devito, K. J. (2017). Potential influence of climate change on ecosystems within the Boreal Plains of Alberta. Hydrological Processes, 31(11), 2110–2124. https://doi.org/10.1002/hyp.11183
5. Gauthier, S., Bernier, P., Burton, P. J., Edwards, J., Isaac, K., Isabel, N., Jayen, K., Le Goff, H., & Nelson, E. A. (2014). Climate change vulnerability and adaptation in the managed Canadian Boreal Forest. Environmental Reviews, 22(3), 256–285. https://doi.org/10.1139/er-2013-0064
6. Stralberg, D., Arseneault, D., Baltzer, J. L., Barber, Q. E., Bayne, E. M., Boulanger, Y., Brown, C. D., Cooke, H. A., Devito, K., Edwards, J., Estevo, C. A., Flynn, N., Frelich, L. E., Hogg, E. H., Johnston, M., Logan, T., Matsuoka, S. M., Moore, P., Morelli, T. L., … Whitman, E. (2020). Climate-change refugia in Boreal North America: What, where, and for how long? Frontiers in Ecology and the Environment, 18(5), 261–270. https://doi.org/10.1002/fee.2188
7. Schneider, R. R., Devito, K., Kettridge, N., & Bayne, E. (2015). Moving beyond bioclimatic envelope models: Integrating upland forest and peatland processes to predict ecosystem transitions under climate change in the Western Canadian Boreal Plain. Ecohydrology, 9(6), 899–908. https://doi.org/10.1002/eco.1707
8. Kuntzemann, C. E., Whitman, E., Stralberg, D., Parisien, M., Thompson, D. K., & Nielsen, S. E. (2023). Peatlands promote fire refugia in boreal forests of Northern Alberta, Canada. Ecosphere, 14(5). https://doi.org/10.1002/ecs2.4510
9. Granath, G., Moore, P. A., Lukenbach, M. C., & Waddington, J. M. (2016). Mitigating wildfire carbon loss in managed northern peatlands through restoration. Scientific Reports, 6(1). https://doi.org/10.1038/srep28498
10. Olefeldt, D., Heffernan, L., Jones, M. C., Sannel, A. B., Treat, C. C., & Turetsky, M. R. (2021). Permafrost Thaw in northern peatlands: Rapid changes in ecosystem and landscape functions. Ecological Studies, 27–67. https://doi.org/10.1007/978-3-030-71330-0_3
Loisel, J., & Gallego-Sala, A. (2022). Ecological resilience of restored peatlands to climate change. Communications Earth & Environment, 3(1). https://doi.org/10.1038/s43247-022-00547-x

WETLANDS ON THE LANDSCAPE: KNOWLEDGE GAPS

The factsheets in Section One, Wetlands and the Landscape, provide an introductory overview of the role of wetlands in the western boreal forest organized by key topics. Section One covers the current state of knowledge of wetland ecosystems, functions, and importance within the region. This information can support the Healthy Landscape Program (HLP) in pursuing a whole landscape approach to ecosystem-based management.

Over the past decade, boreal wetland research has grown significantly. This is driven by an understanding that effective wetland conservation, management, and restoration are needed to manage Canada's water resources, protect biodiversity, adapt to and mitigate the effects of climate change, and maintain other ecosystem services. However, wetlands are complex, the boreal is vast and there remain significant gaps in understanding the relationships between wetlands and the whole landscape. Table 1 provides an overview of key knowledge gaps organized by factsheet topic. The list focuses on gaps that are relevant to the HLP and that could be used to develop detailed research questions in the future. Many of the gaps in Section One may not lead to independent HLP projects, but they could form a part of future HLP projects, present opportunities for partnerships with other researchers (see who is working in this space), or be topics that the HLP continues to monitor and incorporate as new information is developed.

From this list, priority knowledge gaps for the HLP are included in the ***Whole Landscape Road Map*** at the end of this report.

Table 1. Section One topics and their related knowledge gaps.

Wetland Values	1.1	Understanding of Indigenous Knowledge and values, which includes valuable insights into wetland locations and their cultural significance, and knowledge of how to incorporate this information in meaningful and respectful ways to inform ecosystem based management.
	1.2	Monetary valuations of most wetland ecosystem services are lacking, outdated, or for limited areas or circumstances.
Wetland Connectivity	2.1	Understanding under what conditions, such as climate change and land-use changes, are wetlands expected to become wetter or drier and how changes in wetland hydrology affect ecosystems services and interactions with adjacent ecosystems.
	2.2	Swamps are an understudied wetland class, despite their role as hydrological hotspots on the landscape. Improving understanding of swamp hydrology and their role in landscape connectivity can lead to improved wetland management.
	2.3	Enhancing knowledge of hydrologic connections among wetland types and between wetlands and uplands in the Boreal Plains and Foothills ecozones.
Wetland Classification	3.1	Developing or tailoring wetland classification systems to regional conditions. While some jurisdictions (e.g., Alberta, Yukon forthcoming) have a wetland classification system developed for their region, many provinces and territories do not.
	3.2	Developing locally relevant accessible resources (e.g., user-friendly field guides) and training to support the uptake and application of classification systems.

Wetland Inventories	4.1	Wetland inventories have been completed for a portion of Canada and are done on a project basis, so there are differences in availability and the type and quality of information (e.g., scale, underlying classification system). This can make is challenging to utilize the data for projects needing a uniform data source across a large area.
	4.2	Capturing the true depth of shallow open water is still challenging using remote sensing approaches, meaning that in the western boreal it can be difficult to accurately differentiate lakes from shallow open water wetlands. Integrating detailed bathymetry information can help, but access to such data is limited.
	4.3	Incorporating Indigenous Knowledge into wetland inventories. Satellite-based wetland inventories rely heavily on western science and generally do not include Indigenous Knowledge, such as information on wetland location and cultural significance. While valuable for a whole landscape approach to ecosystem-based management, this information is often proprietary to communities.
	4.4	Data used to create inventories varies in cost and availability (e.g., LiDAR) and field data collection for validating is often limited by cost. This impacts the availability, locations, and quality of wetland inventories.
Wetland Hydrology	5.1	Improving understanding of the interactions between precipitation patterns, groundwater flow, and surface water dynamics that influence wetland formation and persistence in the Western Boreal Forest.
	5.2	Wetland hydrology is complex and difficult to understand and evaluate in the field. There's a need for developing user-friendly desktop and field training and tools tailored to applied audiences.
	5.3	Developing practical approaches for early identification of impacts on hydrologic connectivity, as adverse effects may not be immediately evident.
	5.4	Assessing how changing climate conditions, including alterations in temperature, precipitation, and extreme weather events, will affect wetland formation, stability, and species composition.
Wetland Carbon	6.1	Improving the availability of high-quality sub-surface carbon maps by filling data gaps and applying new modelling approaches.
	6.2	Enhancing peat depth and carbon measurements across boreal plain and foothills ecosystems, including using rapid assessment techniques.
	6.3	Understanding the dynamics of wetland wildfires and their impact on carbon storage cycles. Investigating the influence of wetland type, fuel availability, hydrologic regime, and fire severity on greenhouse gas emissions.
	6.4	Assessing the impact of industry activities (e.g., roads, peat harvest, mines, agriculture, forest harvest) on wetland sub-surface carbon storage.
	6.5	Identifying effective practices for minimizing impacts to wetland sub-surface carbon storage as part of forest management activities.
	6.6	Understanding the role of swamps in carbon cycling.
Wetlands and Climate Change	7.1	Predicting wetland distribution and abundance across the western boreal forest under climate change scenarios. Ducks Unlimited Canada's upcoming Boreal Climate Change Modelling Study is addressing this knowledge gap.
	7.2	Understanding how climate change and land use change interact to influence wetland formation, sucessional dynamics, abundance and distribution at multiple scales.
	7.3	Predicting changes in wetland vulnerability to wildfire under future climate scenarios.

NATURAL DISTURBANCE

Section Overview

The western boreal forest is a disturbance driven ecosystem, with wildfire, insect outbreaks, blow downs, and beaver impoundments as the primary natural disturbances influencing water resources and wetlands. Of these, wildfire currently has the greatest impact on wetlands, surrounding ecosystems, and global carbon stores and climate.

Wetlands, particularly those with deep organic soils, are critical in storing and distributing water across the landscape, especially in water-limited regions such as the western boreal forest. Climate change and land use change (indpendently and together) have and will continue to impact wetland hydrological regimes. Changes to wetland hydrology have cascading effects on wetland functions and values, including changes to carbon storage and sequestration, wildfire regimes, and habitat (see ***Factsheet #3*** and ***Section 3***). Due to the level of risk posed by changes in hydrology to to fire risk, and the high level of overlap with the Healthy Landscapes Program, wildifre is the focus of most of the factsheets in this section (Factsheets 8-11) with beavers addressed in ***Factsheet #12***.

Organic wetlands have been a focus of western boreal wildfire and natural disturbance research in recent years because of their abundance relative to other wetland classes, their ecological and hydrological complexity, their higher rate of anthropogenic disturbance (marshes and shallow open waters are prioritized for avoidance), and their deep stores of organic soils that when intact are carbon sinks and often fire breaks, but when disturbed can become significant carbon sources and high risk for wildfire. The factsheets cover all wetland types, but focus on organic wetlands for these reasons.

Understanding the patterns and processes of natural disturbances in wetlands is needed to take a whole landscape approach to ecosystem based management. The Healthy Landscape Program's approach to date has focused understanding and emulating natural distrubance patterns in upland forests. The factsheets in this section will help to build understanding in relation to wetlands.

Topics in this section:

8. **Wetland Fire Behaviour**
9. **Post-Fire Successional Dynamics**
10. **Indigenous Fire Stewardship**
11. **Managing Wetlands for Fire Risk**
12. **Wetlands and Beavers**

NATURAL DISTURBANCE:
Wetland Fire Behaviour

Wildfires are the primary landscape disturbance in the western boreal forest, but over the past 50 years Canada's western boreal has experienced a **rise in the annual burned area, larger fire sizes, increased fire severity, and a prolonged fire season.**[1] These changes are driven by climate change, land use changes, and fire supression activities over this time frame. The boreal forest is a fire adapted ecosystem, that prior to recent decades of fire suppression, experienced high levels of fire disturbance as a part of forest life cycles.

Wetlands, particularly organic wetlands, exhibit a dual nature in their interaction with wildfires. While they can function as effective fire breaks, they are also susceptible to sustaining **high-intensity fires that can contribute to significant fire events.**[2] After several severe fire seasons in the past decade, there is increasing awareness amongst Canadians of wildfire and increasing focus amongst researchers and practitioners on how all parts of the landscape contribute to wildfire. Understanding wetland fire behaviour and patterns of natural disturbance is critical for a whole landscape approach to ecosystem based management.

Wetland Fire Behaviour

While all wetland types can experience wildfire, **treed organic wetlands with deep peat soils are particularly susceptible to ignition and severe and prolonged burning because of the significant amounts of subsurface fuels compared to uplands and the higher likelihood of dry conditions compared to other wetland types.** Treed organic wetlands have been a focus of much of the wetland-fire research, and there is limited information on fire behaviour in other wetland types.

Fire behaviour in organic wetlands is characterized by **below ground burning through smoldering combustion.** Organic wetlands that are sparsely vegetated tend to not be prone to severe burning (e.g., graminoid fens); however, treed organic wetlands can accumulate surface fuel loads similar to upland stands.[1] When surface or crown fire passes through these wetlands, it ignites surface mosses and peat soils, and can smolder deep into the soil profile, sometimes sustaining through the winter and reigniting in the next fire season, making fires extremely difficult to detect and suppress.[1]

Wetland fires can be described by their:

- **Intensity:** The rate of heat energy released during a fire, impacting the amount of biomass burned and area burned by a fire.
- **Severity:** How deep and how long a fire burns in the soil profile.[3] The deeper a fire burns, the greater likeliness of a fire smouldering through the winter and reigniting in the spring, the more carbon loss to the atmosphere, and the greater impacts to landscape hydrology, biochemistry and hydrological connectivity.[1] At the site level fire severity is influenced by:
  - **Moisture Conditions:** Drier peat soils are more flammable and susceptible to deeper and longer burns than wet peat soils.

- **Fuel Load:** Above ground fuel loads can impact the flammability of a peatland. Treed wetlands are more susceptible than non-treed wetlands to fire.[1] Moss species composition can also impact the severity of combustion, with different mosses having different water holding capabilities.[1]
- **Peat Bulk Density:** Higher peat bulk density corresponds to greater burn depth (i.e., more severe fires), while lower peat bulk density results in shallower burners (i.e. less severe fires).[3]

Without interventions, climate change, land use change, and continued fire suppression are expected to continue to interact to result in drier wetland systems and increased fire intensity and severity in these sysems.[1,4]

Wetland Vegetation and Fire Behaviour

In treed wetlands, particularly those dominated by black spruce (*Picea mariana*), above-ground fuel loads can accumulate to levels similar to those found in upland forests. Climate-induced wetland drying can further intensify crown cover in these environments.[1] Black spruce, being a fire-adapted species, can sustain high-intensity crown fires and spread fire via "spotting", or by throwing embers.[1] The fire behaviour in black spruce can lead to the spread to other fire-prone ecosystems, resulting in wetlands shifting from their historical role as fire breaks to contributing to fire spread.[1,4]

Wetland mosses, particularly the *Sphagnum* mosses that dominate organic wetlands, influence fire behavior. *Sphagnum* mosses provide high water-holding capacities and drought tolerance while reducing water loss through evapotranspiration.[5,6,7] However, prolonged drying periods can diminish these protective mechanisms and result in these mosses acting as fire wicks, leading to:

- Enhanced soil and organic matter drying,
- Increased fuel availability, and
- Increased fire vulnerability.[8,9]

Canopy closure also affects wildfire behaviour. Greater canopy closure provides shade, favouring feather mosses which have poorer water retention than *Sphagnum* mosses.[1] Therefore, **feather mosses are more flammable than *Sphagnum* mosses**, and the shift from *Sphagnum* dominated to feather moss dominated contributes to increased fuel availability and fire vulnerability.[2]

More spatially and ecologically diverse wetland complexes are more likely to limit fire spread. For example, Markle et al. (2022) found that wetlands with mostly continuous vegetation cover showed higher fire severity than wetlands interspersed with shallow open water areas. Wetlands with more tree cover, a larger proportion of transition areas, or that become periodically disconnected from groundwater systems (wetlands that have drier soils or are more susceptible to periodicly dry soils) tend to be most vulnerable to high burn severity.[3,10]

Wetland Hydrology and Fire Behaviour

Moisture content in wetland ecosystems is regulated in part by the moisture retention properties of moss and peat, exhibiting variations across different peatland moss species.[11] This regulation of moisture content is crucial in understanding the vulnerability of these ecosystems to wildfires, as highlighted by hydrological feedback processes involving moss growth, peat formation, and evaporation.[12,13] These processes, in conjunction with factors such as thick wet soils, low evapotranspiration rates, and the water retention capabilities of mosses, collectively serve to mitigate wildfire frequency and restrict deep burning under most fire weather conditions.[13]

Hydrological connectivity within organic wetlands, along with water table fluctuations, significantly influence fire behavior within and between other ecosystems. When water demand from upland forests is greater than precipitation inputs, upland forests rely on organic wetlands as water sources which exacerbates water table fluctuations along the margins of organic wetlands, making them more susceptible to hydrologic changes compared to the central areas. This fluctuation leads to increased bulk density at the margins, resulting in deeper burning during fires.[3]

Additionally, surficial geology plays a crucial role in determining peatland susceptibility to fires by influencing groundwater connectivity.[3] This connectivity affects the degree of compaction and rates of decomposition within the peatland, ultimately shaping its bulk density and susceptibility to deep burning. Peatlands characterized by greater water table fluctuations and lower groundwater connectivity are at heightened risk of experiencing deep burns.

