EXPLORING WILDFIRE AND CARBON

For Natural Climate Solutions in Northern Manitoba

A Report Produced for Nature United

By: WildFire AP Ltd. | January 2023

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Executive Summary

Boreal forests store an estimated one-third of global terrestrial carbon. Wildfire disturbance in this landscape may be a threat to boreal carbon, with potentially global consequences for climate change. Wildfire represents a wicked problem, because of boreal wildfire behaviour, the significance of wildfire to the boreal ecosystem, the role of wildfire in carbon cycling, and the complexity of wildfire management coalesce into an issue that is not easily solved through simple, linear interventions.

Understanding boreal wildfire is essential for analyzing potential natural climate solutions that may mitigate carbon loss from wildfire in northern Manitoba.

WildFire AP Ltd. undertook literature review on behalf of Nature United Canada in order to present an overview of the complex relationships between the boreal landscape, wildfire, carbon, climate change, and wildfire management options. *Exploring Wildfire and Carbon For Natural Climate Solutions in Manitoba* is structured to iteratively build an understanding of wildfire in the northern boreal forest, wildfire's characteristics, fire's role within socio-ecological systems, the impact of climate change on historic wildfire regimes, and the impact of wildfire on the boreal forest's carbon cycle in the short- and long-term. The report then reviews and analyzes potential natural climate solutions for managing and mitigating wildfire.

Key Findings

Finding 1: ***Wildfire is an essential component within the biology, ecology, carbon-cycle, and cultures of the boreal landscape.***

The boreal forest's vegetation, ecosystems, cultures, and carbon cycle have evolved and been shaped by the infrequent (averaged 80-year return interval), large (>200 ha) stand-replacing fires that characterize its wildfire regime. Lightning-ignited fires occur across the landscape to burn large areas of the forest as a result of a combination of fuel availability, topography, and fire weather conditions. Fire-disturbance plays an important role in the forest ecosystem by clearing out aging vegetation, limiting insect-disturbances, facilitating the reproductive cycle of fire-adapted vegetation, and promoting new growth. Indigenous peoples have a complex biocultural relationship with fire, and historically used fire to shape the landscape to maximize certain values. Boreal fires influence the carbon cycle through the consumption of fuels resulting in an immediate release of carbon, and the subsequent decadal-long recovery and sequestration of carbon through regrowth. This contributes to the long-term carbon stores in the boreal forest.

Finding 2: ***Climate change is altering the wildfire regime by increasing wildfire occurrence, behaviour, and the area burned, resulting in increased combustion emissions and increased risk for carbon stores in soils and peatlands.***

Climate change is resulting in a more active wildfire regime in the boreal forest, characterized by increasing fire occurrences, extreme fire weather events, fire behaviour, and area burned. A more active wildfire regime increases combustion emissions, may shorten carbon recovery periods (reducing carbon sequestration potential), and threatens the vast stores of carbon in boreal soils and peatlands.

Finding 3: ***Quantifying wildfire carbon emissions and impact on storage is complex and has some uncertainties. Therefore, quantifying the effectiveness of wildfire management options for reducing wildfire-related carbon emissions is challenging and requires site-specific (stand-level) analysis.***

Direct carbon emissions from wildfires have often been overestimated by failing to account for the spatial burn pattern of wildfires, and the partially burnt biomass left after a fire which resists decomposition. Short-term emissions are countered by the long-term carbon recovery through regrowth, which can result in net carbon uptake on a longer timescale (80 years). Complicating this further is the heterogeneity of boreal stands (species, age-class, and growth-rate), and the different ways this impacts carbon emissions, sequestration, and storage.

Quantifying the efficacy of natural climate solution treatments requires accounting for stand-level heterogeneity in carbon pools and the wildfire carbon cycle. Stand-level carbon dynamics must then be compared to a treatment's effect on carbon emissions and storage. Determining the net difference requires comparing the effect of wildfire on carbon emissions and storage of the area if treated versus if the area was left untreated. Given the uncertainty of when and where wildfire occurs on the landscape, treatment efficacy might be impacted by the likelihood that the treatment will interact with fire, and the duration of the treatment.

Finding 4: ***Wildfire management options can reduce wildfire risk, spread, intensity, and severity.***

The four natural climate solutions for fire management studied were found to have the potential to reduce wildfire risk, spread, intensity, and severity. **Wildfire suppression** is responsive to fire, as it occurs on a landscape-scale and has been proven effective at controlling wildland fires. **Forest management** can reduce fuel loads and disrupt fuel continuity, thereby reducing flammability and fire intensity through harvesting and thinning treatments. Preventative silviculture (planting less-flammable deciduous trees) can reduce stand flammability and disrupt fuel continuity. **Prescribed fire** reduces fuel loads through the application of low-intensity fires. **Peatland protection** prevents drainage and drying, to maintain the natural fire-resistance of these ecosystems.

Finding 5: ***Wildfire management options as natural climate solutions have limitations and drawbacks in the boreal forest of Manitoba.***

Fire suppression does not prioritize carbon as a value-at-risk; prioritizing carbon on the landscape would stretch resources and capacity due to the expenses related to actioning fires in remote areas. **Forest management** can have a similar carbon impact as wildfire, has been found to increase fire risk in some cases, has a limited duration of effectiveness, does not incorporate fire risk to carbon into planning strategies, and deploying fire risk mitigation strategies may have negative economic consequences. **Prescribed fire** efficacy and potential in the boreal forest is unknown given the boreal forest fire regime, methodological challenges of developing this program, and critiques related to the efficacy for reducing emissions. **Peatland protection** may be limited by their geographic remoteness and the lack of incentives for protecting peatlands.