THE FIRE WEATHER INDEX SYSTEM AND WETLANDS

The Canadian Fire Weather Index (FWI) system is a widely utilized tool for assessing fire danger across various environments globally. Originally developed and calibrated for upland Jack pine (*Pinus banksiana*) forests, the FWI integrates three moisture codes — Fine Fuel Moisture (FFMC), Duff Moisture (DMC), and Drought (DC) — each reflecting the moisture content of different fuels based on meteorological data.[14]

However, wetlands, often perceived as consistently saturated throughout much of the year, have been **excluded from many wildfire models.[16]**

To help address this gap, Mortelmans et al. (2024) introduced an organic wetland-specific adaptation of the FWI system, termed FWI_{peat}. This modified model replaces the original moisture codes with hydrological estimates tailored to organic wetlands, aiming to enhance the monitoring of fire risk in organic wetlands. Mortelmans et al., (2024) found that adapting the FWI with hydrological information is beneficial in estimating the presence of organic wetland fires. However, the FWI was originally not designed to predict fire presence but rather to estimate fire danger.[14]

Resources:

- Canadian Forest Fire Behaviour Prediction (FBP) System
- Canadian Forest Fire Weather Index (FWI) System
- Mortelmans, J., Felsberg, A., De Lannoy, G. J., Veraverbeke, S., Field, R. D., Andela, N., & Bechtold, M. (2024). Improving the fire weather index system for peatlands using peat-specific hydrological input data. Natural Hazards and Earth System Sciences, 24(2), 445-464.
- Wilkinson, S. L., Moore, P. A., Thompson, D. K., Wotton, B. M., Hvenegaard, S., Schroeder, D., & Waddington, J. M. (2018). The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. Canadian Journal of Forest Research, 48(12), 1433–1440. https://doi.org/10.1139/cjfr-2018-0217
- Thompson, D. K., Simpson, B. N., Whitman, E., Barber, Q. E., and Parisien, M. A.: Peatland hydrological dynamics as a driver of landscape connectivity and fire activity in the Boreal plain of Canada, Forests, 10, 534, https://doi.org/10.3390/f10070534, 2019.
- Wilkinson, S. L., Furukawa, A. K., Wotton, B. M., & Waddington, J. M. (2021). Mapping smouldering fire potential in boreal peatlands and assessing interactions with the wildland-human interface in Alberta, Canada. International Journal of Wildland Fire, 30(7), 552–563. https://doi.org/10.1071/WF21001

1. Wilkinson, S. L., Moore, P. A., Thompson, D. K., Wotton, B. M., Hvenegaard, S., Schroeder, D., & Waddington, J. M. (2018). The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. Canadian Journal of Forest Research, 48(12), 1433–1440. https://doi.org/10.1139/cjfr-2018-0217
2. Kuosmanen, N., Väliranta, M., Piilo, S., Tuittila, E.-S., Oksanen, P., & Wallenius, T. (2023). Repeated fires in forested peatlands in sporadic permafrost zone in Western Canada. Environmental Research Letters. https://doi.org/10.1088/1748-9326/acf05b
3. Hokanson, K. J., Lukenbach, M. C., Devito, K. J., Kettridge, N., Petrone, R. M., & Waddington, J. M. (2016). Groundwater connectivity controls peat burn severity in the boreal plains. Ecohydrology, 9(4). https://doi.org/10.1002/eco.1657
4. Helbig, M., Waddington, J. M., Alekseychik, P., Amiro, B. D., Aurela, M., Barr, A. G., Black, T. A., Blanken, P. D., Carey, S. K., Chen, J., Chi, J., Desai, A. R., Dunn, A., Euskirchen, E. S., Flanagan, L. B., Forbrich, I., Friborg, T., Grelle, A., Harder, S., … Zyrianov, V. (2020). Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. Nature Climate Change, 10(6). https://doi.org/10.1038/s41558-020-0763-7
5. Dickinson, C. H., & Maggs, G. H. (1974). Aspects of the decomposition of sphagnum leaves in an ombrophilous mire. New Phytologist, 73(6). https://doi.org/10.1111/j.1469-8137.1974.tb02154.x
6. Bu, Z. J., Zheng, X. X., Rydin, H., Moore, T., & Ma, J. (2013). Facilitation vs. competition: Does interspecific interaction affect drought responses in Sphagnum? Basic and Applied Ecology, 14(7). https://doi.org/10.1016/j.baae.2013.08.002
7. Kettridge, N., Humphrey, R. E., Smith, J. E., Lukenbach, M. C., Devito, K. J., Petrone, R. M., & Waddington, J. M. (2014). Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire. Journal of Hydrology, 513, 335–341. https://doi.org/10.1016/j.jhydrol.2014.03.019
8. Turetsky, M., Wieder, K., Halsey, L., & Vitt, D. (2002). Current disturbance and the diminishing peatland carbon sink. Geophysical Research Letters, 29(11). https://doi.org/10.1029/2001GL014000
9. Lukenbach, M. C., Devito, K. J., Kettridge, N., Petrone, R. M., & Waddington, J. M. (2016). Burn severity alters peatland moss water availability: Implications for post-fire recovery. Ecohydrology, 9(2). https://doi.org/10.1002/eco.1639
10. Rein, G., Cleaver, N., Ashton, C., Pironi, P., & Torero, J. L. (2008). The severity of smouldering peat fires and damage to the forest soil. Catena, 74(3). https://doi.org/10.1016/j.catena.2008.05.008
11. Markle, C. E., Gage, H. J. M., Tekatch, A. M., Wilkinson, S. L., & Waddington, J. M. (2022). Wetland Successional State Affects Fire Severity in a Boreal Shield Landscape. Wetlands, 42(7). https://doi.org/10.1007/s13157-022-01606-x
12. Mccarter, C. P. R., & Price, J. S. (2014). Ecohydrology of Sphagnum moss hummocks: Mechanisms of capitula water supply and simulated effects of evaporation. Ecohydrology, 7(1). https://doi.org/10.1002/eco.1313
13. Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015). Hydrological feedbacks in northern peatlands. Ecohydrology, 8(1), 113–127. https://doi.org/10.1002/eco.1493
14. Johnston, D. C., Turetsky, M. R., Benscoter, B. W., & Wotton, B. M. (2015). Fuel load, structure, and potential fire behaviour in black spruce bogs. Canadian Journal of Forest Research, 45(7). https://doi.org/10.1139/cjfr-2014-0334

NATURAL DISTURBANCE:

Wetland Post-Fire Successional Dynamics

Healthy Landscapes Program

FACT SHEET #9

Fire plays an important role in shaping the ecological and environmental dynamics of the western boreal. Post-fire successional dynamics in uplands are well understood by the Healthy Landscapes Program, but there are gaps in understanding these processes in other ecosystems. Understanding ecosystem recovery across all ecosystem types is critical for a whole landscape approach to ecosystem-based management.

This factsheet provides an overview of wetland successional dynamics following wildfire. However, like uplands, changes in wetland fire behaviour (Factsheet Fire Behaviour) including **increased fire frequency, intensity, and severity can adversely impact the re-establishment of pre-fire conditions**.[1,2] This means that our understanding of successional dynamics based on historic fire regimes may not reflect recovery from current and future wildfires. Understanding the impacts of wetland fires is a growing, but relatively new field.

Wetlands and Wildfire Refugia

Wildfire rarely results in a uniform and all-encompassing burn across the landscape. Instead, it often leaves patches of unburned vegetation. When areas repeatedly escape fire, they may be referred to as **refugia**. Refugias are typically influenced by topography, with flat areas facilitating fire spread. In the western boreal where there is little topographical relief, **wetlands are critical wildfire refugia**, with their high soil moisture content and ecology.[3] This does not mean that wetlands do not burn, but rather have a lower probability of burning, and typically do not burn as severly as uplands. Wetlands that act as refugia help shape post-fire ecosystem processes by:

- Acting as gene banks for regenerating burn areas where seeds, rhizomes and other plant reproductive elements are preserved, limiting changes to species composition post fire,
- Acting as fire breaks by preventing spread to adjacent ecosystems, and
- Promoting areas of refugia, for vegetation and wildlife (such as boreal caribou) in both wetlands and in upland forest adjacent to hydrologically connected peatlands, such as fens.[3]

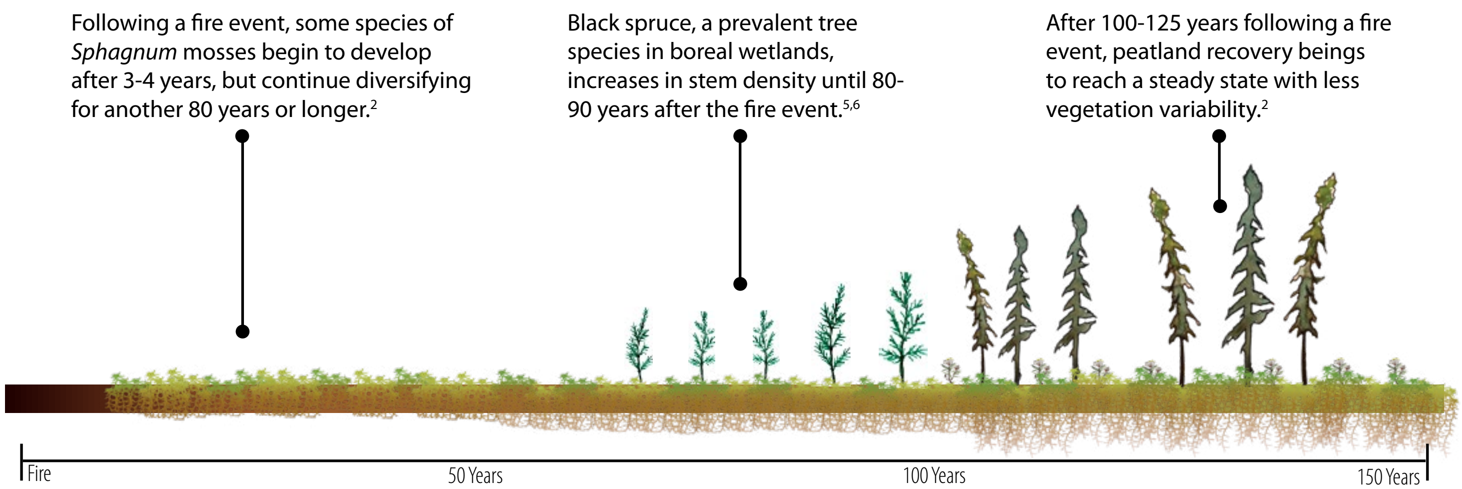
The spatial variations in burn severity serve as key indicators for post-fire regeneration and species composition.[2,4] Microtopography emerges as a critical factor in this context, particularly with *Sphagnum*-dominated dry hummock communities serving as noteworthy indicators. These hummocks, retaining higher levels of moisture and tend to experience less severe burns.[1,4] However, when wetlands are dry (e.g., drought or disconnected from ground water by anthropogenic disturbance) they may no longer act as refugia, but rather as wicks.

Post- Fire Wetland Vegetation

Most wetland succession research has focused on treed organic wetlands, with a gap in the literature related to other wetland types. In studied organic wetlands, low-intensity and severity fires and result in a post-fire nutrient flush that can stimulate vegetation growth and enhance peat accumulation, with rapid recovery of species such as *Sphagnum* mosses.[1] When this occurs, peat accumulation stabilizes quickly and net peat accumulation is not impacted.[1]

Factors that influence wetland recovery include:[2]

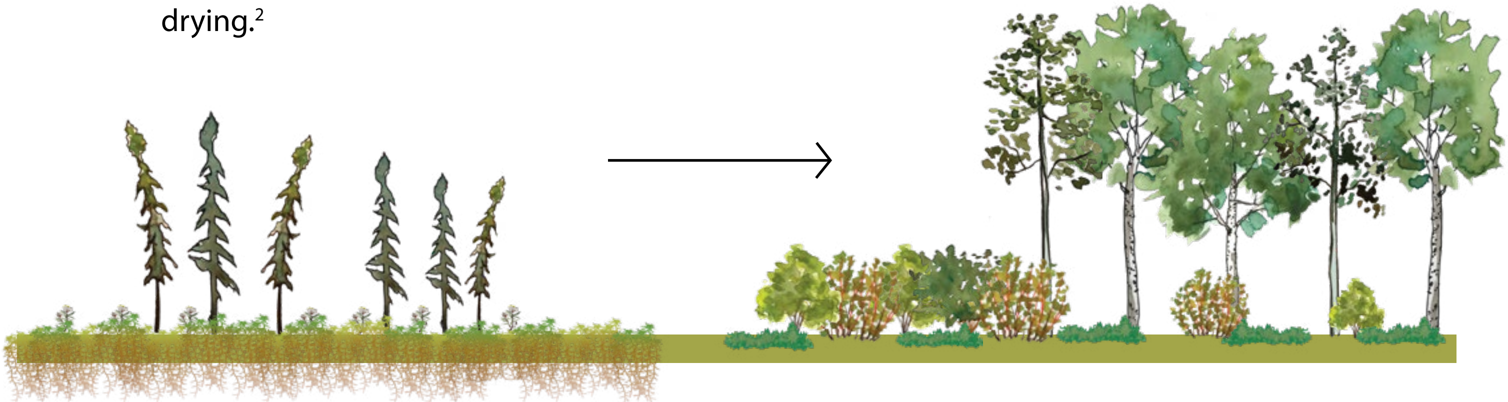
- **Pre-fire site conditions:** Vegetation composition, seed bank, presence of disturbance (i.e. harvesting or wetland draining), and soil moisture conditions.
- **Severity of the burn:** How deep the burn penetrates into the peat profile.
- **Time since last fire:** The amount of time that has passed since the last time the peatland burned.
- **Climate variability:** Climate trends and long-term fire weather such as prolongued wet periods or drought.



Impacts of Climate Change on Fire and Wetland Succession

Increased temperatures due to climate change are expected to often result in warmer and drier wetland conditions. Consequences of these trends that then effect wetland wildfire and post-wildfire succession include:

1. ***Shifts in vegetation composition towards a more terrestrial landscape, characterized by:***
   - Increasing tree and shrub biomass, particularly evident in shrub-dominated wetlands.[2]
   - In organic wetlands, moss composition shifting from *Sphagnum*-dominated to feather moss-dominated. Feather mosses have less capacity for water retention and are more susceptible to drying.[2]



2. ***More severe burns resulting in deeper smouldering potential, longer-lasting fires, and greater carbon release.***

   When dry to due to climate or land use changes, organic wetlands with deep peat soils are particularly susceptible to severe burns. This is because there is abundant sub-surface fuel available to burn (dry peat) and fire can **penetrate protective moss layers** crucial for regulating surface moisture and water storage.[2,7] Severe fires in organic wetlands can overwinter (smoulder below the ground surface), **release large amounts of carbon**, and burn deep into the peat profile.[4,8] Severe fires in peatlands also reprodize these wetland's refugia potential, such as completely eliminate most or all of a wetland's gene bank.

3. ***Increased fire frequency under future climate scenarios creates uncertainy in upland and wetland ecosystem recovery trajectories.[2]***

   Historic fire return intervals for treed boreal wetlands are estimated to be 100 to 120 years or longer.[2,9] However, historic return intervals may not be indicative of current or future intervals as t**he frequency and severity of wildfires have increased and are predicted to continue increasing.**[1,2] This increase in fire return is expected to [2]:

   - Reduce viable seed load, the number of seedlings, conifer density
   - Change soil characteristics
   - Change the vegetation communities of wetlands and surrounding forests
   - Release substantial amounts of carbon dioxide into the atmosphere
   - Increase permafrost thaw
   - Potentially release legacy metals into air and water systems

WATER REPELLENCY IN WETLANDS POST-FIRE

After a wildfire, the hydrology of burned wetlands undergoes significant changes that result in decreased surface evaporation. This reduction in surface evaporation can be due to the development of a water-repellent layer either on the wetland's surface or in the near-surface soil layers after the fire.[10] These dynamics have been studied in organic wetlands with deep peat soils, but are likely to occur in other wetland types.

High soil temperatures can cause organic substances to bond to soil particles, resulting in water repellency in previously hydrophilic soils.[10] This bonding process creates water-repellent layers within the soil, causing water droplets to bead on the surface instead of infiltrating the soil profile. Additionally, the water-repellent layer acts as a physical barrier to the capillary rise of water from the water table to the wetland's surface, reducing moisture lost through evaporation.[10]

The extent of this effect depends on fire severity and vegetation species, with more water repellency observed in feather mosses than in *Sphagnum*.[11] The increased water repellency following a fire can enhance wetland resilience by reducing evaporation, which contributes to a higher water table and helps protect wetland soils from decomposition.

Resources:

- Jones, E. (2021). Wildfire return intervals: impacts of diminishing fire return intervals on boreal peatlands using combined field/lidar approaches. University of Lethbridge (Canada).
- Kettridge, N., Humphrey, R. E., Smith, J. E., Lukenbach, M. C., Devito, K. J., Petrone, R. M., & Waddington, J. M. (2014). Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire. Journal of Hydrology, 513, 335–341. https://doi.org/10.1016/j.jhydrol.2014.03.019
- Kuntzemann, C. E., Whitman, E., Stralberg, D., Parisien, M. A., Thompson, D. K., & Nielsen, S. E. (2023). Peatlands promote fire refugia in boreal forests of northern Alberta, Canada. Ecosphere, 14(5). https://doi.org/10.1002/ecs2.4510

1. Kuosmanen, N., Väliranta, M., Piilo, S., Tuittila, E.-S., Oksanen, P., & Wallenius, T. (2023). Repeated fires in forested peatlands in sporadic permafrost zone in Western Canada. Environmental Research Letters. https://doi.org/10.1088/1748-9326/acf05b
2. Jones, E. (2019). Wildfire return intervals: impacts of diminishing fire return intervals on boreal peatlands using combined field/lidar approaches.
3. Kuntzemann, C. E., Whitman, E., Stralberg, D., Parisien, M. A., Thompson, D. K., & Nielsen, S. E. (2023). Peatlands promote fire refugia in boreal forests of northern Alberta, Canada. Ecosphere, 14(5). https://doi.org/10.1002/ecs2.4510
4. Benscoter, B. W., Kelman, W. R., & Vitt, D. H. (2005). Linking microtopography with post-fire succession in bogs. Journal of Vegetation Science, 16(4). https://doi.org/10.1111/j.1654-1103.2005.tb02385.x
5. Sirois, L., & Payette, S. (1989). Postfire black spruce establishment in subarctic and boreal Quebec. Canadian Journal of Forest Research, 19(12). https://doi.org/10.1139/x89-239
6. Wieder, R. K., Scott, K. D., Kamminga, K., Vile, M. A., Vitt, D. H., Bone, T., Xu, B., Benscoter, B. W., & Bhatti, J. S. (2009). Postfire carbon balance in boreal bogs of Alberta, Canada. Global Change Biology, 15(1). https://doi.org/10.1111/j.1365-2486.2008.01756.x
7. Benscoter, B. W., & Wieder, R. K. (2003). Variability in organic matter lost by combustion in a boreal bog during the 2001 Chisholm fire. Canadian Journal of Forest Research, 33(12). https://doi.org/10.1139/x03-162
8. Benscoter & Wieder, 2003
9. Wilkinson, S. L., Furukawa, A. K., Wotton, B. M., & Waddington, J. M. (2021). Mapping smouldering fire potential in boreal peatlands and assessing interactions with the wildland-human interface in Alberta, Canada. International Journal of Wildland Fire, 30(7), 552–563. https://doi.org/10.1071/WF21001
10. Kettridge, N., Humphrey, R. E., Smith, J. E., Lukenbach, M. C., Devito, K. J., Petrone, R. M., & Waddington, J. M. (2014). Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire. Journal of Hydrology, 513, 335–341. https://doi.org/10.1016/j.jhydrol.2014.03.019

NATURAL DISTURBANCE:

Indigenous Fire Stewardship

Indigenous fire stewardship is the use of cultural burning practices by Indigenous Peoples to mange the landscape for multiple values. **Cultural burning has been used since time immemorial to enhance biodiversity, reduce wildfire risk, maintain cultural connections to the land, and manage the natural resources vital for sustaining diverse aspects of Indigenous life.[1]** Through cultural burning practices, Indigenous communities shaped fire regimes, adapted to climate variations, and managed local environmental conditions.[1]

Deep rooted in traditional knowledge and historical culture, Indigenous fire stewardship offers unique insights from centuries of observation and adaptation. Wildfire is one of the most complex land management challenges in Canada and bringing together Indigenous and western knowledge can strengthen efforts to use fire stewardship to manage the whole landscape for multiple values.

A History of Fire Stewardship

Indigenous Peoples have a rich history of **coexisting with fire-prone ecosystems,** ingrained in their traditions and cultures through their deep understanding of fire-dependent species and ecological processes.[2] The intergenerational teachings of Indigenous fire stewardship encompass a comprehensive understanding of fire regimes, the consequences of fire, and the cultural significance of controlled burns.[1] This holistic approach integrates diverse elements such as climatic cycles, ignition sources, fire behavior, landscape topography, and vegetation, providing a nuanced comprehension of fire threats, impacts, and benefits.[1,3]

Indigenous fire knowledge uses **proactive methods, incorporating intentional burning to reduce fuel loading, thereby mitigating the intensity and severity of fires across the landscape.[2]** Through the practice of frequent, low-intensity fires, Indigenous communities actively promote fire-adapted vegetation, fostering increased biodiversity and creating a heterogeneous landscape.[1,4]

Fire-adapted plants, understory species, and early seral vegetation often hold cultural significance as keystone species, providing valuable resources such as wildlife habitat, food, materials, and medicine for Indigenous communities.[1]

Indigenous fire applications differ from natural ignitions in frequency and seasonal timings and align with plant and fungus phenology and the timing of animal breeding and migration cycles.[2] This intentional approach to fire management demonstrates a connection between Indigenous knowledge and the ecological well-being of their environments.

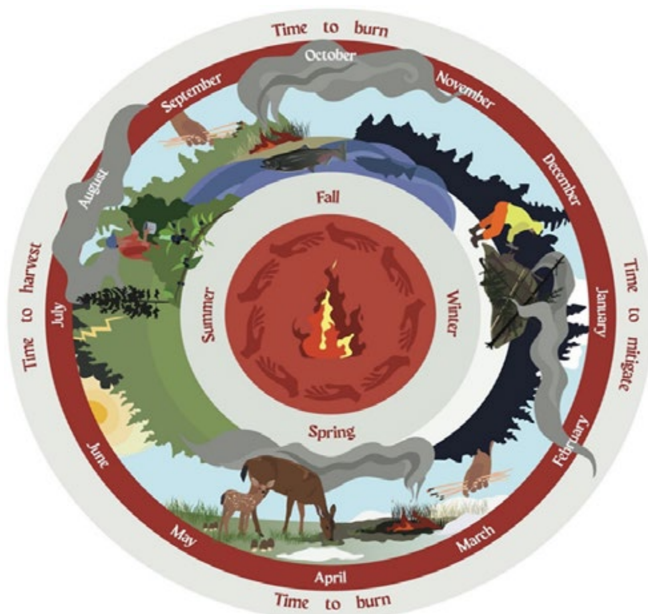


Figure 1. A seasonal calendar illustrating aspects of Indigenous fire stewardship.[5]

Fire Stewardship Supports Biodiversity

A history of fire suppression and restrictions on Indigenous rights to practice cultural burning, has led to a notable decline in understory biodiversity.[5,6] Changes to the wildfire regime and fuel loading are recognized as a significant threat to biodiversity on a global scale.[7]

Low-severity fires play an important role in enhancing biodiversity by creating diverse habitats across different seral stages. Low-severity fires leave behind fire refugia or unburnt patches, promoting the germination of fire-adapted species' seeds and providing essential habitat features like fallen logs or snags for wildlife. Wetlands can play an important role supporting species during low-severity fires, with intact wetlands providing wildfire refugia where species can shelter during fire.

Low severity wildfire can support biodiversity in the boreal forest. By promoting regular, low-severity fires through cultural burning practices, Indigenous Peoples are able to promote and support biodiversity on their lands.

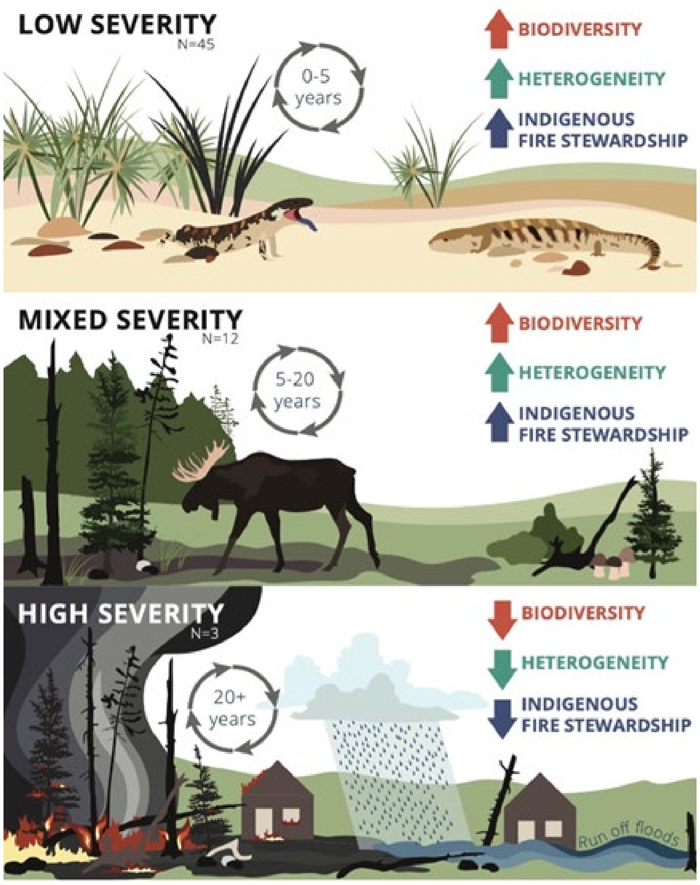


Figure 2. Conceptual illustration of the relationship between the severity of wildfires, biodiversity, heterogeneity, and Indigenous fire stewardship.[16]

A CASE STUDY WITH HISTORICAL CONTEXT

In a study of a dry mixed-conifer forest in Knife Creek, British Columbia, historic ignitions were caused by a combination of lightning and Indigenous fire stewardship.[8] These fires were typically low-severity surface fires with burn intervals under 50 years and occasional high-severity fires every 250 years.[9] This region now faces an increased threat of more frequent and severe fires due to climate change and fire suppression.[10,11]

Evidence from tree ring studies paired with oral histories and documented community records, indicate a shift away from Indigenous fire stewardship towards fire suppression. This can be attributed to the arrival of European colonization in the 1860s, which severely restricted Indigenous fire stewardship.[12,13] The suppression of fire was enforced through:

- **Bush Fire Act (1874):** Enforced fines or imprisonment if an individual purposely set fire and damaged private or crown land.[10]
- **Forest Act (1912):** Financially supported and maintained a fire prevention management strategy.[10,12]

Due to colonization and western perspectives of fire as destructive to timber supply and dangerous to communities, Indigenous fire stewardship practices were severely limited.[1] Today, many Indigenous communities face high risks of destructive wildfires.[14] A potential solution lies in cross-cultural fire stewardship that integrates western science and Indigenous knowledge, offering protection to communities and fostering social acceptability of controlled fire in the wildland-urban interface.[15]

Fire Stewardship and Ecosystem-Based Management

Indigenous fire stewardship supports wetland stewardship by enhancing biodiversity, managing natural resources, and mitigating the risk of high-severity fires. After a fire, a nutrient flush can stimulate vegetation growth and enhance peat accumulation in organic wetlands, further highlighting the interconnectedness between Indigenous fire stewardship and wetland health and resilience.

Indigenous fire stewardship can support multiple natural resource management objectives. Cultural burning can promote drought-tolerant, fire-adapted species and remove fire-intolerant species or diseased trees, as well as remove woody vegetation, shift vegetation communities, and alter hydrologic regimes in wetlands.[2] These changes can enhance biodiversity and culturally important species, maintain below-ground carbon stores (by reducing likelihood of severe wildfires), and reduce overall wildfire risk.[2]

Barriers to Indigenous Fire Stewardship

1. **Perceptions, authority, and jurisdiction:** There is insufficient understanding by wildfire agencies, decision-makers, and the public about the relationship between Indigenous Peoples and fire.
2. **Governance, laws, and management:** Colonial impacts pose barriers to engaging in and leading cultural burning. Historically under colonial rule and persisting today in government land management regulations, Indigenous communities have been restricted from practicing cultural burning.
3. **Access, accreditation, and training:** Wildfire science and management courses do not adequately address cultural burning and there are knowledge gaps amongst western science practitioners and government decision-makers.
4. **Liabilities and insurance:** Insufficient financial support and requirements for extensive insurance hinders all forms of fire stewardship, but Indigenous fire stewardship faces additional barriers.
5. **Capacity and resources:** Limited funding for Indigenous fire stewardship and loss of knowledge within many communities due to historic and ongoing restrictions on use of cultural burning practices.[5]

Resources:

- The Good Fire Podcast
- Blazing the Trail: Celebrating Indigenous Fire Stewardship
- Media Relations. (2021). Indigenous fire stewardship promotes global biodviersity. Waterloo News.
- Brookes, W., Daniels, L. D., Copes-Gerbitz, K., Baron, J. N., & Carroll, A. L. (2021). A Disrupted Historical Fire Regime in Central British Columbia. Frontiers in Ecology and Evolution, 9. https://doi.org/10.3389/fevo.2021.676961
- Hoffman, K. M., Christianson, A. C., Dickson-Hoyle, S., Copes-Gerbitz, K., Nikolakis, W., Diabo, D. A., McLeod, R., Michell, H. J., Mamun, A. Al, Zahara, A., Mauro, N., Gilchrist, J., Ross, R. M., & Daniels, L. D. (2022). The right to burn: barriers and opportunities for Indigenous-led fire stewardship in Canada. Facets, 7. https://doi.org/10.1139/FACETS-2021-0062
- Hoffman, K. M., Christianson, A. C., Dickson-Hoyle, S., Copes-Gerbitz, K., Nikolakis, W., Diabo, D. A., McLeod, R., Michell, H. J., Mamun, A. Al, Zahara, A., Mauro, N., Gilchrist, J., Ross, R. M., & Daniels, L. D. (2022). The right to burn: barriers and opportunities for Indigenous-led fire stewardship in Canada. Facets, 7. https://doi.org/10.1139/FACETS-2021-0062

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1. Lake, F. K., & Christianson, A. C. (2019). Indigenous Fire Stewardship. In Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. https://doi.org/10.1007/978-3-319-51727-8_225-1
2. Lake, F. K. (2021). Indigenous fire stewardship: Federal/Tribal partnerships for wildland fire research and management. Fire Management Today, 79(1).
3. Huffman, M. R. (2013). The many elements of traditional fire knowledge: synthesis, classification, and aids to cross-cultural problem solving in fire-dependent systems around the world. Ecology and Society, 18(4).
4. Mistry, J., Bilbao, B. A., & Berardi, A. (2016). Community owned solutions for fire management in tropical ecosystems: Case studies from Indigenous communities of South America. In Philosophical Transactions of the Royal Society B: Biological Sciences (Vol. 371, Issue 1696). https://doi.org/10.1098/rstb.2015.0174
5. Hoffman, K. M., Christianson, A. C., Dickson-Hoyle, S., Copes-Gerbitz, K., Nikolakis, W., Diabo, D. A., McLeod, R., Michell, H. J., Mamun, A. Al, Zahara, A., Mauro, N., Gilchrist, J., Ross, R. M., & Daniels, L. D. (2022). The right to burn: barriers and opportunities for Indigenous-led fire stewardship in Canada. Facets, 7. https://doi.org/10.1139/FACETS-2021-0062
6. Hart-Fredeluces, G. M., Ticktin, T., & Lake, F. K. (2021). Simulated Indigenous fire stewardship increases the population growth rate of an understorey herb. Journal of Ecology, 109(3). https://doi.org/10.1111/1365-2745.13542
7. Coop, J. D., Massatti, R. T., & Schoettle, A. W. (2010). Subalpine vegetation pattern three decades after stand-replacing fire: Effects of landscape context and topography on plant community composition, tree regeneration, and diversity. Journal of Vegetation Science, 21(3). https://doi.org/10.1111/j.1654-1103.2009.01154.x8. (Coogan et al., 2021)
9. (BC Ministries of Environment and Forests, 1995)
10. Brookes, W., Daniels, L. D., Copes-Gerbitz, K., Baron, J. N., & Carroll, A. L. (2021). A Disrupted Historical Fire Regime in Central British Columbia. Frontiers in Ecology and Evolution, 9. https://doi.org/10.3389/fevo.2021.676961
11. Abbott, G., & Chapman, M. (2018). Addressing the New Normal: 21st Century Disaster Management in British Columbia: Executive Summary. BC Flood and Wildfire Review.
12. Parminter, J. (1991). Fire history and effects on vegetation in three biogeoclimatic zones of British Columbia. In Fire and the environment: ecological and cultural perspectives (pp. 263-272).
13. Day, J. K. (1998). Selection management of interior Douglas-fir for mule deer winter range (Doctoral dissertation, University of British Columbia).
14. McGee, T. K., Nation, M. O., & Christianson, A. C. (2019). Residents' wildfire evacuation actions in Mishkeegogamang Ojibway Nation, Ontario, Canada. International Journal of Disaster Risk Reduction, 33. https://doi.org/10.1016/j.ijdrr.2018.10.012
15. Lake, F. K., Parrotta, J., Giardina, C. P., Davidson-Hunt, I., & Uprety, Y. (2018). Integration of traditional and Western knowledge in forest landscape restoration. In Forest landscape restoration (pp. 198-226). Routledge.
16. Media Relations. (2021). Indigenous fire stewardship promotes global biodviersity. Waterloo News.

NATURAL DISTURBANCE:

Managing Wetlands for Fire Risk

In the western boreal, wetlands form significant parts of the wildland-urban interface and wildland-industry interface and are often older than their historic natural range of variation, but are rarely targeted for proactive wildfire risk management.[1] This is primarily due to widely held assumptions that all wetlands are wildfire refugia, a focus on avoiding wetland disturbance (and potential regulatory barriers associated with any disturbance), a lack of knowledge of the mitigation techniques that could be effective and appropriate in wetlands, and a lack of clarity with respect to who is responsible for managing wetland fire risk on crown land.

There is a growing understanding that **some wetland types, primarily forested organic wetlands, are susceptible to high-intensity burns, characterized by severe smoldering combustion and substantial carbon losses.** As awareness of the potential risks grows, so does the need for techniques that effectively manage fuel loads to reduce wildfire risk and severity in wetlands (***Factsheets #8***).[1]

This factsheet provides an overview of the current state of knowledge of managing wetlands for fire risk. These approaches should be considered alongside Indigenous fire stewardship (***Facsheet #10***). The purpose of this factsheet is to increase awareness of the need for fuel management in some wetlands, the types of techniques being explored, and how these techniques may differ from uplands. For example, fuel management in uplands has focused on managing above ground fuel, but that is insufficient in organic wetlands where sub-surface fuel is the primary risk factor.[2] This information is important to consider when taking a whole landscape approach to ecosystem based management.

Need for Wetland Fuel Management

Managing fuel loads in wetlands can help reduce the amount of above ground fuel available and restore the hydrological and vegetation conditions that make wetlands more resistant and resilient to fire (***Factsheet #8***).

Driven by historic fire suppression, climate change, and land use change, there are more older and drier wetlands than historic patterns suggest. These conditions have increased the risk of fire ignition, severity, intensity, and season length.[1] This in turn increases potential effects to other ecological values, severe wetland fires can:

- Release significant amounts of carbon into the atmosphere from below-ground carbon stores;
- Transition a burned wetland to a different wetland type, or an upland ecosystem, altering wetland functions such as water resources, habitat, or presence of culturally important species;
- Propogate fire to adjacent areas contributing to significant fire events and putting at communities, infrastructure, and resources (e.g., timber) at risk and over-winter fire in peat soils; and,
- Potentially release legacy metals into the air and water systems.[1]

Fuel Management Treatments in Wetlands

Wildfire in wetlands is managed using a combination of fuel management treatments (passive suppression) and extinguishing fire once detected (active suppression). Wetland management in wetlands must adress both above-ground and below-ground fuel sources. Table 1 provides an overview of passive suppression techniques that are being trialed in wetlands. Current research focuses on treed organic wetlands because these wetland types pose the greatest fire risk on the landscape to due the large amount of subsurface fuels (peat) available to burn when dry and their sensitivity to climate and land use change.

Treatment Type	Description	Considerations
Prescribed Burns	Deliberately setting fires under controlled conditions to reduce excessive fuel loading on the landscape.	Appropriateness and success as a management tool depends on the size of the area, season, and hazard conditions. Because of these factors, perscribed burning is not appropriate in many circumstances, but can be extremely effective when it is. Incorporating Indigenous Knowledge and cultural burning practices can enhance the effectiveness, increase biodiversity, and promote ecological resilience (***Factsheet #10***).
Thinning	Selectively removes vegetation to decrease fuel loads and reduce fire intensity and rate of spread.[2]	While shown to be effective in upland forests, evidence shows that thinning does not reduce the rate of spread or fire intensity in treed organic wetlands. Reducing the canopy cover in wetlands results in drier surface fuels due to greater wind and sun exposure.[2] Thinning did show to reduce the intensity of burn, and reduced canopy do suggest that thinning practices may support active suppression.[2]
Mulching	Mechanically shredding surface fuels and trees, reducing crown bulk density and ladder fuels.[1,3]	Mulching can maintain peat moisture content and reduce evaporation from the moss surface, further aiding fire prevention and control.[1,4,5] Mulching also required thinning above-ground biomass, but unlike thinning alone, the mulch results in beneficial outcomes such as *Sphagnum* moss establishment due to increased sun availability and increased soil moisture content.[6]
Compression	Mechanically compressing moss and peat layers to maintain soil moisture.[6]	Manual compression of peat soils from machinery has shown increased moisture retention capabilities, and the vertical transport of water to the ground surface has been shown to reduce the depth of burn and potential for smouldering.[3,8,9] By compressing the soil, the peat bulk density increases, which could result in increased carbon loss if soils were to burn in future unknown conditions.