Recommendations

Recommendation 1: ***Develop system for researching, monitoring, and evaluating the effect of climate change on carbon dynamics and wildfire risk in the boreal region of Manitoba***

Responds to ***Key Findings 1****,* ***2****, and* ***3****.*

Ongoing research that focuses on specific geographic areas will be required to determine a finer grained analysis of wildfire risk, carbon balance, and potential for implementation of successful natural climate solutions for carbon. A system for monitoring carbon balance and wildfire risk across the boreal region can provide the foundation for modelling what, how, and where natural climate solutions could be implemented, as well as a means for evaluating the efficacy of those solutions.

Furthermore, a system that enables modelling carbon dynamics and wildfire risk together may be able to overcome the primary limitations of this report: estimating the efficacy and cost of different treatment options. Determining the efficacy, and cost of interventions requires: 1) data on stand-level carbon dynamics, 2) local landscape fire-carbon dynamics, 3) data on the efficacy of interventions in the specific geographies of northern Manitoba, and 4) data on the cost of treatment, which varies depending on the specific geographic areas being treated.

Recommendation 2: ***Advocate for the development of an integrated and proactive Fire-Smart forest management approach in Manitoba's forest management license areas (FMLAs).***

Responds to ***Key Findings 1-5*** *and building off* **Recommendation 1***.*

Wildfire in the boreal forest is a landscape-level issue, because of the scale of wildfires and uncertainty of where and when wildfires will occur. This means that natural climate solutions must be integrated, proactive, and address fire on a landscape-level. Within Manitoba, the small number of large FMLAs offer an opportunity for integrating carbon values and wildfire risk into landscape-level strategic planning. Strategic planning for FMLAs (e.g., the in-development 20-year Forest Management Plan for FML-2) already incorporates significant modelling for a variety of values across the landscape, so integrating carbon values and wildfire risk as variables to be managed could be possible. Fire simulation models (e.g., BURN-P3) have been used in a Canadian context for Fire-smart forest management.

Integrating Fire-smart forest management into the FMLA planning process can be a way to bring together different stakeholders (e.g., forest management companies, Manitoba Wildfire Service, First Nations), and identify appropriate treatment options (e.g., fire suppression, harvest locations, preventative silviculture, prescribed fire) that balance carbon and fire risk values with other values on the landscape. Fire-Smart forest management has been found to be successful in protecting valuable timber stands and for reducing landscape fire risk, so it could add value to forest management in Manitoba beyond potential emissions reductions.

Recommendation 3: ***Investigate potential for existing or new programs to integrate wildfire emissions reductions as an additional outcome or benefit.***

Responds to Key Findings 1-5, builds off Recommendation 1, and acts as an additional or alternative to Recommendation 2 by focusing on opportunities other than forestry.

There are a wide range of values (e.g., cultural, wildlife, habitat, etc.) in the boreal landscape that interact with the carbon cycle in different, often unacknowledged, ways. For this reason, it is worth investigating whether there are opportunities for existing programs or activities to incorporate carbon objectives or realize benefits. For example, Indigenous-led Conservation and Guardians programs could be a program that could contribute to peatland protection. Another example, integrating carbon emissions reductions into existing prescribed burn programs has resulted in carbon-offsets programs in Australia (though further research is needed to apply this to a boreal context). Looking for synergies for existing and new programs to add carbon objectives or benefits may be an important way to avoid concerns about natural climate solutions being too carbon-centric.

Recommendation 4: ***Pursue climate change mitigation activities that reduce greenhouse gas (GHG) emissions.***

Responds to Key Finding 1-2.

Climate change is altering the wildfire regime to the extent that it is a threat to carbon stores in the boreal forest. The boreal forest has been accumulating carbon in spite, or because, of its fire regime. The most effective way to reduce wildfire carbon emissions is to slow climate change by reducing anthropogenic greenhouse gas emissions. The emissions from boreal wildfires are naturally recovered through regrowth, which makes avoiding these emissions less significant than anthropogenic GHG emissions. Capping climate change at 0.3°C per decade (currently at 0.44°C per decade) would save 6 Gt of carbon this century from peat fires alone.

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Introduction

Natural climate solutions are strategies or actions that aim to protect, restore, and better manage forests, grasslands, wetlands, and soils to reduce greenhouse gas (GHG) emissions, while also providing additional benefits. Natural climate solutions have been found to have significant potential for reducing GHG emissions in Canada. Forestry is one of the key sectors where natural climate solutions can deliver greenhouse gas emission reductions. Forest management, with an increased focus on carbon (C) management, can reduce emissions by 11.9 megatonnes of CO_2 equivalent per year (Mt CO_2e/yr) by 2030, and potentially 24.9 Mt CO_2e/yr by 2050.[1] One potential challenge or opportunity for achieving these reductions will be the impact of wildfires, as a source of greenhouse gas emissions and as a variable in the forested landscape. The impacts of wildfire are of particular interest in the boreal forest, where wildfire is the largest **natural disturbance**[2] and plays a critical role in the boreal ecosystem. This report is a literature review that seeks to provide an overview of wildfire and carbon in the boreal forest of northern Manitoba to better understand the potential for managing fire to support natural climate solutions for emissions reductions. The report is divided into four chapters:

- **Chapter 1** provides an overview of fire in the boreal forest by exploring: the interconnection between fire, the boreal landscape, and the people of the boreal region; the wildfire regime, the 'why' and 'how' fire occurs on the boreal landscape; fire's place within the socio-ecological system of the boreal forest; how climate change is, and will, affect wildfire.
- **Chapter 2** provides a broad description of carbon in the boreal in order to explore the complex effect of wildfire has on carbon dynamics and the potential effects climate change will have on wildfire-related emissions.
- **Chapter 3** presents and analyzes four potential options for natural climate solutions to wildfire emissions: Wildfire Management (Suppression); Forest Management; Prescribed Fire; and Peatland Fire Management.
- **Chapter 4** draws from Chapters 1-3 to present key findings and provide recommendations.

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[1] Nature United, "Natural Climate Solutions," 2021, https://www.natureunited.ca/what-we-do/our-priorities/innovating-for-climate-change/natural-climate-solutions/.

[2] A natural disturbance is an event or process that disrupts the functioning of an ecosystem. Disturbances are normal and a necessary part of the boreal forest as they contribute to maintaining diversity, stimulating growth and regenerating the ecosystem.

Chapter 1: Fire in the Northern Boreal Forest of Manitoba

Fire has been integral to the evolution of the boreal forest ecosystem through its disturbance-regeneration cycle (Langston 2009). Fire has shaped the forests of northern Manitoba since their establishment after the last ice age. Anthropogenic (human-caused), and naturally occurring (lightning-caused) fire was present in the forests that emerged in Manitoba as glaciers receded approximately ten thousand years ago.[3] Fire disturbance continues to play an essential role in forest ecosystem dynamics by replacing older forests with new growth. As a result, the dominant vegetation species found within the boreal forest are those that have adapted to fire.

For the purpose of this review, the primary focus is the boreal forest in Northern Manitoba. In Manitoba, the boreal forest is predominantly located within the Boreal Plains and Boreal Shield West ecozones, with some of the forest extending into the Taiga Shield West ecozone in the far North. The climate for this region is characterized by short summers, which are cooler in the north and warmer in the south, and long, cold winters. Annual precipitation varies throughout this region annually, but averages between 400mm and 600mm with about one third falling as snow.[4] The Boreal Plains (stretching from Alberta to Manitoba) and Boreal Shield West (stretching from Northern Saskatchewan to Northwest Ontario) ecozones accounted for 57.1% of total fire occurrences in all of Canada and 48.8% of the total area burned.[5] This is due to the fire ecology of these ecozones, but also in part to the remoteness of these ecozones and the subsequent policies that contribute to less aggressive fire suppression in these areas (Chapter 3.1).

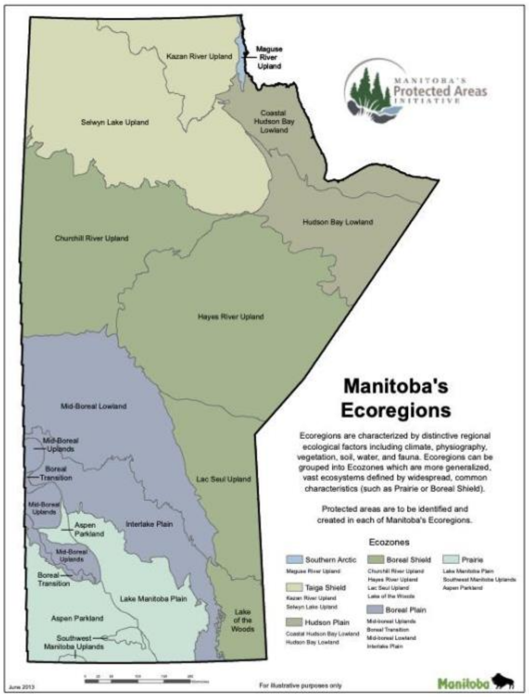

Figure 1: Manitoba's Ecoregions. From Manitoba Government. Accessed https://www.gov.mb.ca /sd/pai/pdf/ecoregion_map_2014.pdf.

One of the complexities of describing this wildfire regime is that fire in the boreal forest has been significantly shaped through human activity. Indigenous peoples interacted with fire in the boreal

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[3] T A Waldrop, D L White, and S M Jones, "Fire Regimes for Pine-Grassland Communitites in the Southeastern United States," *Forest Ecology and Management* 47 (1992): 195–210.

[4] R. E. Smith et al., "Terrestrial Ecozones, Ecoregions and Ecodistricts: An Ecological Stratification of Manitoba's Natural Landscapes," *Technical Bulletin 98–9E.*, 1998.

[5] Yueyang Jiang et al., "Characterization of Wildfire Regimes in Canadian Boreal Terrestrial Ecosystems," *International Journal of Wildland Fire* 18, no. 8 (2009): 992–1002, https://doi.org/10.1071/WF08096.

forest for thousands of years before colonial fire management altered that relationship.[6] In addition, anthropogenic climate change has become a significant influence on wildfire regimes. This chapter will describe the boreal forest wildfire regime and its impact on the ecosystem of northern Manitoba in order to contextualise the boreal forest's carbon balance and the carbon effects of wildfire.

1.1. Boreal Forest: A Cultural Landscape

The boreal forest is a cultural landscape; its structure and ecology has been influenced by historic and contemporary cultural activities and uses.[7] Anthropogenic and naturally occurring fire has altered, both intentionally and unintentionally, the culture, biology and the landscape of the boreal forest. The boreal forest, as we know it, has emerged through this relationship to fire. Indigenous Nations, living in the boreal forest since time immemorial, historically had, and continue to hold, knowledge about the interaction of fire and the landscape, and have relationships and practices with the landscape and fire. Given the complex relationship between humans, fire, and the landscape, it is nearly impossible to describe a 'natural' fire cycle in the boreal forest that excludes the role of humans in the boreal forest fire.[8] Most wildland fire histories of the boreal forest describe a regime dominated by large-scale periodic stand-replacing fires; however these histories often do not account for frequent, small-scale fires that were lit intentionally and unintentionally by Indigenous people.[9]

Indigenous peoples have used fire in a variety of ways to modify the boreal landscape. This includes promoting the growth of early succession forests, maintaining habitats, establishing gardens or blueberry patches, reducing wildfire risk around communities, and modifying habitat for game and fur-bearing species.[10] Indigenous peoples have extensive knowledge about the use

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[6] Henry T. Lewis, "A Time for Burning," 1982; S J Pyne, "The Perils of Prescribed Fire: A Reconsideration," *Natural Resources Journal* 41, no. 1 (2001): 1–8, isi:000168015300001; Amy Christianson, "Social Science Research on Indigenous Wildfire Management in the 21st Century and Future Research Needs," *International Journal of Wildland Fire* 24, no. 2 (2015): 190–200, https://doi.org/10.1071/WF13048.