Table 1. Wetland fuel management techniques and considerations in application.

Challenges for Implementing Fuel Management Techniques in Wetlands

Implementing effective fuel management techniques in wetlands is challenging due to their distinctecology and need for specialized approaches for fire management. Socio-economic, political, and economic factors can compound these challenges (Table 2).

Ecological	Wetlands pose unique challenges for implementing fuel management techniques due to their complex hydrology and deep organic soils (organic wetlands). Their unique ecology means that upland fuel management techniques may not be directly applicable and research is needed to develop techniques tailored to wetlands. As well, techniques that are effective in one wetland type (e.g., treed fen) may not be effective in another wetland type (e.g., treed swamp).
Socioeconomic	Determining who is responsible for funding and leading fuel management in wetlands is a significant obstacle. Divergent stakeholder interests, economic constraints, and varying community engagement levels contribute to the complexity of decision-making and implementation processes.
Economic	Developing and executing fuel management techniques requires substantial financial and time investment and there is no immediate offset to the cost (e.g., fuel management in uplands may provide some merchantable timber). The remote locations of many wetlands in the western boreal also presents financial and logistical barriers for implementing fuel management practices.
Political	Policy and regulatory frameworks governing wetlands restrict disturbances and permission for fuel management may require additional steps. Techniques perceived as risky, such as prescribed burning, face additional regulatory barriers.
Risk	Similar to uplands, wetlands most in need of fuel management may also be too risky for some fuel management techniques such as prescribed burning as there can be a heightened potential for fire escape and rapid spread under high-hazard conditions.[7]

Table 2. Challenges associated with implementing peatland fuel management techniques.

PELICAN MOUNTAIN RESEARCH SITE

The Pelican Mountain Research Site near Slave Lake, Alberta is a partnership between Alberta Wildfire and FPInnovations to evaluate the effects of various fuel management techniques. The research site is predominantly bog and fen ecosystems with black spruce cover and the partnership is supported by multiple wetland research affiliations. Wetland focused projects such as WILDPHIRE utilize the site to test novel wetland fuel treatments.

Resources:

- Canadian Forest Fire Behaviour Prediction (FBP System)
- Natural Resources Canada National Guide for Wildland-Urban Interface Fires (2021)
- Canada Wildfire Burn - P3 Model
- Mortelmans, J., Felsberg, A., De Lannoy, G. J., Veraverbeke, S., Field, R. D., Andela, N., & Bechtold, M. (2024). Improving the fire weather index system for peatlands using peat-specific hydrological input data. Natural Hazards and Earth System Sciences, 24(2), 445-464.
- Wilkinson, S. L., Moore, P. A., Thompson, D. K., Wotton, B. M., Hvenegaard, S., Schroeder, D., & Waddington, J. M. (2018). The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. Canadian Journal of Forest Research, 48(12), 1433–1440. https://doi.org/10.1139/cjfr-2018-0217

1. Wilkinson, S. L., Moore, P. A., Thompson, D. K., Wotton, B. M., Hvenegaard, S., Schroeder, D., & Waddington, J. M. (2018). The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. Canadian Journal of Forest Research, 48(12), 1433–1440. https://doi.org/10.1139/cjfr-2018-0217
2.Thompson, D. K., Schroeder, D., Wilkinson, S. L., Barber, Q., Baxter, G., Cameron, H., Hsieh, R., Marshall, G., Moore, B., Refai, R., Rodell, C., Schiks, T., Verkaik, G. J., & Zerb, J. (2020). Recent crown thinning in a boreal black spruce forest does not reduce spread rate nor total fuel consumption: Results from an experimental crown fire in Alberta, Canada. Fire, 3(3). https://doi.org/10.3390/fire3030028
3.Kane, J. M., Varner, J. M., & Knapp, E. E. (2009). Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. International Journal of Wildland Fire, 18(6). https://doi.org/10.1071/WF08072
4. Price, J., Rochefort, L., & Quinty, F. (1998). Energy and moisture considerations on cutover peatlands: Surface microtopography, mulch cover and Sphagnum regeneration. Ecological Engineering, 10(4). https://doi.org/10.1016/S0925-8574(98)00046-9
5. Kreye, J. K., Varner, J. M., & Knapp, E. E. (2012). Moisture desorption in mechanically masticated fuels: Effects of particle fracturing and fuelbed compaction. International Journal of Wildland Fire, 21(7). https://doi.org/10.1071/WF11077
6. Deane, P. J., Wilkinson, S. L., Verkaik, G. J., Moore, P. A., Schroeder, D., & Waddington, J. M. (2022). Peat surface compression reduces smouldering fire potential as a novel fuel treatment for boreal peatlands. Canadian Journal of Forest Research, 52(3). https://doi.org/10.1139/cjfr-2021-0183
7.Hvenegaard, S., Refai, R., Mackinnon, B., & Benson, M. (2020). Fuel Amendment as a Forest Fuel Removal Treatment: Exploratory Trials in Black Spruce Fuels at the Fort Providence Wildfire Experimental Site.

NATURAL DISTURBANCE:

Wetlands and Beavers

Beavers (*Castor spp.*) are **keystone species** and **ecosystem engineers** with significant impacts on wetlands, altering the ecosystem's function through tree cutting and dam construction.[1] Beavers play a transformative role in wetlands and wetland complexes, resulting in the creation of wetland habitats. Beavers can transform upland deciduous forests into wetlands in just a matter of years.[2] Beaver activities have wide-ranging effects, influencing organic wetland formation, hydrological dynamics, and wildfire resiliency at a landscape scale. **Beavers possess the remarkable capacity to construct, destroy, modify, and restore wetlands through damming streams.[2]**

While beaver activity can be beneficial for returning wetlands to the landscape and reducing fire risk, it can also cause challenges such as plugging culverts and affecting road performance or flooding merchantable forests. Understanding how beavers can naturally alter the landscape and how they can be used or directed to shape the landscape is important for ecosystem based management in the western boreal forest.

Beaver Activity: Creating Wetland Habitats

A common misconception is that open water is a prerequisite for beaver colonization.[1] Beavers can create ponds in organic wetlands by damming ground water and subsurface flows using disturbed vegetation.[1] This practice transforms landscapes by replacing deciduous stands and shrubs with herbaceous plants, essentially **reversing succession**.[1] The harvested vegetation is used to build dams, dens, and food caches.[1]

Beaver ponds are temporary and follow a cycle of creation, abandonment, and eventual washout.[1] Once the food supply is depleted in an area, beavers will migrate and abandon their dams. The longevity of their impact differs between stream and organic wetland systems:

- In streams, the lack of maintenance to the dam often results in the dam washing away.
- In organic wetlands, the lasting impact of these dams is expected to be more significant because they cannot be easily washed away by surface flows.[1]

Beavers are a natural disturbance with many benefits for ecosystem function; however, they can also cause significant challenges for land managers. Some of the wetland values created in beaver influenced landscapes may come at the expense of other values, with problems typically associated with tree cutting or flooding. For example, beavers routinely plug culverts leading to road performance and safety concerns, cause flooding of agricultural fields or merchantable timber stands, and can even interfere with septic systems.

Beaver Activity and Wetland Hydrology

Beaver dams exert a significant influence on wetland hydrology with the primary impact of a **heightened water table**, resulting in:

- Increased area and water storage,
- Expansion of the wetland's boundary, and
- Alteration of connectivity and flow. [1,3]

Wetlands with beaver activity have more open water than those without any beaver activity.[4] This is due to the diffusion of water flow by the dam, which causes greater water accumulation in the wetland. Changes in hydrologic connectivity can lead to the integration of wetlands with nearby streams. This transformation, can also divert water elsewhere on the landscape, enhancing subsurface hydrologic connectivity, regionally channeling water, and serving as a point for groundwater recharge.[1] **Beaver dams enhance the complexity of wetlands, fostering groundwater and surface water connectivity between smaller and larger wetlands in the landscape.[3]**

Beavers actively manage the water table to align with the crest of their dam, contributing to greater water table stability than anticipated in hydrologically dynamic wetlands like fens.[1] Consequently, fens affected by beaver activity maintain saturation throughout the growing season, deviating from the typical wetting and drying cycles.

Beaver effects on hydrology can be both positive and negative depending on the circumstances and the values that are considered. Flooding can have negative effects on areas where flooding is not desirable such as crops, residential areas, infrastructure, and harvest blocks.

BEAVER ACTIVITY AND CARBON

Beaver activity can significantly impact wetland carbon dynamics. Higher water tables created by beaver dams can alter vegetation composition, affecting the wetland's ability to sequester carbon. High water tables support increased carbon storage as they foster the thriving of peat-forming vegetation.

However, current climate predictions suggest a decline in water tables, resulting in drier conditions, which heightens the risk of ignition for this vegetation under dry circumstances.[1] Abandonment of dams may also result in a drop in water table, potentially drying out the wetland and increasing the risk of fire.

Beaver Activity and Vegetation

The presence of higher water tables due to beaver activity can lead to a shift in the vegetation community, which can have long-lasting impacts on wetland functions including hydrology and carbon storage and sequestration. The increase in water tables, contributes to increases in soil moisture and nutrient availability, notably nitrogen and phosphorus essential for plant growth.[2,5]

Beaver dams may also modify stream sediment dynamics, reducing flow speeds and leading to sediment accumulation behind dams and on pond beds.[2] Sediment accumulation can facilitate the emergence of new riparian landforms.[2,6,7] Over time, plant communities are replaced based on their ability to tolerate varying hydric conditions.[2,8,9]

Beaver ponding has two main effects on vegetation:

1. **A shift to terrestrial vegetation that is unique to beaver-influenced wetlands:** Because vegetation in wetlands is highly sensitive to water fluctuations, shifts in vegetation are unique to each system. Vegetation that does not thrive in wet soils will die off.[1]
2. **A shift from terrestrial to aquatic vegetation:** Mosses, shrubs, and other terrestrial plants die off and aquatic plants start to dominate.[1]

Beavers' foraging behavior primarily focuses on the leaves and bark of deciduous trees and shrubs, often leaving much of the woody biomass they cut unconsumed. This practice serves important roles in forest health and diversity and the tree cutting can also stimulate vigorous sprouting and early growth in affected plants, ultimately influencing the ecosystem structure and dynamics.[2]

Beaver influenced changes to vegetation are not always desirable. Beavers can remove trees and other desired vegetation, particularly impacting rural and urban natural habitats where trees may be limited. As well, beaver influenced flooding can cause unwanted shifts in vegetation when crops or merchantable timber are affected. Taking a whole landscape approach to ecosystem based management requires considering the positive effects on some ecosystem values alongside the negative effects on others. In recent years, there has been an increasing understanding of the value that beaver bring to the boreal landscape.

Credit: Charles Erdman/Trout Unlimited

BEAVER ACTIVITY AND WILDFIRE RESILIENCE

Beaver dams are renowned for their ability to promote groundwater recharge and sustain green vegetation during droughts. Additionally, areas with beaver activity exhibit enhanced ecological resilience, but also provide fire-resistant riparian corridors.[10] When fires burn through an area, these beaver-influenced areas remain verdant, offering temporary refuge to the diverse wildlife that inhabits them.[10] Beavers could be an effective tool to explore as part of ecosystem based management and there is a growing body of research looking into their role in wildfire and carbon management.

Resources:

- Working with Beavers
- Beaver Beneficial Managements Practices Interactive Decision Tree
- How Beavers Build Fire Resistant Landscapes
- Karran (2018). The Engineering of Peatland Form and Function by Beaver. University of Saskatchewan, Saskatoon, Canada.
- Fairfax, E., & Whittle, A. (2021). Smokey the Beaver: Beaver-Dammed Riparian Corridors Stay Green During Wildfire Throughout the Western USA. The Bulletin of the Ecological Society of America, 102(1). https://doi.org/10.1002/bes2.1795
- Westbrook, C. J. (2020). Beaver as agents of plant disturbance. In Plant Disturbance Ecology: The Process and the Response. https://doi.org/10.1016/B978-0-12-818813-2.00014-9

1. Karran (2018). The Engineering of Peatland Form and Function by Beaver. University of Saskatchewan, Saskatoon, Canada.
2. Westbrook, C. J. (2020). Beaver as agents of plant disturbance. In Plant Disturbance Ecology: The Process and the Response. https://doi.org/10.1016/B978-0-12-818813-2.00014-9
3. Markle, C. E., Gage, H. J. M., Tekatch, A. M., Wilkinson, S. L., & Waddington, J. M. (2022). Wetland Successional State Affects Fire Severity in a Boreal Shield Landscape. Wetlands, 42(7). https://doi.org/10.1007/s13157-022-01606-x
4. Westbrook, C. J., & Bedard-Haughn, A. (2016). Sibbald Research Wetland: Mountain peatland form and ecohydrologic function as influenced by beaver. Forestry Chronicle, 92(1). https://doi.org/10.5558/tfc2016-011
5. Johnston, C. A., Pinay, G., Arens, C., & Naiman, R. J. (1995). Influence of Soil Properties on the Biogeochemistry of a Beaver Meadow Hydrosequence. Soil Science Society of America Journal, 59(6). https://doi.org/10.2136/sssaj1995.03615995005900060041x
6. Pollock, M. M., Beechie, T. J., & Jordan, C. E. (2007). Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms, 32(8). https://doi.org/10.1002/esp.1553
7. Westbrook, C. J., Cooper, D. J., & Anderson, C. B. (2017). Alteration of hydrogeomorphic processes by invasive beavers in southern South America. Science of the Total Environment, 574. https://doi.org/10.1016/j.scitotenv.2016.09.045
8. Donkor, N. T., & Fryxell, J. M. (1999). Impact of beaver foraging on structure of lowland boreal forests of Algonquin Provincial Park, Ontario. Forest Ecology and Management, 118(1–3). https://doi.org/10.1016/S0378-1127(98)00487-3
9. Donkor, N. T., & Fryxell, J. M. (2000). Lowland boreal forests characterization in Algonquin Provincial Park relative to beaver (Castor canadensis) foraging and edaphic factors. Plant Ecology, 148(1). https://doi.org/10.1023/A:1009860512339
10. Fairfax, E., & Whittle, A. (2021). Smokey the Beaver: Beaver-Dammed Riparian Corridors Stay Green During Wildfire Throughout the Western USA. The Bulletin of the Ecological Society of America, 102(1). https://doi.org/10.1002/bes2.1795

NATURAL DISTURBANCE: KNOWLEDGE GAPS

The factsheets in Section Two provide an overview of the primary natural disturbances that affect wetlands in the western boreal forest. Natural disturbances play a crucial role in defining landscape dynamics and ecosystem functions. While the Healthy Landscapes Program (HLP) has developed a strong understanding of how natural disturbances influence upland forests, understanding how these disturbances shape wetlands is equally important for applying a whole landscape approach to ecosystem-based management.

Recent research has increasingly recognized the complexity of natural disturbances in the western boreal forest, including the role of fire, insect outbreaks, windthrow, and beavers. These disturbances can significantly alter wetland characteristics, influencing hydrology, vegetation, and ecosystem services. Despite progress, gaps remain in our understanding of how these disturbances interact with wetlands and affect the broader landscape. Section Two focuses on the top two natural disturbances in wetlands – fire and beavers and Table 1 provides an overview of key knowledge gaps organized by factsheet topic. The list focuses on gaps that are relevant to the HLP and that could be used to develop detailed research questions in the future. Many of the gaps in Section Two are directly relevant to themes that the HLP is exploring in upland forests. While wetland-specific projects are possible, incorporating wetlands into wildfire research questions and projects that the HLP is exploring in uplands

From this list, priority knowledge gaps for the HLP are included in the ***Whole Landscape Road Map*** at the end of this report.

Table 2. Section Two topics and their related knowledge gaps.

Wetland Fire Behaviour	8.1	Improving understanding of how wetland age, vegetation composition, and hydrology contribute to wetland wildfire behaviour.
	8.2	Incorporating information from knowledge gap 9.1 into wildfire models to improve the applicability of predictions to wetlands.
	8.3	Understanding the impacts of human activities (e.g., roads, well pads, seismic lines, etc.), climate change (see knowledge gaps under Section One), and the combined effects of both on wildfire risk, fire severity, and smoldering potential in wetlands.
	8.4	Exploring the conditions under which wetlands can serve as effective fire breaks against wildfires.
	8.5	Estimating greenhouse gas emissions resulting from various types and severities of wetland wildfires, including how factors such as peat presence and depth, burn severity, above-ground vegetation, etc., in contribute to total fire emissions.
	8.6	Developing strategies for monitoring wetland ecological variables and anthropogenic effects across large areas so that this information is available to address knowledge gaps 9.1 – 9.4. Ecological data is often lacking in wetlands compared to more actively managed ecosystems (e.g., upland forests). In most jurisdictions, information about cumulative human footprint (for uplands and wetlands) is lacking or out of date.