[7] Waldrop, White, and Jones, "Fire Regimes for Pine-Grassland Communitites in the Southeastern United States"; Edward A. Johnson, K. Miyanishi, and J. M. H. Weir, "Wildfires in the Western Canadian Boreal Forest: Landscape Patterns and Ecosystem Management," *Journal of Vegetation Science* 9, no. 4 (1998): 603–10, https://doi.org/10.2307/3237276.

[8] Stephen J Pyne, "Fire Primeval," *The Sciences* 22, no. 6 (August 9, 1982): 14–20, https://doi.org/https://doi.org/10.1002/j.2326-1951.1982.tb02087.x; Kurtis Ulrich, "Prescribed Fire and Design: Two Biocultural Design Case Studies From Northwestern Ontario" (University of Manitoba, 2019); Johnson, Miyanishi, and Weir, "Wildfires in the Western Canadian Boreal Forest: Landscape Patterns and Ecosystem Management."

[9] Amy Cardinal Christianson et al., "Centering Indigenous Voices: The Role of Fire in the Boreal Forest of North America," *Current Forestry Reports* (Springer Science and Business Media Deutschland GmbH, 2022), https://doi.org/10.1007/s40725-022-00168-9.

[10] Iain J. Davidson-Hunt, "Indigenous Lands Management, Cultural Landscapes and Anishinaabe People of Shoal Lake, Northwestern Ontario, Canada," *Environments* 31, no. 1 (2003): 21–42; Omer C. Steward, *Forgotten Fires: Native Americans and the Transient Wilderness*, ed. Henry T. Lewis and M. K. Anderson (Oklahoma: University of Oklahoma Press, 2002); Henry T. Lewis and Theresa A. Ferguson, "Yards, Corridors, and Mosaics: How to Burn a Boreal Forest," in *Indians, Fire, and The Land in the Pacific Northwest*, ed. Robert Boyd (Corvallis: Oregon State

of fire in the boreal forest, including the optimal timing, fuel conditions, humidity, wind, and the use of fire breaks.[11] Indigenous knowledge of fire was not just about practical applications, but also about the relationship between people and fire. Some Indigenous nations view fire as a spirit, and it is therefore bound up in cultural practices and belief systems.[12] The relationship between Indigenous people and fire has shifted over time. As traditional burning practices were curtailed by colonial authorities, Indigenous people stepped into the role of firefighters, thus continuing their tradition as fire managers and knowledge holders.[13] Over time, firefighting became an economic opportunity for Indigenous people.[14] The role of colonization also had negative consequences for Indigenous-fire relationships.[15] In addition to losing access to traditional burning practises on the landscape, communities were forced to give up their nomadic lifestyles and settle in reserves that are vulnerable to wildfire. Large, intense wildfires have emerged as an increasing threat to Indigenous values in the landscape.[16]

One of the limitations of this review is that most wildfire literature has been produced by non-Indigenous researchers, who have studied fire in the boreal forest without including Indigenous peoples in the process.[17] Most of the research then has been conducted from a western-science lens, which does not account for Indigenous Knowledge and the **biocultural**[18] relationships between Indigenous peoples and the fire-driven boreal forest. While this paper sets to provide an overview of fire and carbon in the boreal forest to provide direction for future natural climate solutions, we acknowledge that this is a fairly limited and specific focus that does not account for the wide variety of values, relationships, and cultural practices that exist within the boreal forest.

University Press, 1999), 164–84; Stephen J. Pyne, *Fire in America: A Cultural History of Wildland and Urban Fire* (Princeton University Press, 1982).

[11] Christianson et al., "Centering Indigenous Voices: The Role of Fire in the Boreal Forest of North America"; Lewis, "A Time for Burning."

[12] Iain J. Davidson-Hunt, "Indigenous Lands Management, Cultural Landscapes and Anishinaabe People of Shoal Lake, Northwestern Ontario, Canada," *Environments* 31, no. 1 (2003): 21–42; Christianson et al., "Centering Indigenous Voices: The Role of Fire in the Boreal Forest of North America."

[13] Christianson, "Social Science Research on Indigenous Wildfire Management in the 21st Century and Future Research Needs."

[14] Alex Zahara, "Breathing Fire into Landscapes That Burn: Wildfire Management in a Time of Alterlife," *Engaging Science, Technology, and Society* 6 (2020): 555–85, https://doi.org/10.17351/ests2020.429.

[15] Christianson et al., "Centering Indigenous Voices: The Role of Fire in the Boreal Forest of North America"; William D. Nikolakis and Emma Roberts, "Indigenous Fire Management: A Conceptual Model from Literature," *Ecology and Society* 25, no. 4 (2020): 1–20, https://doi.org/10.5751/ES-11945-250411.

[16] Zahara, "Breathing Fire into Landscapes That Burn: Wildfire Management in a Time of Alterlife"; Christianson et al., "Centering Indigenous Voices: The Role of Fire in the Boreal Forest of North America."

[17] Christianson et al., "Centering Indigenous Voices: The Role of Fire in the Boreal Forest of North America."

[18] Biocultural refers to the ongoing and historical interaction between Indigenous and local cultures with the natural environment in which they live. Landscapes and organisms are shaped by cultural practices and, through their close relationships with them, these cultures are also shaped by the landscapes and organisms.

1.2. Wildfire Regime

Wildfire Regime Characteristics

The boreal forest in Canada features a fire-disturbance regime that drives forest regeneration, nutrient cycling, habitat creation, and biodiversity.[19] The boreal forest **fire regime**[20] is characterized by numerous small low-intensity fires, and infrequent large high-intensity, stand-replacing crown fires, which burn large areas of the forest (estimated 3% of fires burn 97% of the total area).[21] The average **fire interval**[22] is 80 years for upland boreal forest stands (though this can range between 50-500 years), and can range between 80 to 1100 in boreal peatlands.[23] Fires can be human-caused or ignited by lightning, with lightning-caused fires resulting in 85% of large fires and accounting for 91% of the area burned across Canada's boreal forest. Human-caused fires account for the remainder.[24] Manitoba's fire statistics, which begin in 1914 and are available up until 2020, show that lightning-caused fires have accounted for 75.5% of total area burned in Manitoba over this 106-year timeframe. This data also indicates that 35.3% of wildfires in Manitoba over this time were caused by lightening, which means that the majority of detected fires were human-caused, but the largest areas burned were caused by those lit by lightning.[25] However, this data may be skewed, as many remote lightning-caused fires do not get mapped and satellite detection of small and remote fires only began in the early 2000's. A more precise breakdown of human versus natural caused fire in northern Manitoba would require a GIS analysis that falls outside the scope of this report. The result of this fire regime is that an average of 2.4 million hectares of forest have burned annually in Canada since 1990, though there is significant variation between years. The area burned annually by wildland fire has been increasing, nearly doubling since the 1970s.[26]

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[19] Johnson, Miyanishi, and Weir, "Wildfires in the Western Canadian Boreal Forest: Landscape Patterns and Ecosystem Management"; J. Rowe and G. W. Scotter, "Fire in the Boreal Forest," *Quaternary Research* 3 (1973): 444–64, https://doi.org/10.1016/0033-5894(73)90008-2.

[20] In Canada, a fire regime is the description of the occurrence and impact of fires based on various factors such as frequency, size, intensity, and seasonality. The type of fire (such as surface, crown, or ground fire) and the cause of the fire (e.g., lightning or human-caused) are also important considerations in fire regimes.

[21] Chelene C. Hanes et al., "Fire-Regime Changes in Canada over the Last Half Century," *Canadian Journal of Forest Research* 49, no. 3 (2019): 256–69, https://doi.org/10.1139/cjfr-2018-0293; Marc André Parisien et al., "Fire Deficit Increases Wildfire Risk for Many Communities in the Canadian Boreal Forest," *Nature Communications* 11, no. 1 (2020), https://doi.org/10.1038/s41467-020-15961-y.

[22] Length of time between stand-replacing fire events.

[23] Mike Flannigan et al., "Impacts of Climate Change on Fire Activity and Fire Management in the Circumboreal Forest," *Global Change Biology* 15, no. 3 (2009): 549–60, https://doi.org/10.1111/j.1365-2486.2008.01660.x; Bailu Zhao et al., "North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016," *Scientific Reports* 11, no. 1 (December 1, 2021), https://doi.org/10.1038/s41598-021-87343-3.

[24] Hanes et al., "Fire-Regime Changes in Canada over the Last Half Century."

[25] Manitoba Wildfire Service, "Manitoba Wildfires: 1914-2020," Manitoba Goverment Conservation and Climate Website, accessed January 12, 2023, https://www.gov.mb.ca/conservation_fire/Fire-Historical/firestatistic.html.," n.d.

[26] S Sankey, *Blueprint for Wildland Fire Science in Canada (2019-2029)*, 2018.

The primary factors that influence fire occurrence, wildfire behaviour (**intensity**[27], **severity**[28]) and burn pattern are bottom-up drivers: fuels and topography; and top-down drivers: weather and climate. These drivers form the legs of the wildfire behaviour triangle.

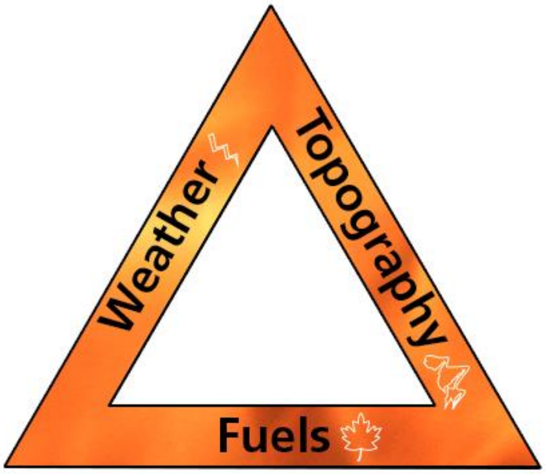

Figure 2: Wildland Fire Behaviour Triangle. From: https://www.nps.gov/articles/wildland-fire-behavior.htm

Fuels

Wildland fuels are the flammable material present in an ecosystem that can potentially contribute to the spread of fire. The quantity (available fuel), arrangement, and condition of fuel present, determine flammability. Fine fuels are the needles, fallen leaves, small twigs, and cured grasses that dry quickly, are easily ignitable, and are rapidly consumed by fire. Dry fine fuels are an essential factor for wildfire ignition to occur. Medium fuels are branches, coarse woody debris, and shrubs that are not as easily ignitable but will be consumed in a fire. Other fuels present include standing stem wood (both living and dead), and ground fuels, which are found beneath the layer of forest litter, such as roots.

Within the boreal forest, the dominant wildland fuels that shape the stand-replacing fire regime are the extensive closed-canopy, needle-bearing coniferous stands, primarily composed of black spruce and jack pine.[29] These fire-adapted coniferous species have evolved to encourage fire, as they need fire to promote new growth, and for reproduction through serotiny.[30] The closed-canopy structure of these forest types encourage high intensity crown fires, which are fires that climb into

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[27] Fire Intensity: The energy that is released from a fire, or characteristics of wildfire behaviour like rate of spread or flame length.