Post-Fire Successional Dynamics	9.1	Improving understanding of historic fire return intervals in wetlands across the western boreal forest.
	9.2	Predicting changes in fire return intervals in wetlands based on historic return intervals and considering predicted climate and land use changes.
	9.3	Understanding how wetland fire severity and intensity is changing (and predicting future changes), and exploring the impacts of altered fire severity on-site recovery and successional dynamics within wetland ecosystems.
	9.4	Understanding post-fire mechanisms that retain moisture in peat and the breakdown of soil water-repellency.
	9.5	Understanding the role of historic fire suppression in wetlands (and resulting increase of 'old' wetlands on the landscape) on fire return intervals, fire severity, and post-fire successional dynamics.
Indigenous Fire Stewardship	10.1	Testing approaches to bring together and apply Indigenous fire stewardship and western wildfire science.
	10.2	Indigenous fire stewardship is guided by traditional knowledge that may be proprietary to a community or predominantly documented through oral history. Approaches for documenting and safeguarding knowledge in ways that respect community preferences are needed.
	10.3	Understanding cultural burning practices that have been historically applied in wetlands specifically. While this information likely exists within communities, it is not documented in western science literature.
Managing Wetlands for Fire Risk	12.1	Developing approaches to prioritize wetlands for fuel management based on predicted fire likelihood, severity, and consequences. This would rely on first filling knowledge gaps under the Fire Behaviour section.
	12.2	Testing the effectiveness of prescribed burning (through western approaches and/ or Indigenous fire stewardship) for managing wetland wildfire risk.
	12.3	Understanding the effects of prescribed burning (through western approaches and/ or Indigenous fire stewardship) on other wetland values (e.g., carbon storage, biodiversity, food and medicine species, water quality, etc.).
	12.4	Improving understanding of the effectiveness, practicality, and cost of mechanical approaches to managing wildfire risk. Test current techniques (e.g., mulching, thinning) and explore new techniques to manage wetland fuel load.
	12.5	Exploring the policy, legal, and organizational landscape and changes needed to trial and/or implement these approaches at a larger scale (e.g., who is responsible? Who has the skills? Who pays?).
	12.6	Exploring how existing wildfire risk management programs (e.g., Firesmart) address wetlands and whether guidance needs to be adapted to effectively manage wildfire risk in wetlands.
	12.7	Exploring whether elements of wildfire management programs (e.g., Firesmart) could be applied across larger areas outside of the urban-wildland interface.
Wetlands and Beavers	13.1	Understanding factors influencing beaver colonization and the effects of beaver colonization in the western boreal forest. Most research on organic wetlands has been in montane regions.
	13.2	Understanding the impacts of beaver dam abandonment in organic wetlands.
	13.3	Developing approaches to incorporate beavers into land management decisions and practices, including as a tool to manage fire risk.

ANTHROPOGENIC DISTURBANCE

Wetlands in Canada's western boreal forest are important ecosystems characterized by unique hydrology, biodiversity, and ecological functions. Industry expansion across the boreal has led to increased pressure on all ecosystems, including wetlands. While forest management and oil, and gas are the prominent industries operating in the boreal, other sectors, such as other energy, mining, utilities, and peat harvesting, also have growing footprints that often intersect with wetlands.

Applications of ecosystem-based management through the Healthy Landscapes Program have focused on the use of forest management as a tool for emulating natural disturbance. Anthropogenic activities, as currently conducted in Canada's western boreal, typically do not emulate the natural disturbances that affect wetlands.

Topics in this section:

Anthropogenic activities can result in permanent wetland loss (e.g., oil sands mine), temporary wetland loss with the expectation of restoring the wetland when the activity is complete (e.g., resource road), or wetland degradation (e.g., hydrologic impacts of a road that blocks water flow). These effects can be especially pronounced in organic wetlands because they may have less stringent requirements compared to shallow open water or marsh wetlands, they may be harder to identify and therefore less likely to be avoided or appropriately accommodated compared to shallow open water or marsh wetlands, and their deep organic soils and complex hydrology can be challenging to work in and to restore.

Establishing a baseline understanding of the effects of anthropogenic activities on wetlands is needed so that the full suite of potential effects (across industries and across the landscape) to wetland values and functions can be considered as part of ecosystem-based management.

Healthy Landscapes Program
FACT SHEET #13

ANTHROPOGENIC DISTURBANCE:

Resource Roads

Due to industry activities and public pressure, there has been a growing need to construct new roads to access remote areas. Across the boreal forest, there is approximately **600,000 km of linear disturbances, with roads and seismic exploration accounting for an estimated 80% of linear disturbances.**[1] Road construction typically avoids open-water wetlands (marshes and shallow open waters), but complete avoidance of all wetland types can be difficult and impractical in areas with high wetland abundance.

Compared to uplands, road construction through wetlands presents construction and management challenges due to the presence and flow of surface and subsurface water, saturated soils, and deep peat deposits in organic wetlands. Peat, the organic soil found in organic wetlands, can contain approximately **90-98% water,** making it an unsuitable foundation for roads and potentially leading to challenges with road integrity, safety, and environmental performance.[2,3] Wetland road design and construction practices have improved over time, but may be variably applied across industries, companies, and geographies. Roads can affect wetlands directly (e.g., loss of habitat) or indirectly (e.g., downstream or long-term effects of blocked surface or subsurface flow), as shown below. Though, road builing practices, the use of bridges, and culvert standards, design and layout can mitigate some of the impacts of roads on wetlands. Understanding how roads contribute to the cumulative disturbance footprint in wetlands, and practices that can be employed to mitigate these disturbances is needed to practice ecosystem based management. This factsheet specifically focuses on the impacts of roads to wetland fuctions, with resources on road and wetland best management practices listed in the ***Resources*** section at the end of the factsheet.

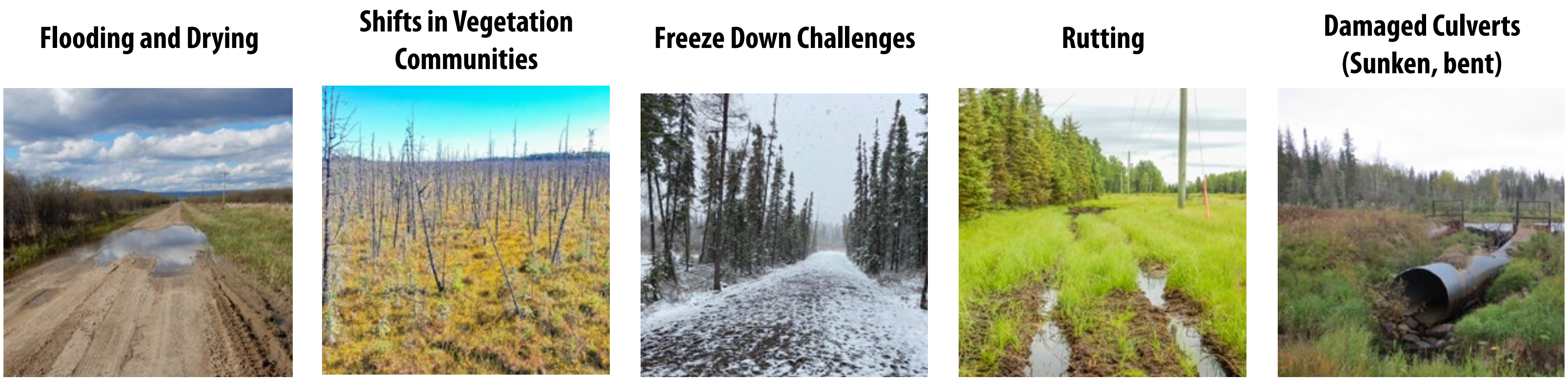


Figure 1. Examples of effects of road construction in organic wetlands.

Effects of Roads on Wetlands

Building roads through wetlands can cause challenges for road construction timing and costs, road performance (e.g., flooding, rutting, icing) and maintenance (e.g., maintaining or fixing culverts, and road safety. In return, roads can also affect wetland function and hydrology in various ways:

1. **Roads can alter wetland soils, and therfore their hydrological function.**

    - Roads built though wetlands can result in **soil compaction**, reducing the soil pore space (by increasing the bulk density) needed for water transmission, often leading to redirection or blockage of subsurface flows.[1,4]
    - By disturbing wetland soils for road construction, water movement (e.g., rainfall or run-off) or wind over disturbed, exposed and often dry soil, can reslt in **erosion**. Erosion can affect soil quality, structure, stability, and texture, making it more difficult for plants to establish due to the loss of nutrients and organic matter, and for the soil to retain moisture due to low surface permeability and textural changes affecting water-holding capacity.[5]

- Erosion results in the transport of sediment into nearby wetlands, lakes, and streams, or, **sedimentation**.[6] This results in impacts to water clarity and filling in of wetland habitats initiating changes in vegetation communities, and losses to aquatic invertebrate biodiversity.

2. Roads can affect quantity, timing and direction of overland and subsurface water flow.

- Road surfaces generate **overland flow** as they are impermeable to water, resulting in reduced infiltration rates and increased surface water flow.[4,6]
- Soils with coarse substrates, such as sand, experience greater rates of **subsurface water transmission** compared to easily compactable, organic soils such as those found in peatlands.[7] Roads built in peatlands can result in redirection or blockage of subsurface flows.[3,4]

3. Roads can affect vegetation communities.

- When roads block surface or subsurface flow, flooding on the upstream side of the crossing reduces available soil oxygen resulting in vegetation die off and a shift to water-tolerant vegetation. Drying on the downstream side leads to deeper root growth and increased canopy cover, resulting in vigorous vegetation growth and shifts in understory vegetation communities (see image below).[7,8,9]
- Changes in vegetation communities can reflect changes in wetland types and affect habitat use by species, wildfire susceptibility, traditional uses and other wetland values described in ***Factsheet #1.***

The impacts of roads often outlast the lifespan of the road itself.

When roads are decommissioned and restored, their effects may persist on the landscape, making it difficult to restore a wetland back to its original form and function. Older roads often have greater impacts on wetland flow than new roads, they have not been build to the same standards. New wetland restoration techniques can improve restoration outcomes, but may not reverse long-term changes in wetland ecosystems.[6]

Figure 2. Example of tree mortality and vigorous vegetation growth due to subsurface flow blockage from road construction in a boreal treed fen.

WINTER ROADS

Winter roads are widely recommended to mitigate the impact of wetland road crossings on wetland soil and hydrology.[10] However, research suggests that changes in tree canopy cover and soil compression by heavy equipment may alter local thermal, hydrological, and ecological conditions. Roads constructed in winter conditions can have higher bulk density, shallower water tables, higher graminoid cover, and have been observed to thaw earlier than the adjacent, undisturbed wetland.

Resources:

- Boreal Wetlands Conservation Codes of Practice - Manitoba
- Alberta Watercourse Crossing Collaborative Guide
- Resource Roads and Wetlands: A Guide for Planning, Construction, and Maintenance
- Forest Road Wetland Crossings Operational Guide
- Bocking, E., Cooper, D. J. & Price, J. (2017). Using tree ring analysis to determine impacts of a road on a boreal peatland. Forest Ecology and Management, 24-30, 404.
- Millier, C. A., Benscoter, B. W. & Turetsky, M. R. (2015). The effect of long-term drying associated with experimental drainage and road construction on vegetation composition and productivity in boreal fens. Wetlands Ecology and Management, 845-854, 23(5).
- Sarawati, S., Petrone, R., McDermid, G. J., Xu, B. & Strack, M. (2020). Hydrological effects of resource-access road crossings on boreal forested peatlands. Journal of Hydrology, 584.

1. Elmes, M. C., Kessel, E., Wells, C. M., Sutherland, G., Price, J. S., Macrae, M. L. & Petrone, R. M. (2022). Evaluating the hydrological response of a boreal fen following the removal of a temporary access. Journal of Hydrology, 594.
2. Karran (2018). The Engineering of Peatland Form and Function by Beaver. University of Saskatchewan, Saskatoon, Canada.
3. Willams-Mounsey, J., Richard, G., Alistair, C. & Joseph, H. (2021). A review of the effects of vehicular access roads on peatland ecohydrological processes. Earth-Science Reviews, 214.
4. Tague, C. & Band, L. (2001). Simulating the impact of road construction and forest harvesting on hydrologic response. Earth Surface Processes and Landforms, 135-151, 26(2).
5. Ritter, J. and Eng, P. (2012) Soil Erosion-Causes and Effects. Ontario Ministry of Agriculture and Rural Affairs, 12-105. http://www.omafra.gov.on.ca/english/engineer/facts/12-053.htm
6. Webster, K. I., Beall F. D., Creed, I. F. & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. Environmental Reviews, 78-131, 23(1).
7. Willier, C. N. (2017). Changes in peatland plant community composition and stand structure due to road induced flooding and desiccation. Department of Renewable Resources, University of Alberta.
8. Bocking, E., Cooper, D. J. & Price, J. (2017). Using tree ring analysis to determine impacts of a road on a boreal peatland. Forest Ecology and Management, 24-30, 404.
9. Millier, C. A., Benscoter, B. W. & Turetsky, M. R. (2015). The effect of long-term drying associated with experimental drainage and road construction on vegetation composition and productivity in boreal fens. Wetlands Ecology and Management, 845-854, 23(5).
10. Lauren A, Lepilin D, Uusitalo J, Fritze H, Laiho R, Kimur B, Tuittila ES. 2021. Response of Vegetation and Soil Biological Properties to Deformation in Logging Trails in Drained Boreal Peatlands. Canadian Journal of Forest Research. in press.

ANTHROPOGENIC DISTURBANCE:

Forest Harvest

Forests play a crucial role in regulating microclimatic conditions in interconnected ecosystems, influencing factors such as light, wind, temperature, and moisture.[1] Forests also regulate hydrologic conditions such as hydroperiod, water budget, and water storage potential. In the western boreal forest, characterized by a mosaic of upland forests and wetland ecosystems, **activities that occur in forests, such as forest harvest, may affect adjacent or nearby wetlands.**

Forest harvest may affect wetland extent, hydrology, soils, and nutrient cycling. The type and magnitude of effects depend on the harvest methods, season, wetland classification, and environmental conditions. While wetlands may be considered part of the non-productive land base in forest management planning and operations, theyare highly interconnected with upland forests (***Factsheet #2***) and these interconnections need to be considered as part of a whole landscape approach to ecosystem based management.

Good planning combined with an understanding of wetland classification and inventory (***Factsheet #2*** and ***Factsheet #3***), wetland hydrology (***Factsheet #4***), and wetland values (***Factsheet #1***), can minimize potential impacts to wetlands.

Effect of Forest Harvest on Wetland Extent

Merchantable timber harvesting in forested wetlands is not common in the western boreal forest.[1,2] Treed wetlands are typically avoided during harvesting because they are often perceived as unproductive with unmerchantable harvest volume.

However, treed wetlands may be crossed to access harvest sites or used for landings. Some incidental harvest may occur when merchantable margins are harvested, due to the difficulty of identifying treed wetland classes from treed uplands. Treed wetlands such as conifer swamps and treed organic wetlands can be mistaken for upland forests, especially during dry periods.

In instances where wetlands are harvested, the regeneration process may shift towards an upland forest community, leading to the loss of wetland area.[3] These shifts can lead to a loss of wetland functions and values (***Factsheet #1***).

Figure 1. A buffered wetland witin a harvest block.

Effects of Forest Harvest on Wetland Water Quality and Quantity

The main hydrologic processes that can be affected by forest harvest activities are:

- Seasonal pattern of flooding duration, frequency, and water depth (hydroperiod);
- Changes in water volume from precipitation, streamflow, or groundwater (water budget); and,
- Capacity of the wetland to store water (storage potential).[4]

Harvesting may directly alter hydrology by reducing canopy interception and evapotranspiration, leading to **increased surface flow increased groundwater recharge and decreased soil moisture potential.[5]**

Figure 1. A harvest blog next to a treed wetland.

"**Watering up**," or a rise in the water table, is a consistent finding in western boreal wetlands adjacent to harvest sites, immediately post-harvest .[6,7,8] Following harvesting, peatlands typically experience an increase in water table height, ranging from **4 to 30 cm**.[5,6] This rise in the water table is linked to reduced interception and evapotranspiration due to tree removal, but can also be attributed to flow path disturbances from access road construction.[8,9] Depending on topography, soil, and surficial geology, these alterations to the water table can lead to:

- **Increased surface runoff:** water flows over the ground surface from excess precipitation.
- **Increased groundwater recharge:** water moves downward from surface water to groundwater.
- **Reduced forest productivity**: high water tables and flooding can result in paludification, the process by which upland forest is converted to peatland.[6,8]

The above effects are typically seen, but are dependent on local conditions. Some studies have found contrary effects on the water table in wetlands following the harvest of adjacent forests:

- Thompson et al. (2018) found limited water table increases from aspen harvesting near peatlands. However, it should be noted that the adjacent peatland was characterized as having glacial substrate under the cut blocks, resulting in low hydraulic conductivity, deep-water tables, and low connectivity between adjacent uplands and hillslopes which may have masked the potential water table increase.
- Plach et al. (2016) discovered a decline in soil moisture from clear-cut harvesting immediately adjacent to a peatland. Canopy cover loss resulted in increased rates of wind causing increased evapotranspiration and reduced soil moisture.

Harvesting not only alters the hydrology of the harvested area but also has the potential to **effect connected wetlands and uplands**, though this is dependent on storage capacity and underlying geology. Some paired-catchment studies reveal a direct relationship between harvesting and increased streamflow in downstram systems, while others indicate that harvesting has little to no effect on downstream systems in areas with large storage capacity and deep glacial deposits.[9]

Effects of Forest Harvest on Wetland Soils

Forest management activities in or adjacent to wetlands can potentially result in erosion and sedimentation (*Factsheet #13*), the introduction of deleterious materials via mechanical leaks (e.g., fuels, hydraulic fluids), and vegetation management inputs (i.e., herbicides), which can significantly affect wetland water quality and soil health.

Activities that expose soils, including construction of access roads, site preparation, and bared areas (e.g., landings), may increase erosion risk, with soil being transported into wetlands' surface water if mitigation strategies are not implemented. If sedimentation occurs, it can:

- Alter plant community structure by reducing seedling establishment or suffocate growth;
- Affect aquatic invertebrates, fish and amphibians by burying bottom dwelling organisms and eggs;
- Lower community biomass, diversity, and richness; and,
- Increase turbidity levels from suspended sediment can reduce light penetration, reduce plant growth and reduce visibility for fish.[10,11]

In the western Boreal, a small shift in evapotranspiration can have significant effects on hydrology.[1]

Drying peat can become hydrophobic, meaning that until it reaches a certain soil moisture content again, it will repel water and infiltration, leading to runoff and erosion.[12] Therefore, the effects of harvest cannot be assumed in the boreal plains as there are a variety of factors that impact how they might respond to adjacent harvest.

Effects of Forest Harvest on Wetland Nutrient Cycling

Disturbing wetland soild during harvesting can create hydrologically mobile sources of dissolved organic carbon (DOC).[6] Since wetlands are often hydrologically connected to lakes, this can lead to an increase in surface water DOC concentrations in boreal lakes post-harvest.[6] Changes in DOC can modify the relative abundance of different organisms in wetland environments and create food-web imbalances.