[28] Fire Severity: Ecosystem impacts of fire, such as tree mortality or depth of burn.

[29] R E Smith et al., *Terrestrial Ecozones, Ecoregions and Ecodistricts, An Ecological Stratification of Manitoba's Natural Landscapes, Technical Bulletin 98–9E. Land Resource Unit, Brandon Research Centre, Research Branch, Agriculture and Agri-Food Canada, Winnipeg, Manitoba.*, 1998.

[30] Jacques C. Tardif et al., "Fire Regime in Marginal Jack Pine Populations at Their Southern Limit of Distribution, Riding Mountain National Park, Central Canada," *Forests* 7, no. 10 (2016): 1–25, https://doi.org/10.3390/f7100219.

the canopy and are able to move from tree top to tree top due to the dense and continuous canopy arrangement. This type of fire disturbance creates opportunities for new forest growth by removing older forest stands and releasing nutrients back into the soil for renewed plant growth.

Serotiny: Serotinous plants have a delayed seed dissemination that requires a disturbance, often fire, to result in germinated seeds. For example, jack pine, one of the most dominant and important tree species in the northern boreal forest, requires fire to open its seed cones to disseminate seeds, a process known as serotiny. Thus, fire is important to the lifecycle of jack pine. Without fire, jack pine stands can be replaced by other species as a jack pine stand ages out.

Mixedwood stands, which dominate the southern portions of the boreal region, have a more variable fuel composition that changes throughout the season. Deciduous trees (e.g., trembling aspen and white birch) in mixedwood stands are less flammable than conifers, particularly when in full leaf, because of their ability to hold moisture. However, in early and late season, deciduous trees contribute leaves to the fine fuel load of the forest floor, and when not leafed out do not hold as much moisture. As a result, these fuels can affect fire intensity and spread differently during different seasons.[31] Like boreal conifers, mixedwood stands benefit from fire disturbance, with different species benefiting at different periods of succession. This variability of species succession is due to their differing abilities to rebound from fire. Early successional mixedwood forests are aspen-dominated, while late stages are spruce-fir-birch dominated.[32]

Other important wildland fuels include surface fuels such as grasses, shrubs, and duff, which is the organic layer of fallen leaves, twigs, and other plant debris that makes up much of the forest floor. Surface fuels enable surface fires, which can remain low intensity, or under the right conditions can climb into the forest canopy and become a high-intensity crown fire. In the boreal shield, bogs and peatlands contain a significant amount of ground fuel that may be susceptible to fire under the right conditions. The wet conditions of these peatlands make them resistant to fire, though drought conditions or drainage resulting from forestry or peat mining is resulting in more peatland fires.[33] Unlike upland forest and grasslands stands where fuel is a limiting factor for fire, in peatlands, moisture is the limiting factor for fire.[34] These peatlands are particularly important given their carbon storage capacity.[35]

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[31] Martin P. Girardin et al., "Fire in Managed Forests of Eastern Canada: Risks and Options," *Forest Ecology and Management* 294 (2013): 238–49, https://doi.org/10.1016/j.foreco.2012.07.005; Yves Bergeron et al., "Boreal Mixedwood Stand Dynamics: Ecological Processes Underlying Multiple Pathways," *Forestry Chronicle* 90, no. 2 (2014): 202–13, https://doi.org/10.5558/tfc2014039.

[32] Nicholas J. Payne et al., "Carbon Storage and Net Primary Productivity in Canadian Boreal Mixedwood Stands," *Journal of Forestry Research* 30, no. 5 (October 1, 2019): 1667–78, https://doi.org/10.1007/s11676-019-00886-0.

[33] Merritt R Turetsky et al., "Global Vulnerability of Peatlands to Fire and Carbon Loss," *Nature Geoscience* 8, no. 1 (2015): 11–14, https://doi.org/10.1038/ngeo2325.

[34] Mike D. Flannigan et al., "Implications of Changing Climate for Global Wildland Fire," *International Journal of Wildland Fire* 18, no. 5 (2009): 483–507, https://doi.org/10.1071/WF08187; Turetsky et al., "Global Vulnerability of Peatlands to Fire and Carbon Loss."

[35] Matthew Carlson et al., "Maintaining the Role of Canada's Forests and Peatlands in Climate Regulation," *Forestry Chronicle* 86, no. 4 (2010): 434–43, https://doi.org/10.5558/tfc86434-4.

Topography

In Manitoba, topography affects fire behaviour through fuel arrangement, most importantly through fuel continuity. Lakes, rivers, and wetlands can act as fire breaks by disrupting fuel continuity through increased moisture in the surrounding fuels. Recent disturbances, by fire, insects, or harvesting, may also reduce fuel loads and affect continuity. Recently burned areas can resist re-burning for about 30 years, due to a lack of fuel that supports ignition and spread.[36] One study found that of the total area burned in Canada over a 31-year period, only 4.8% of the area burned more than once.[37] Recently burned areas can affect subsequent fires by limiting the area burned, which can result in a patchy burn pattern (spatial heterogeneity). Elevation variation in the terrain can affect fire behaviour, as fires travel faster up inclines and slower down declines, while lower elevation areas tend to have more moisture resulting in patchier burns. [38]

Fire weather

Weather and climate exert a significant top-down control on fire occurrence and behaviour in the boreal forest. Weather influences fire over short periods of time (hours to days) through high temperatures, high winds, and low humidity, and these conditions dry wildland fuels. These dried fuels become more susceptible to ignition (both from lightning and anthropogenic sources), increasing both fire spread rates and fire severity, as fire can burn deeper into the soil organic layer based on ground fuels' moisture levels. High and extreme fire weather also correlates with the conditions required for lightning strikes, which ignite most large fires.[39] Fires can have feedback on weather, as smoke can promote more lightning ignitions.[40]