Similar nutrient flushing effects are observed for phosphorus and nitrogen, influencing peat oxidation during summer water table drawdowns and weed establishment in disturbed areas of peatlands.[2,7]

TEMPORAL IMPACT OF FOREST HARVEST

Recovery from disturbances, such as forest harvest, is influenced by regional conditions, pre-harvest forest composition, and the harvested tree species. In wetlands adjacent to harvest sites, a consistent finding is watering up, characterized by a rise in the water table, with post-harvest oragnic wetlands typically showing increases in water table height ranging from 4 to 30 cm.[5,6]

- In studies conducted in the eastern boreal region in a coniferous stand, it was observed that **five to ten years after harvesting**, water tables in adjacent peatlands had still not recovered.[8,11]
- Conversely, another study in the boreal plains located in an aspen stand, found that the water table returned to pre-harvest levels **two years post-harvest**.[5] Aspen has a higher regeneration rate than coniferous species resulting in greater water uptake demands in the years immediately following harvest.[8] The greater water demands counteract the watering-up impacts that wetlands experience post-harvest, allowing expedited recovery.

While these two studies differ by ecoregion and, therefore, have different controls on wetland development and function, they both indicate that recovery was triggered upon the initiation of canopy regeneration and subsequent crown closure.[5,13]

Resources:

- Forestry and Waterfowl: Assessing and Mitigating Risk Practitioner Guide
- Guiding Principles for Wetland Stewardship and Forest Management Practitioner Guide
- Wetland Best Management Practices for Forest Management Planning and Operations Practitioner Guide
- Resource Roads and Wetlands: A Guide for Planning, Construction, and Maintenance
- Forest Road Wetland Crossings Operational Guide

1. Lavoie, M., Paré, D., Fenton, N., Groot, A., & Taylor, K. (2005). Paludification and management of forested peatlands in Canada: A literature review. In Environmental Reviews (Vol. 13, Issue 2, pp. 21–50). https://doi.org/10.1139/a05-006
2. Locky, D. A., & Bayley, S. E. (2007). Effects of logging in the southern boreal peatlands of Manitoba, Canada. Canadian Journal of Forest Research, 37(3), 649–661. https://doi.org/10.1139/X06-249
3. Forest Management and Wetland Stewardship Initiative (FMWSI). (2018). Guiding principles for wetland stewardship and forest management: Technical report. Ducks Unlimited Canada.
4. Devito, K. and C. Mendoza. 2006. Maintenance and dynamics of natural wetlands in western boreal forest: Synthesis of current understanding from the Utikuma Research Study Area. Cumulative Environmental Management Association. Alberta, Canada. Pg. 84.
5. Thompson, C., Devito, K. J., & Mendoza, C. A. (2018). Hydrologic impact of aspen harvesting within the subhumid Boreal Plains of Alberta. Hydrological Processes, 32(26), 3924–3937. https://doi.org/10.1002/hyp.13301
6. Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015a). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. In Environmental Reviews (Vol. 23, Issue 1, pp. 78–131). National Research Council of Canada. https://doi.org/10.1139/er-2014-0063
7. Locky, D. (2010). Early stand-level assessment of forest harvesting in western Boreal Peatlands [Research Note Series]. Athabasca University. https://auspace.athabascau.ca/bitstream/handle/2149/2430/Locky%20SFMN%20RN%20En57%202010%20Peatland.pdf?sequence=1&isAllowed=y
8. Marcotte, P., Roy, V., Plamondon, A. P., & Auger, I. (2008). Ten-year water table recovery after clearcutting and draining boreal forested wetlands of eastern Canada. Hydrological Processes, 22(20), 4163–4172. https://doi.org/10.1002/hyp.7020
9. Mahaney, W. M., Wardrop, D. H., & Brooks, R. P. (2005). Impacts of sedimentation and nitrogen enrichment on wetland plant community development. Plant Ecology, 175(2). https://doi.org/10.1007/s11258-005-0011-2
10. Devito, K.J., Creed, I.F., Gan, T., Mendoza, C., Petrone, R., Silins, U., Smerdon, B., 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? Hydrol. Process. 19, 1705–1714. https://doi.org/10.1002/hyp.5881
11. Gleason, R. A., Euliss, N. H., Hubbard, D. E., & Duffy, W. G. (2003). Effects of sediment load on emergence of aquatic invertebrates and plants from wetland soil egg and seed banks. Wetlands, 23(1). https://doi.org/10.1672/0277-5212(2003)023[0026:EOSLOE]2.0.CO;2
12. Thompson, D. K., & Waddington, J. M. (2008). Sphagnum under pressure: towards an ecohydrological approach to examining Sphagnum productivity . Ecohydrology, 1(4), 299–308. https://doi.org/10.1002/eco.31
13. Pothier, D., Prévost, M., & Auger, I. (2003). Using the shelterwood method to mitigate water table rise after forest harvesting.

ANTHROPOGENIC DISTURBANCE:
Cumulative Effects

Industrial expansion in the western boreal forest has led to a growing footprint from oil and gas, mining, peat harvesting, hydroelectricity, and other sectors. The footprints of these industries intersect with wetlands in a variety of ways with potential for temporary or permanent effects to wetlands. This includes effects to adjacent wetlands (e.g., forest harvest, *Factsheet #14*), potential temporary wetland loss or disturbance (e.g., resource road, seismic line), permanent wetland loss (e.g., hydroelectricity facility, mine site), other changes in wetland structure and function.

While wetland avoidance occurs for many activities (e.g., routing roads, delineating harvest blocks), it is not feasible or prioritized for all. For example, peat harvest necessarily occurs in organic wetlands, seismic lines will cross all ecosystems in their path, and valuable minerals can be overlain by wetlands.

With expected growth in many of these industries in the western boreal, considering their cumulative effects on wetlands and other ecosystems is necessary to effectively practice ecosystem-based management. This factsheet provides an overview of the effects of oil and gas infrastructure, hydroelectricity, mining, and peat harvesting on wetlands in the western boreal.

Oil and Gas Infrastructure

Oil and gas facilities, including mines and well sites, directly impact an estimated 338,000 hectares of land.[3] There is an estimated 600,000 km of linear disturbances.[1,2] Of these, **353,000 km are composed of seismic lines and pipelines, the remainder being access roads.[1,2,3]**

Linear infrastructure and the extraction of oil and gas affect water resources and wetlands throughout all developmental stages. Each extraction method, whether it's from conventional oil fields, oil sands, or hydraulic fracturing, requires extensive infrastructure, that has varying degrees of environmental impact, depending on the specific requirements and techniques used.[4] These extraction activities pose contamination risks such as at well sites, excavation sites, tailing ponds, pipelines, and groundwater.[4,5,6,7]

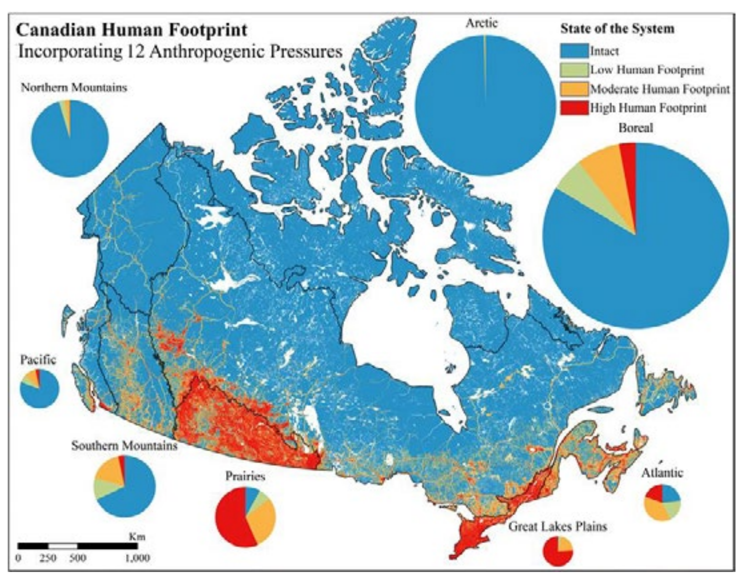


Figure 1. Map of human footprints across Canada, showing a concentration of boreal human impacts being in the western boreal forest.[8]

Seismic Lines

Seismic lines are linear, anthropogenically-modified corridors that use explosive charges to locate underground reservoirs of oil and natural gas by analyzing sub-surface sound wave reflections.[9,10,11] These lines are the most common linear disturbances associated with the energy sector, covering approximately **4,022 km² in the western boreal forest.[10,11,12]**

Seismic line construction techniques have shifted from wider exploration practices (up to 10 meters wide) to narrower methods (1.75 to 3 meters wide) in recent decades.[10] Technological advancements, regulatory incentives, and environmental awareness have driven the adoption of **low-impact seismic (LIS) lines as narrow as 1.5 meters and specialized management practices like winter operations.**[10] However, seismic lines typically do not prioritize wetland avoidance and even with efforts to reduce the overall disturbance footprint, seismic lines effect wetlands in a number of ways, including:

- Vegetation community composition
- Nutrient cycling, such as increased nutrient availability and increased decomposition
- Soil compaction
- Surface and subsurface water flow
- Species composition and predator-prey dynamics
- Greenhouse gas emissions, such as increased carbon losses.[13]

Wetlands, particularly treed organic wetlands, are some of the least likely ecosystems to regenerate naturally following the initial disturbance. Significant effort has gone into testing and applying new restoration techniques (e.g., mounding to re-establish local microtopography using mechanical site preparation [13]) to improve restoration outcomes in wetlands. Even with new techniques, wetlands continue to be challenging and costly ecosystems to restore.

Pipelines

Pipelines, including construction, operation/ presence, and leaks or ruptures, can effect wetland hydrophysical properties and hydrologic regimes.[14,15] **While marshes and shallow open water wetlands are typically avoided in pipeline routing, organic wetlands and swamps are often crossed.** Beyond the immediate ecological impacts, pipeline construction introduces operational risks. When wetlands with subsurface water movement (e.g., fens) have been aligned perpendicular to the wetland's flow, there are examples of increased fluctuations in the rise and fall of the water table.[14]

Without regular maintenance or monitoring, **pipelines may corrode due to factors such as high water content, low pH, and the presence of microbial communities in wetland soils, particularly in organic wetlands like bogs and fens.** Due to the low shear strength and high compressibility of peat soils, there is potential for pipeline instability and movement. Peat soils may also exhibit negative buoyancy, placing upward pressure on buried pipes, resulting in pipeline stress and risks to pipeline integrity. Furthermore, increased movement is expected in soils with higher moisture content, and frost heave and permafrost melt can result in soil movement, thus exerting pressure on the pipeline. Lastly, pipeline leaks and ruptures can significantly impact wetland environments, including waterfowl habitat, water quality, and soil health. As wetlands are highly connected, spilled material can be transported, exacerbating the environmental implications.

Well Pads

Well pads are used to extract bitumen from deposits situated more than 75 meters below the surface.[16] Typically, these well pads occupy an area of less than 4 hectares.[16] However, **well pads require supporting infrastructure, including access roads, pipelines, and storage facilities.[16]**

The average operational lifespan of a well pad is approximately 20 years.[16] **Nevertheless, the impact on vegetation species may persist for up to 50 years following the initial disturbance.[17]** Well pad construction starts with removing woody vegetation (trees and shrubs), then the remaining ground vegetation is covered with geotextile, and a mineral fill composed of clay, gravel, sand, and loam—ranging from 1.5 to 4 meters thick—is layered on top.[16] These construction methods may lead to ground surface compaction beneath the well pad, resulting in alterations to the peatlands' chemistry, hydrology, and soil properties.[16] Re-establishing wetlands, particularly organic wetlands, as part of well pad decommissioning and restoration is challenging due to soil compaction, changes in hydrologic regime, and the presence of mineral fill (which may not be economical to remove).

Electric Power Development

The electric power development sector consists of various industries that contribute to electricity generation, transmission, and distribution. This sector includes industries that are involved in producing electricity from sources, such as hydroelectric power, fossil fuels, nuclear power, and renewable sources like solar, wind, and geothermal energy.

In 2019, **60% of Canada's energy cam from hydroelectric sources**, and the remaining was generated from a combination of natural gas, nuclear, wind, coal, biomass, solar, and petroleum.[18]

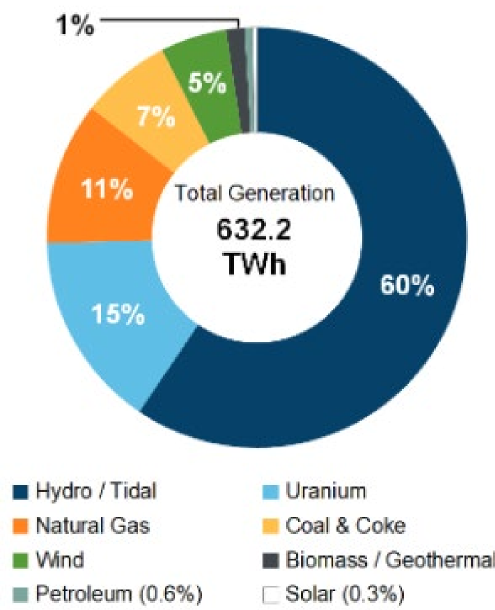


Figure 2. Electricity generation by source in Canada.[3]

Hydroelectric Production

Canada holds the fourth position globally in hydroelectricity production.[18] The environmental impacts of hydroelectric power generation, including effects on wetlands, vary depending on the method employed.[4,19] The three main methods of hydroelectric generation utilized in Canada are:

- **Conventional hydroelectric power:** the most common type of power generation in the boreal zone, it involves constructing dams to impound water for electricity generation.[4]
- **Thermal power generation:** Relies on fossil fuels or uranium heat energy to power steam turbines.[4]
- **Run-of-the-river installations:** Utilize minimal water retention within reservoirs, relying on the natural flow of rivers.[4]

Although these hydroelectric production methods differ in their process and the land base needed, all methods require additional clearing for infrastructure, such as transmission lines and substations, to route power across the landscape. As conventional hydroelectric power is predominant in the boreal zone, this fact sheet will concentrate on the impacts of conventional hydroelectric power on wetlands. Hydroelectric dams can impact both upstream and downstream ecosystems of the dam.[4]

Upstream Impacts	Flooding of Riparian, Wetlands, and Upland Habitats	Convention hydroelectric dams often result in the inundation of riparian zones, wetlands, and adjacent upland habitats due to reservoir creation, profoundly altering these ecosystems.
	Conversion of Lotic to Lentic Environments	The transformation from flowing water (lotic) to stagnant water (lentic) environments is a common consequence of hydroelectric dam construction, disrupting the natural flow in wetland ecosystems.
	Alteration of Groundwater Recharge	The construction of dams and subsequent reservoir formation can significantly modify groundwater recharge patterns, affecting the hydrological balance of wetlands and surrounding areas.
	Sedimentation and Nutrient Enrichment	Hydroelectric dams can induce sedimentation and nutrient enrichment in upstream areas due to flood material leaching into the water, leading to changes in the ecological dynamics and vegetation composition of wetlands.
	Mercury Methylation in Wetlands	The high density of organic matter deposits found in wetlands and riparian areas, coupled with natural and anthropogenic mercury deposits and induced anoxic conditions from flooding, can result in mercury methylation, posing risks to aquatic organisms. Flooding of wetlands is particularly detrimental due to the higher concentration of organic matter, leading to the production of methylmercury for longer periods, thus amplifying the ecological impact.
Downstream Impacts	Decreased Groundwater Recharge	Hydroelectric dams can lead to a reduction in groundwater recharge downstream, impacting the hydrological balance and water availability in wetland ecosystems.
	Streambank Erosion	The construction and operation of dams can exacerbate stream bank erosion downstream.
	Changes in Stream Morphology	Hydroelectric dams can induce changes in the morphology of downstream streams, affecting flow patterns and sediment and nutrient transport dynamics.
	Altered Timing of Water Flow	Dams often regulate water flow to meet electricity demands, resulting in significant alterations to the timing and magnitude of downstream flows, which can disrupt natural wetland hydrology and ecological processes.

Table 5. Impacts of hydroelectric dams, upstream and downstream of dams.[4]

Mining

Globally, Canada is a , with 80% of Canada's mining activities concentrated in the boreal.[4] Various metals, including ferrous, precious, and base metals, oil sands, as well as coal and gems, are extracted within this region. The effects of mining on wetlands depends on the type of mining, location (e.g., in or adjacent to wetlands), and the stage in the mining cycle. However, consistent findings include the potential to **disrupt surface and groundwater quantity and quality**. Impacts to wetlands during mining phases include[4]:

1. Exploration Phase

Disrupting surface water flow: Seismic lines, roads, and camps established during initial stage prospecting can disrupt surface water flow patterns.

Disrupting groundwater flow: Sampling and drilling activities may interfere with groundwater flow, especially if they come into contact with subsurface aquifers.

2. Extraction Phase

Surface Water Alteration: Surface mining operations can alter surface water flow pathways, diverting rivers and lakes to access underlying materials.

Removal of peat: Open-pit mining involves large-scale removal of overburden (i.e. soil and peat) leading to changes in hydraulic gradients and a rise in the water table.[3]

Altered biodiversity: Discharge or seepage of mine effluents and acid mine draining can alter aquatic biodiversity.

Dewatering: To manage rising water tables, excess water is pumped away, increasing the surrounding land's vertical recharge, decreasing groundwater levels near the excavation, and reducing surface water levels which can be lead to peatland drying.

Wetland loss: Wetlands are often drained, and peat is removed during mining operations in these areas.

3. Processing Phase

Reduced water quantity: Extraction and diversion of water for processing, cooling, diluting, or treating mined materials can affect overall water quantity.

Reduced water quality: Mine-related effluents, seepages, and emissions contribute to water contamination, impacting water quality.

4. Closure Phase

Leaching and tailings: persist even after mine closure, potentially leading to acid drainage and increased metal concentrations in receiving waters. Historical operations in older and abandoned mines show evidence of long-term water quality impacts, indicating the lasting consequences of mining activities.