Under extreme fire weather conditions (i.e., high temperatures, high winds, low humidities) fires increase likelihood of ignition, and exhibit more extreme fire behaviour, such as faster spread, and greater intensity and severity. These fires are more likely to result in the stand-replacing crown fires, which result in the largest areas burned. These fires are also more difficult for fire suppression activities, as they are more likely to escape controls. It has been found that a large proportion of the area burned during boreal forest fires occurs on a relatively small number of days, when extreme fire weather causes fire to spread rapidly.[41] Additionally, extreme fire weather can result in fuel-limited areas, such as recently burned or harvested stands, being more susceptible to burning despite their resistance to fire under less extreme conditions.[42]

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[36] Ellen Whitman et al., "Short-Interval Wildfire and Drought Overwhelm Boreal Forest Resilience," *Scientific Reports* 9, no. 1 (2019): 1–12, https://doi.org/10.1038/s41598-019-55036-7.

[37] Zhao et al., "North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016."

[38] Ignacio San-Miguel et al., "What Controls Fire Spatial Patterns? Predictability of Fire Characteristics in the Canadian Boreal Plains Ecozone," *Ecosphere* 11, no. 1 (2020), https://doi.org/10.1002/ecs2.2985.

[39] Hanes et al., "Fire-Regime Changes in Canada over the Last Half Century."

[40] Sandra Lavorel et al., "Vulnerability of Land Systems to Fire: Interactions among Humans, Climate, the Atmosphere, and Ecosystems," *Mitigation and Adaptation Strategies for Global Change* 12, no. 1 (2007): 33–53, https://doi.org/10.1007/s11027-006-9046-5.

[41] Xianli Wang et al., "Increasing Frequency of Extreme Fire Weather in Canada with Climate Change," *Climatic Change* 130, no. 4 (2015): 573–86, https://doi.org/10.1007/s10584-015-1375-5.

[42] Whitman et al., "Short-Interval Wildfire and Drought Overwhelm Boreal Forest Resilience."

Fire climate

Climate, being an averaged description of weather conditions, has a longer-term influence on fire conditions than weather. Climate impacts wildfire through vegetation productivity and distribution (fuel build-up), fire season duration, and drought occurrence. Extended warm seasons may result in an increased growth season, which can increase fuel loads and result in more periods of dry conditions that are susceptible to fire when weather conditions are right. The majority of area burned occurs during periods of drought, which are brought about by temperature fluctuations.[43] This explains why there is significant interannual variation in the area burned each year in Canada, ranging from less than 0.5 million hectares per year to more than 7.5 million hectares per year.[44]

Ecosystem Effect of Fire

The boreal forest shapes, and is shaped by, fire. This occurs through its species makeup, composition of forest structure, and **mosaic**[45] of ecosystems.[46] Different forest types interact in varied ways with fire; first as fire fuel, and then through regrowth post-fire, with different species exhibiting different adaptations to fire (e.g., serotiny of jack pine or aspen regeneration through suckering). Fires have historically varied in size, intensity, duration, and seasonality, which has created mosaics within the forest that limited the extent of stand-replacing fires and other disturbances, such as insect outbreaks. Due to the pattern of fire in the boreal, the mosaic that was created featured large burn areas, with small burns within and around them.

Although the boreal forest is a stand-replacing fire regime, this does not mean that a fire will result in complete mortality for stands within a burn area. Partial mortality and unburned areas within a fire perimeter are common, and probably a result of varying fire severities.[47] Small patches of surviving old growth trees are also present within this mosaic.[48] One study found remnants averaging 41% of the area burned in boreal-shield fires, which suggests that lower intensity burning, similar to a surface area, occurred during stand-replacing fire events.[49] Fires may appear to burn large swaths of forest; however, local and micro-climate conditions, along with natural fire barriers within forest stands, may alter a fire's burn area. The result is a patchiness of burn

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[43] San-Miguel et al., "What Controls Fire Spatial Patterns? Predictability of Fire Characteristics in the Canadian Boreal Plains Ecozone"; Whitman et al., "Short-Interval Wildfire and Drought Overwhelm Boreal Forest Resilience."

[44] Flannigan et al., "Impacts of Climate Change on Fire Activity and Fire Management in the Circumboreal Forest."

[45] An interspersed pattern of different ecosystem patches that may feature different age-classes and species.

[46] Johnson, Miyanishi, and Weir, "Wildfires in the Western Canadian Boreal Forest: Landscape Patterns and Ecosystem Management"; K Miyanishi, S. R. J. Bridge, and E. A. Johnson, "Wildfire Regime in the Boreal Forest and the Idea of Suppression and Fuel Buildup," *Conservation Biology* 15, no. 6 (2001), https://doi.org/10.1046/j.1523-1739.2002.16502.x; Rowe and Scotter, "Fire in the Boreal Forest."

[47] San-Miguel et al., "What Controls Fire Spatial Patterns? Predictability of Fire Characteristics in the Canadian Boreal Plains Ecozone."

[48] Johnson, Miyanishi, and Weir, "Wildfires in the Western Canadian Boreal Forest: Landscape Patterns and Ecosystem Management"; Miyanishi, Bridge, and Johnson, "Wildfire Regime in the Boreal Forest and the Idea of Suppression and Fuel Buildup."

[49] David W Andison, "Wildfire Patterns in Western Boreal Canada: Healthy Landscapes Research Series Report No. 8," no. 8 (2013): 140.

consistency; some areas may burn completely, while others may contain pockets or strips of surviving vegetation. This results in the variation of ecosystems, stand age-classes, and species that are found in, and contribute to, the healthy functioning of the boreal landscape.