Peat Harvesting

Peat harvesting occurs in organic wetlands (peatlands) and is the process of removing peat (soil formed from decayed wetland plant material) for commercial uses e.g., as a horticultural growing medium. Peat harvesting affects a relatively small area but significantly impacts wetland hydrology.[4]

There are two methods for peat harvesting:

- **Dry Harvesting:** Requires draining the peatland, facilitating the extraction of dried peat through sod peat production, milled peat production, or vacuum peat production. Subsequently, the extracted peat undergoes further dewatering processes to create briquettes or pellets.
- **Wet Harvesting:** Extracting peat without solar drying or transportation for dewatering and thermal drying, utilized particularly when drainage is challenging, extending the peat production season with lower costs, although it is not currently widely adopted on a large scale in Canada.

Canada is one of the leading global exporters of horticultural peat.

Annually, Canada produces 11.8 million cubic meters of horticultural peat, approximately 0.03% of Canadian peatlands equivalent to 34,000 hectares, are harvested.[4] The majority of production areas, approximately 70%, are situated in eastern provinces such as New Brunswick and Quebec, while the central and western regions contribute to the remaining 30%.[4]

Impacts on water quality and quantity vary depending on extraction method. However, both methods result in significant peat material removal, leading to **permanent losses in water storage capacity**.[4] Peat harvesting results in a loss of stored carbon from the harvested wetland and can affect green house gas emissions.

Resources:

- [Strategy for Responsible Peatland Management 6th Edition (International Peatland Society)]
- [Treatment Process Flowchart: Landscape (NAIT)]
- [Reclamation Decision Support System (DSS) - NAIT]

- Elmes, M. C., Petrone, R. M., Volik, O., & 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. https://doi.org/10.1016/j.ejrh.2022.101031
- Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. In Environmental Reviews (Vol. 23, Issue 1, pp. 78–131). National Research Council of Canada. https://doi.org/10.1139/er-2014-0063
- Rooney, R. C., Bayley, S. E., & Schindler, D. W. (2012). Oil sands mining and reclamation cause massive loss of peatland and stored carbon. Proceedings of the National Academy of Sciences of the United States of America, 109(13), 4933–4937. https://doi.org/10.1073/pnas.1117693108

1. Pasher, J., Seed, E., & Duffe, J. (2013). Development of boreal ecosystem anthropogenic disturbance layers for Canada based on 2008 to 2010 Landsat imagery. Canadian Journal of Remote Sensing, 39(1). https://doi.org/10.5589/m13-007
2. Elmes, M. C., Kessel, E., Wells, C. M., Sutherland, G., Price, J. S., Macrae, M. L., & Petrone, R. M. (2021). Evaluating the hydrological response of a boreal fen following the removal of a temporary access road. Journal of Hydrology, 594. https://doi.org/10.1016/j.jhydrol.2020.125928
3. Pickell, P. D., Gergel, S. E., Coops, N. C., & Andison, D. W. (2014). Monitoring forest change in landscapes under-going rapid energy development: Challenges and new perspectives. In Land (Vol. 3, Issue 3, pp. 617–638). MDPI AG. https://doi.org/10.3390/land3030617
4. Webster, K. I., Beall F. D., Creed, I. F. & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. Environmental Reviews, 78-131, 23(1).
5. National Energy Board. 2009. A Primer for Understanding Canadian Shale Gas. Energy Brief. https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/natural-gas/report/archive/primer-understanding-shale-gas-2009/a-primer-understanding-canadian-shale-gas-energy-briefing-note.pdf
6. Canadian Association of Petroleum Producers (CAPP). 2010. Responsible water management in Canada's oil and gas industry. Available from http://www.capp.ca/getdoc.aspx?DocID=173950 [accessed November 2011].
7. Environment Canada — Oil Sands Advisory Panel. 2010. A foundation for the future: Building and environmental monitoring system for the oil sands.
8.Hirsh-Pearson, K., Johnson, C. J., Schuster, R., Wheate, R. D., & Venter, O. (2022). Canada's human footprint reveals large intact areas juxtaposed against areas under immense anthropogenic pressure. FACETS7398–419. https://doi.org/10.1139/facets-2021-0063
9. Energy, Mines, and Resources (EMR). 2006. Best management practices – oil and gas; seismic exploration. Yukon Government, Energy Mines and Resources, Oil and Gas Management Branch, Whitehorse, Y.T.
10. Dabros, A., Pyper, M., & Castilla, G. (2018). Seismic lines in the boreal and arctic ecosystems of North America: Environmental impacts, challenges, and opportunities. In Environmental Reviews (Vol. 26, Issue 2). https://doi.org/10.1139/er-2017-0080
11. Abib, T. H., Chasmer, L., Hopkinson, C., Mahoney, C., & Rodriguez, L. C. E. (2019). Seismic line impacts on proximal boreal forest and wetland environments in Alberta. Science of the Total Environment, 658. https://doi.org/10.1016/j.scitotenv.2018.12.244
12. Chen, S., McDermid, G. J., Castilla, G., & Linke, J. (2017). Measuring vegetation height in linear disturbances in the boreal forest with UAV photogrammetry. Remote Sensing, 9(12). https://doi.org/10.3390/rs9121257
13. Davidson, S. J., Goud, E. M., Franklin, C., Nielsen, S. E., & Strack, M. (2020). Seismic Line Disturbance Alters Soil Physical and Chemical Properties Across Boreal Forest and Peatland Soils. Frontiers in Earth Science, 8. https://doi.org/10.3389/feart.2020.00281
14. Elmes, M. C., Petrone, R. M., Volik, O., & 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. https://doi.org/10.1016/j.ejrh.2022.101031
15. Volik, O., Elmes, M., Petrone, R., Kessel, E., Green, A., Cobbaert, D., & Price, J. (2020). Wetlands in the athabasca oil sands region: The nexus between wetland hydrological function and resource extraction. Environmental Reviews, 28(3). https://doi.org/10.1139/er-2019-0040
16. Lemmer, M., Xu, B., Strack, M., & Rochefort, L. (2023). Reestablishment of peatland vegetation following surface leveling of decommissioned in situ oil mining infrastructures. Restoration Ecology, 31(3). https://doi.org/10.1111/rec.13714
17. Chasmer, L., Lima, E. M., Mahoney, C., Hopkinson, C., Montgomery, J., & Cobbaert, D. (2021). Shrub changes with proximity to anthropogenic disturbance in boreal wetlands determined using bi-temporal airborne lidar in the Oil Sands Region, Alberta Canada. Science of the Total Environment, 780. https://doi.org/10.1016/j.scitotenv.2021.146638
18. (https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-canada.html)
19. Baxter, R. M. (1977). Environmental Effects of Dams and Impoundments. Annual Review of Ecology and Systematics, 8(1), 255-283.

ANTHROPOGENIC DISTURBANCE: KNOWLEDGE GAPS

The factsheets in Section Three provide an overview of anthropogenic disturbances in western boreal forest wetlands, with a focus on road construction, forest harvest, and cumulative effects of other key industries (oil and gas, electricity, mining, and peat harvest). While the Healthy Landscapes Program (HLP) has a strong understanding of the effects of forest management on upland forests and a growing understanding of the effects of other industries (e.g., oil and gas) on managed upland forests, the extent and effects of these and other industries often differ in wetlands. Understanding the scope and potential effects of anthropogenic activities on wetland functions and services is needed for a whole landscape approach to ecosystem-based management.

There is growing understanding of the effects of anthropogenic disturbances on boreal wetlands, with increasing focus on hydrology, carbon storage and greenhouse gases, species at risk, and biodiversity. However, many knowledge gaps remain, particularly with respect to the cumulative effects of different industries and the interacting effects of anthropogenic disturbance and climate change. Table 1 provides an overview of key knowledge gaps organized by factsheet topic. Many of the gaps in Section Three are likely to be of relevant to HLP members but may not be high priority for the HLP to address through specific projects (e.g., wetland road crossings are an forest management consideration for all partners but are unlikely to be a focus of an ecosystem-based management project). Similarly, knowledge gaps for Factsheet #15, cumulative effects, are relevant questions but many may fall outside of the HLP's current scope or membership.

From the list in Table 3, priority knowledge gaps for the HLP are included in the Whole Landscape Road Map at the end of this report.

Table 3. Section Three topics and their related knowledge gaps.

Wetland Resource Roads	13.1	Understanding the long-term impacts of roads on wetlands, including habitat fragmentation, increased human and predator access, invasive species, and changes to watershed hydrology and climate.
	13.2	Developing field and desktop tools for practitioners to understand wetland flow amounts and direction.
	13.3	Evaluating road construction practices for maintaining hydrologic connectivity, reducing impacts on greenhouse gas emissions and carbon storage, and improving reclamation outcomes.
	13.4	Developing approaches and programs for effectively and efficiently monitoring wetland crossings.
	13.5	Developing best practices for wetland road decommissioning and reclamation.
	13.6	Understanding impacts, developing best practices, and exploring alternatives as winter roads become unsuitable or unreliable due to climate change.

Forest Harvest	14.1	Understanding immediate and long-term effects of forest harvest on wetland hydrology, soil structure, biodiversity, and ecosystem functions (when forested wetlands are harvested).
	14.2	Understanding immediate and long-term effects of forest harvest on adjacent or downstream wetlands on hydrology, carbon storage, biodiversity, and ecosystem function.
	14.3	Evaluating effects of forest management activities, including site preparation, fertilization, and harvesting, on water quality.
	14.4	Exploring the mechanisms that shift regeneration of harvested wetlands towards upland forest communities, along with strategies to promote wetland regeneration post-harvest.
	14.5	Adapting forest management practices to the growing variability of weather and climate conditions.
Cummulative Effects	15.1	Understanding current and potential future footprint of individual and cumulative industry activities. There are few datasets or products that summarize cumulative footprints and information about predicted future footprints are lacking across all jurisdictions.
	15.2	Working with other sectors to understand how other industry disturbances can be considered alongside sustainable forest management to practice ecosystem-based management to incorporate all disturbances on the landscape.
	15.3	Understanding the social, political, and economic barriers and opportunities for managing cumulative impacts.
	15.4	Understanding the impacts of other industry activities on hydrologic connectivity at a landscape scale and how this can affect upland managed forests.
	15.5	Understanding the subsurface impacts of industry activities (oil and gas infrastructure, mining, peat harvest) on wetlands, including the effects on groundwater quality, soil structure, and subsurface contamination.
	15.6	Understanding the long-term ecological consequences of industry activities (oil and gas infrastructure, mining, peat harvest) on wetlands, including the recovery processes and the persistence of impacts over time.
	15.7	Developing and evaluating effective restoration strategies for wetlands impacted by other industries (oil and gas, mining, electrical).

A Whole Landscape Approach to Ecosystem-Based Management:

WETLANDS ROAD MAP

This report provides an overview of the current state of knowledge of wetland functions and values, the effects of anthropogenic and natural disturbances, and a summary of key wetland knowledge gaps related to ecosystem-based management. The report is organized into three sections - Wetlands on the Landscape, Anthropogenic Disturbance, and Natural Disturbance. The contents of the report are summarized in a Road Map (Figure 1) that can be used to guide how the HLP applies the key learnings in its work across the western boreal forest. As HLP moves through this Road Map, it may change. It is recommended that this Road Map is revaluated on a regular basis.

The starting point in the Road Map is incorporating information from Section One, Wetlands on the Landscape, into how the HLP considers the landscape. Once this foundational understanding is established, it is possible to examine how various disturbances - natural and anthropogenic - affect wetland functions and values and can inform ecosystem-based management in wetlands.

Each of the three sections of the report concludes with a list of knowledge gaps relevant to the section. While important, not all of these gaps are a priority for the HLP. As part of the Road Map, we identified six priority knowledge gap themes that are relevant to the work HLP is pursuing today and is looking to explore in the future. These priorities are opportunities for the HLP to incorporate wetlands and continue to grow a whole landscape approach to ecosystem-based management.

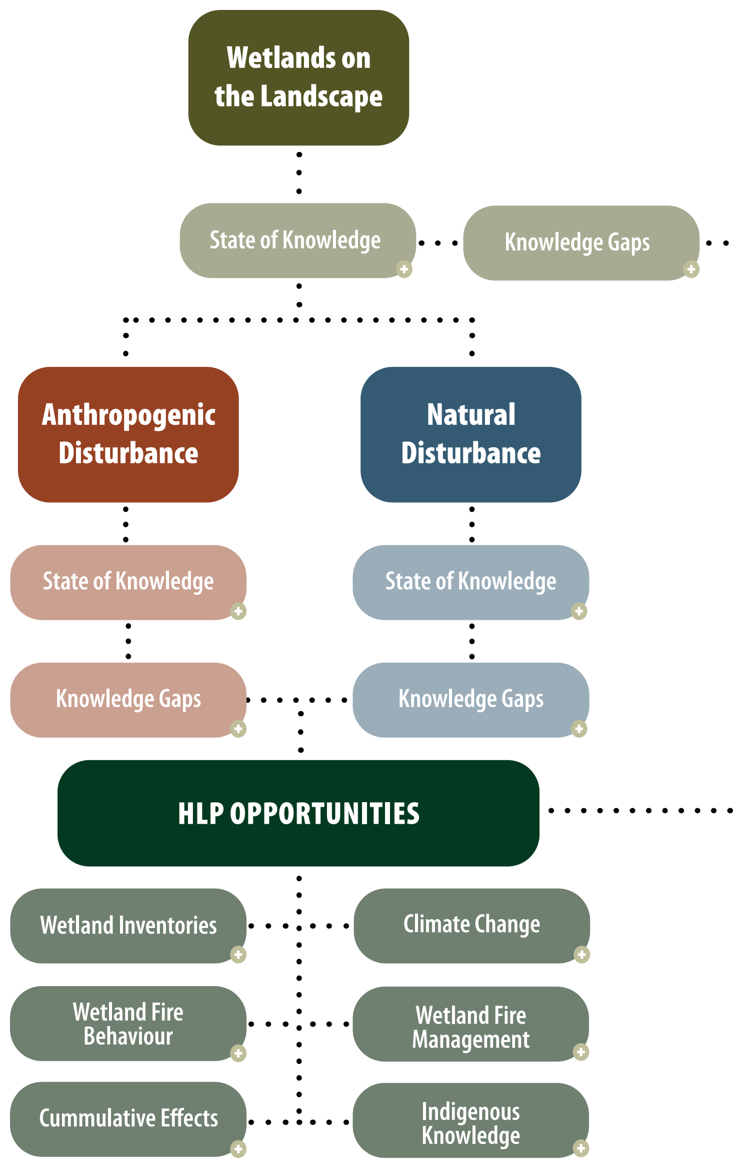
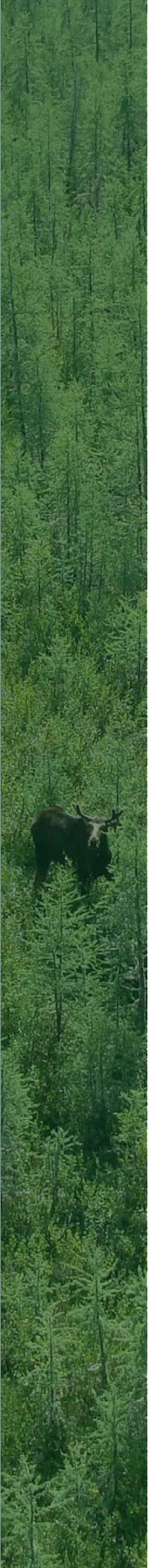


Figure 1. Road Map outlining report contents and future opportunities for HLP projects.



Priority Gap #1 – Wetland Inventories

What type of wetlands are located where?

Detailed and up to date forest inventories are an important resource for managing upland forests. Similarly detailed and up to date wetland inventories are needed for a whole landscape approach to ecosystem-based management. However, wetlands are often not well captured in land inventories, and wetland specific inventories are typically done on a project-by-project basis, leaving data gaps and variations in quality, scale, and the classification system used. These gaps and variations create challenges for projects that require uniform data across large landscapes, such as those taken on by the HLP. Inventories are also only a snapshot in time and need regular updates to capture changes caused by natural events, climate change, and human activities.

Opportunities for filling the wetland inventory knowledge gap include:

1. Completing and maintaining up-to-date wetland inventories across the western boreal forest.
2. Enhancing the classification methods used in land inventories (e.g., provincial vegetation or lad classification inventories) to better capture wetland classes.
3. Developing new approaches to remotely monitor land changes over time.

While the HLP may not lead the development of wetland inventories, there are opportunities for HLP partners to support the development of these products for their tenure areas or jurisdictions. Wetland inventories are increasingly in demand by various industries, governments, and Indigenous communities so project work is ongoing to fill knowledge and data gaps. Keeping up to date on inventories that are completed or in progress across the western boreal forest will help address this gap.

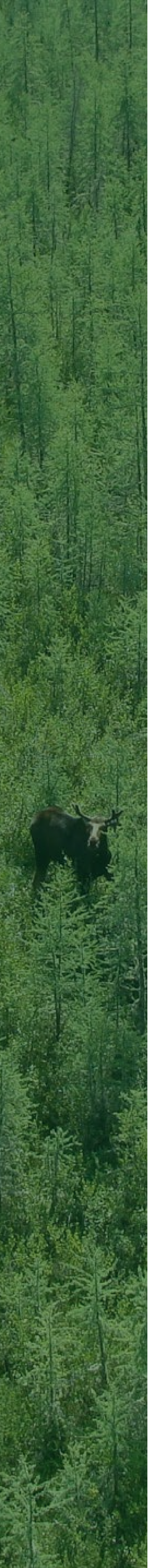
Priority gap #2 – Climate Change

How will climate change affect wetland abundance, distribution, and functions?

Understanding how climate change will affect the abundance, distribution, and functions of boreal wetlands is needed to both mitigate the effects of anthropogenic land uses on climate change and to adapt practices to respond to climate change. While there is a general understanding of the types of changes boreal wetlands are anticipated to experience, improved knowledge is needed to understand how specific conditions—like climate and land-use changes—may lead wetlands to become wetter or drier, impact ecosystem services, and influence interactions with surrounding ecosystems.

Opportunities for filling climate change related knowledge gaps include:

1. Providing input, as part of industry and government engagement, into the Boreal Climate Change Modelling Study being led by Ducks Unlimited Canada (2023-2026). This project is developing predictive models to forecast changes in wetland distribution and abundance across the western boreal forest.
2. Predicting the vulnerability of wetlands to wildfire under future climate scenarios.
3. Exploring how human activities, such as the construction of roads, well pads, and seismic lines, interact with climate change to alter wildfire risks and fire dynamics in wetlands.
4. Understanding how shifts in temperature, precipitation, and extreme weather influence wetland stability, formation, sucessional dynamics and species composition.



Priority #3 – Fire Behaviour

What wetland characteristics or conditions influence wetland fire behaviour and recovery?

As wildfire intensity and frequency increase in the western boreal forest, improving our understanding of wetland fire behaviour is needed for a whole landscape approach to ecosystem-based management. While an improved understanding for all wetland types is beneficial, treed organic wetlands are the highest priority focus because of the heightened risk of severe burning.

Opportunities for filling wetland fire behaviour knowledge gaps include:

1. Understanding of how factors such as wetland age, vegetation composition, and hydrology influence wetland wildfire behavior.
2. Understanding landscape-scale variables that contribute to higher fire risk in wetlands (e.g., historic fire suppression, anthropogenic activities, climate change) and identifying areas with heightened risk.
3. Predicting changes in wetland fire return intervals by analyzing historical patterns and considering projected climate and land use changes.
4. Assessing how fire severity, intensity, and return intervals affect wetland post-fire recovery and succession.

Research on this topic is growing and the over-arching opportunity for the HLP is to connect with wetland wildfire researchers to capture up to date information in current and future wildfire focused HLP-led projects.

Priority #4 – Fire Management

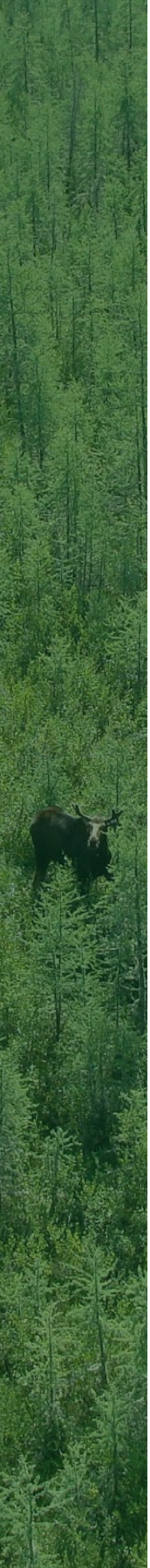
How can we best manage wetland fire risk?

As the HLP explores approaches to manage for fire risk in upland managed forests, there are also opportunities to improve understanding of approaches to manage for fire risk in wetlands; however, it is less clear who holds the authority and responsibility for fuel management in wetlands. Section Two explored approaches to manage wetland fire risk using Indigenous fire stewardship, fuel management, and nature-based solutions such as beavers.

Opportunities for filling wetland fuel management knowledge gaps include:

1. Understanding and documenting cultural burning practices historically applied in wetlands, as this knowledge exists within Indigenous communities but is often not recorded in western scientific literature.
2. Testing the effectiveness of prescribed burning, whether through western methods or Indigenous fire stewardship.
3. Improving understanding of the effectiveness, practicality, and cost of mechanical fuel management approaches—such as mulching and thinning—for managing wildfire risk in wetlands.
4. Addressing policy, legal, and organizational challenges is necessary to test and scale up wetland fuel management approaches, including clarifying responsibilities, skills required, and funding mechanisms.

Some of these opportunities can be addressed alongside similar questions targeting managed upland forests; however, #4 is critical because there are a few key barriers associated with wetland fuel management that differ from upland fueld management (e.g., different regulatory requirements, no or minimal merchantable timber).



Priority #5 – Cumulative Effects

How does the HLP extend a whole landscape ecosystem-based management approach to encompass all industries operating in the western boreal forest?

A whole landscape approach to ecosystem-based management requires understanding and accounting for activities and disturbances across the whole landscape. By nature of the organizations involved in the HLP (primarily forest industry, government forest branches, forest researchers) and because of the immense challenges of working across multiple sectors, the HLP's approach to date has primarily focused on ecosystem-based management as a tool for sustainable forest management. If the HLP is looking to grow its scope to encompass all parts of the landscape, there is also a need to explore how cumulative effects from other anthropogenic activities could be considered as part of that scope.

Opportunities for starting to fill the cumulative effects knowledge gap include:

1. Improving understanding of current and predicted future footprint of individual and cumulative industry activities across the western boreal forest.
2. Working with other sectors to understand how the effects of their activities can be considered alongside sustainable forest management explore approaches to ecosystem-based management that consider all disturbances on the landscape.
3. Understanding the social, political, and economic barriers and opportunities for managing cumulative impacts.

These opportunities aren't limited to wetlands and are equally applicable to upland forests and other ecosystem types. As covered in Section Three, wetlands are affected by a range of different industries, from peat harvest to oil and gas, and the effects they experience often differ from uplands. Meaningful ecosystem-based management in wetlands needs to consider the effects of all activities.

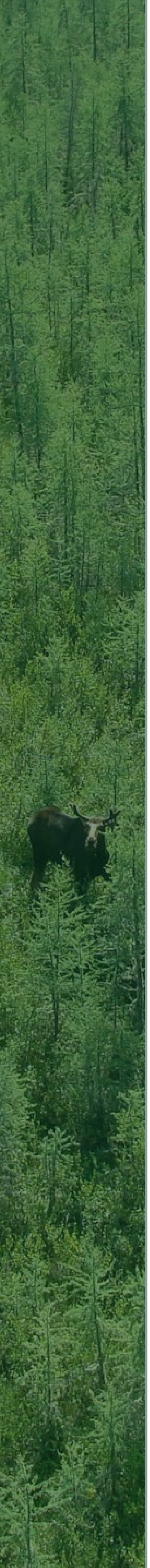
Priority #6 – Indigenous Knowledge

How can the HLP incorporate Indigenous knowledge to inform a whole landscape approach to ecosystem-based management?

This document and the whole landscape definition (cite) were developed from a western science perspective and without the input of Indigenous knowledge or perspectives. This is a gap, particularly when the goal is to take a whole landscape approach to ecosystem-based management. Wetland management has often neglected Indigenous knowledge and values, which provide valuable insights into wetland locations and their cultural significance. Incorporating this knowledge could significantly enhance our understanding and management of boreal wetlands and inform a holistic approach to ecosystem-based management.

The first step to addressing this knowledge gap is continuing to build and invest in relationships with Indigenous knowledge holders, working towards incorporating other knowledge systems into HLP projects and research. Building relationships would facilitate the integration of two-eyed seeing, a concept that incorporates both western and Indigenous knowledge systems, into HLP projects and research. From those relationships, specific topics to explore include:

1. Expanding the Whole Landscape Definition to capture Indigenous knowledge.
2. Where appropriate, growing understanding of traditional knowledge and values across the whole landscape, including capturing knowledge in spatial products such as land or wetland inventories.
3. Growing HLP's understanding of cultural burning practices used in wetlands (and



other ecosystems). Where appropriate, this could include working with communities to document knowledge and practices or applying practices as part of prescribed burn trials.

4. Exploring new ways to bring together Indigenous knowledge and western science.

Recognizing that Indigenous knowledge is often proprietary to a community and there may be rules or concerns with sharing knowledge outside of the community. Respectful approaches are needed to document and safeguard this knowledge according to community preferences.

Conclusion

The six priority knowledge gaps represent key areas for the HLP to explore as the program continues to evolve its whole landscape approach to ecosystem-based management. While some of these gaps may be independent HLP-led projects, many are more likely to be addressed as part of projects the HLP is already considering. It is also important to note that these knoowledge gaps and the Road map is not static, and these priorities may shift over time.

Addressing these knowledge gaps may involve including new partners, or simply widening the scope to encompass wetlands. Wetland research in the western boreal forest has grown significantly in the past decades and with the global focus on climate change adaptation and mitigation, biodiversity loss, wildfire, and water security, this is likely to continue. This growing body of research will help to fill the priority knowledge gaps, and the more specific knowledge gaps identified in each of the three sections, and continuing to monitor research outcomes and incorporate new findings will strengthen HLP's work. Wetlands are not the only other part of the landscape and applying a similar approach to other ecosystems (e.g., grasslands, shrublands) will support the HLP in continuing to develop a whole landscape approach to ecosystem based management.

Appendix 1. Who is Working in this Space

This table identifies organizations, researchers, and governments working in wetlands, with a focus on those working on projects related to organic wetlands in the boreal forest. This list is a living document, there may be projects, researchers, organizations and topics missing from this list.

Org Type	Organization	Department/Lab	Researcher	Topic of Interest	Related Factsheet(s)
Association	Canadian Sphagnum Peat Moss Association			Post-peat-harvest peatland restoration.	15. Cummulative Effects
Association	Saskatchewan Research Council		Dr. Mark Johnston	Retired. Forest ecology, environmental modelling, and climate change vulnerability.	6. Wetland Soil Carbon
Government	Government of Alberta			Land use planning and sustainable development.	3. Wetland Classification 4. Wetland Inventories
Government	Government of Canada	Environment and Climate Change Canada	Dr. Kelly Bona	Peatland carbon dynamics, ecosystem modeling, and ecology.	4. Wetland Inventories 6. Wetland Soil Carbon
Government	Government of Canada	Natural Resources Canada	Dr. Kara Webster	Forest soil carbon and nutrient cycles.	6. Wetland Soil Carbon
Government	Government of Canada	Natural Resources Canada	Dr. Jaime Pinzon	Cumulative effects and sustainable forest management.	14. Forest Harvest
Government	Government of Canada	Natural Resources Canada	Dr. Anna Dabros	Ecosystem response to disturbance, cumulative effects, and restoration.	15. Cummulative Effects

Government	Government of Canada	Natural Resources Canada	Dr. Dan Thompson	Hydrology of disturbed landscapes, boreal wildfire spread	8. Wetland Fire Behaviour 9. Post Fire Successional Dynamics 11. Managing Wetlands for Fire Risk 15. Cummulative Effects
			Alex Zahara	Wildfire response; Indigenous studies; anti-colonial methodologies in science	10. Indigenous Fire Stewardship
	Government of the United States	US Forest Service	Dr. Frank K. Lake	Wildland fire effects, traditional ecological knowledge and management, and climate change.	1. Wetland Values 9. Post Fire Successional Dynamics 10. Indigenous Fire Stewardship
Non-Profit	Alberta Native Trout Collaborative			Watershed conservation and rehabilitation for native trout	12. Wetlands and Beavers
	Alberta Watercourse Crossing Collaborative			Watercourse crossings, watercourse health, and fish passage	13. Resource Roads
	BC Wildlife Federation			Conservation and sustainable use of BC's land, and resources	3. Wetland Classification
	Blood Tribe Land Management			Land use planning and traditional knowledge.	12. Wetlands and Beavers
	Cows and Fish			Riparian areas, watercourse health, and land stewardship.	12. Wetlands and Beavers
	Ducks Unlimited Canda	Institute for Wetland and Waterfowl Research		Waterfowl, wetlands, biodiversity, wetland distribution and abundance	5. Wetland Hydrology 7. Climate Change

Non-Profit	Ducks Unlimited Canda	National Boreal Program		Wetland mapping and classification, predicting future wetland distribution and abundance, wetland training	3. Wetland Classification 4. Wetland Inventories 7. Climate Change 13. Resource Roads 14. Forest Harvest 15. Cummulative Effects
	FPInnovations			Resource roads, sustainable forestry, and fire management in the boreal forest.	11. Managing Wetlands for Fire Risk 13. Resource Roads 14. Forest Harvest 15. Cummulative Effects
	Indigenous Leadership Initiative		Dr. Amy Cardinal Christianson	Indigenous fire stewardship, Indigenous wildland firefighters, Indigenous research	1. Wetland Values 8. Wetland Fire Behaviour 9. Post Fire Successional Dynamics 10. Indigenous Fire Stewardship
	North American Waterfowl Council			Wetland conservation, wetland policy and awareness, and waterfowl management	4. Wetland Inventories
	The Beaver Institute			Beavers and ecosystem health.	12. Wetlands and Beavers
	Trout Unlimited Canada			Trout conservation and protection and restoration of freshwater ecosystems	12. Wetlands and Beavers
	Wildlife Conservation Society Canada	Forests, Peatlands and Climate Change	Dr. Lorna Harris	Peatlands formation and development and peatland development in response to climate change and disturbance.	5. Wetland Hydrology 6. Wetland Soil Carbon 14. Forest Harvest 15. Cummulative Effects

University	Athabasca University		Dr. Leslie Main Johnson	Traditional ecological knowledge, ethnography, and cultural anthropology.	1. Wetland Values
		AU Hydrology	Dr. Scott Ketcheson	Hydrology between forests, wetlands, and streams.	5. Wetland Hydrology 8. Wetland Fire Behaviour 11. Managing Wetlands for Fire Risk 13. Resource Roads 14. Forest Harvest
	Brandon University		Dr. Peter Whittington	Peatland restoration and soil hydrology.	15. Cummulative Effects
	Laval University	Peatland Ecology Research Group	Dr. Line Rochefort	Peatland restoration techniques after peat extraction and development of the moss-layer-transfer technique.	15. Cummulative Effects
	McMaster University	McMaster Ecohydrology Lab	Dr. Mike Waddington	Wetland soil carbon and the impacts of wildfire, drought, and resource development on wetland systems.	5. Wetland Hydrology 8. Wetland Fire Behaviour 9. Post Fire Successional Dynamics 11. Managing Wetlands for Fire Risk 14. Forest Harvest 15. Cummulative Effects
	Mount Royal University		Dr. Felix Nwaishi	Ecosystem ecology, climate change, braiding knowledge systems, and impact mitigation.	5. Wetland Hydrology 13. Resource Roads 15. Cummulative Effects
		Miistakis Institute		Ecological connectivity, biodiversity, and ecosystem-based climate adaptation.	12. Wetlands and Beavers

University	Northern Alberta Institute of Technology (NAIT)	Centre for Boreal Research	Dr. Bin Xu	Peatland restoration, greenhouse gas emissions from peatlands, and linear features in peatlands.	5. Wetland Hydrology 13. Resource Roads 14. Forest Harvest 15. Cummulative Effects
	Olds College		Dr. Daniel James Karran	Ecohydrology and phytoremediation of agricultural runoff.	12. Wetlands and Beavers
	Plymount Univerity	Wetlands Resilience Research Group	Dr. Scott J. Davidson	Drivers of greenhouse gases and peatlands as nature-based solutions.	6. Wetland Soil Carbon
	Simon Fraser University		Dr. Sophie Wilkinson	Ecohydrology, environmental change, and wildfire science	8. Wetland Fire Behaviour 9. Post Fire Successional Dynamics 11. Managing Wetlands for Fire Risk
	University of Alberta		Dr. Kevin Devito	Impacts of large-scale disturbance on hydrology, ecohydrology, wetland soil carbon, restoring hydrology after large scale disturbance.	15. Cummulative Effects
		Fire Management Systems Laboratory	Dr. Mike Flannigan	Retired. Fire and weather/climate interactions, impact of climatic change, and wildland fires.	8. Wetland Fire Behaviour
		Alberta Biodiversity Monitoring Institute		Wetland inventories, species distribution maps, biodiversity trend monitoring.	4. Wetland Inventories 7. Climate Change

University	University of Alberta	Catchment and Wetland Sciences Research Group	Dr. David Olefeldt	Impacts of disturbances and management on wetland functions	5. Wetland Hydrology 7. Climate Change 11. Managing Wetlands for Fire Risk
	University of Boulder Colorado		Dr. Merritt Turetsky	Climate change, wildfire, and permafrost thaw.	7. Climate Change 8. Wetland Fire Behaviour
	University of British Columbia		Dr. Ignacio San-Miquel	Fire management policies, remote sensing, and environmental monitoring.	11. Managing Wetlands for Fire Risk
		UBC Tree Ring Lab	Dr. Kira M. Hoffman	Fire ecology, fire behaviour, pyrodiversity, and Indigenous- led fire stewardship.	8. Wetland Fire Behaviour 9. Post Fire Successional Dynamics 10. Indigenous Fire Stewardship
	University of Kansas		Dr. Melinda Adams	Revitalization of cultural burns, traditional ecological knowledge, and soil carbon storage.	1. Wetland Values 10. Indigenous Fire Stewardship
	University of Minnesota		Dr. Emily Fairfax	Beavers and drought, fire, climate mitigation and remote sensing.	12. Wetlands and Beavers
	University of Saskatchewan	Beaver Ecohydrology Lab	Dr. Cherie Westbrook	Ecohydrology of beaver-dominated landscapes.	5. Wetland Hydrology 12. Wetlands and Beavers
	University of Toronto		Dr. Irena Creed	Watershed processes and responses to global change, impacts of global change on ecosystem structure, function, and services.	1. Wetland Values

University	University of Waterloo	Hydrometerology Research Group	Dr. Rich Petrone	Catchment hydrometeorological processes, ecohydrological processes, and wetland reclamation.	5. Wetland Hydrology 15. Cummulative Effects
		TRANT Ecological Legacies Lab	Dr. Andrew Trant	Ecological legacy, biodiversity, biogeography.	10. Indigenous Fire Stewardship
		Waterloo Wetland Laboratory	Dr. Rebecca Rooney	Wetland ecology, wetland assessment, and impacts of disturbances.	5. Wetland Hydrology 15. Cummulative Effects
		Wetland Soils & Greenhouse Gas Exchange Lab	Dr. Maria Strack	Interactions between ecology, hydrology, biogeochemistry and soil properties in wetland ecosystems. Peatland soil greenhouse gas fluxes, wetland restoration, and ecohydrology.	5. Wetland Hydrology 6. Wetland Soil Carbon 11. Managing Wetlands for Fire Risk 13. Resource Roads 15. Cummulative Effects
		Wetlands Hydrology Lab	Dr. Jonathan Price	Wetland hydrology, peatland reclamation, resource development, and contaminant transport in peatlands,	15. Cummulative Effects
	Wilfrid Laurier University	Cold Regions Research Centre	Dr. William Quinton	Hydrology of cold regions, permafrost, and peatlands.	5. Wetland Hydrology