1.3. Climate Change Effects on Wildfire

Fire Weather

Climate change is now the most significant anthropogenic influence on the boreal forest and its fire regime. The fire regime is already being impacted by climate change, with the effects on fire weather being particularly noticeable. Polar amplification is causing temperatures in the boreal forest to rise at nearly twice the global average.[50]

Extreme fire risk is increasing, with an estimated increase of 1.5 to 6 times in western Canada in the last decade.[51] Fire weather indices are expected to rise for the majority of the boreal forest (with some exceptions in the eastern boreal forest), and this change is amplified by different climate change scenarios.[52] Temperature increases also result in drier fuel conditions, which increases flammability. Lightning strikes are expected to increase with weather changes, and increasing drought frequencies and fire-conducive weather patterns mean that lightning fires are expected to continue to increase.[53] As lightning fires burn the largest total area, this will contribute to the increasing area burned.

Using climate models, it is expected that in Manitoba the average number of extreme fire weather days (those days when most high fire spread occurs) will increase from 7 (in the 2010s) to 18 (in the 2080s).[54] It is anticipated that climate change will extend the fire seasons in Canada, though there is a suggestion that in Manitoba the season could become shorter.[55]

Area Burned

Anthropogenic climate change, resulting in warmer temperatures, is causing an increase in the area burned by fire in Canadian forests.[56] The area burned has nearly doubled in boreal forests in the

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[50] Carly A Phillips et al., "Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management," *Sci. Adv*, vol. 8, 2022, https://www.science.org.

[51] Sean C.P. Coogan et al., "Scientists' Warning on Wildfire — a Canadian Perspective," *Canadian Journal of Forest Research* 49, no. 9 (2019): 1015–23, https://doi.org/10.1139/cjfr-2019-0094.

[52] Flannigan et al., "Implications of Changing Climate for Global Wildland Fire"; Wang et al., "Increasing Frequency of Extreme Fire Weather in Canada with Climate Change."

[53] Hanes et al., "Fire-Regime Changes in Canada over the Last Half Century"; Lavorel et al., "Vulnerability of Land Systems to Fire: Interactions among Humans, Climate, the Atmosphere, and Ecosystems"; B. M. Wotton, C. A. Nock, and M. D. Flannigan, "Forest Fire Occurrence and Climate Change in Canada," *International Journal of Wildland Fire* 19, no. 3 (2010): 253–71, https://doi.org/10.1071/WF09002.

[54] Wang et al., "Increasing Frequency of Extreme Fire Weather in Canada with Climate Change."

[55] Hanes et al., "Fire-Regime Changes in Canada over the Last Half Century."

[56] N. P. Gillett et al., "Detecting the Effect of Climate Change on Canadian Forest Fires," *Geophysical Research Letters* 31, no. 18 (2004), https://doi.org/10.1029/2004GL020876.

past 60 years, with large fires having doubled in frequency over the past 57 years.[57] One model that used projections of annual mean temperature and climate moisture index projected the annual area burned in northern Manitoba to exceed 10% of the boreal forest land base in 2071-2100.[58] This would mean the area burned annually would exceed the area burned during the most severe fire season recorded in Manitoba, 1989 fire season, when 9% of Manitoba's forested area was burned.[59] Area burned would increase by ⅓ under a $2xCO_2$ climate change scenario, but could double under a $3xCO_2$ scenario.[60]

Peatlands

Peatlands are expected to be at increased risk of fire as a result of climate.[61] This is due to high temperatures and increasing drought conditions drying peatlands; making them more susceptible to ignition and increased fire severity (burn depth).[62] In addition, wildfires can cause permafrost in peatlands to melt, which can contribute to drying and the release of greenhouse gases.[63] As peatlands perform a vital role in carbon sequestration, peatland vulnerability to fire under climate change is of particular concern.

Vegetation Patterns and Regrowth

Climate change is anticipated to influence future vegetation patterns. In the boreal forest, this will occur through increasing droughts, fires, and tree mortality.[64] As the annual area burned and fire severity increases, this will have impacts on regrowth, particularly if burns destroy seedbeds, or reburns occur before new seeds are produced in that area. Extreme fire conditions that can overcome fuel load limitations when combined with increasing fire frequency may increase the probability of fires that occur before young stands mature enough to produce adequate seeds for stand regeneration.[65]

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[57] Phillips et al., "Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management"; Hanes et al., "Fire-Regime Changes in Canada over the Last Half Century."

[58] Dominique Boucher et al., "How Climate Change Might Affect Tree Regeneration Following Fire at Northern Latitudes: A Review," *New Forests* 51, no. 4 (2020): 543–71, https://doi.org/10.1007/s11056-019-09745-6.

[59] Hirsch, K. G., "A chronological overview of the 1989 fire season in Manitoba," *The Forestry Chronicle*, *67*(4) (1991), 358–365. https://doi.org/10.5558/tfc67358-4

[60] Flannigan et al., "Implications of Changing Climate for Global Wildland Fire."

[61] Flannigan et al.; Turetsky et al., "Global Vulnerability of Peatlands to Fire and Carbon Loss."

[62] K. Nelson et al., "Peatland-Fire Interactions: A Review of Wildland Fire Feedbacks and Interactions in Canadian Boreal Peatlands," *Science of the Total Environment* (Elsevier B.V., May 15, 2021), https://doi.org/10.1016/j.scitotenv.2021.145212.

[63] Carolyn M. Gibson et al., "Wildfire as a Major Driver of Recent Permafrost Thaw in Boreal Peatlands," *Nature Communications* 9, no. 1 (2018), https://doi.org/10.1038/s41467-018-05457-1.

[64] Diana Stralberg et al., "Wildfire-Mediated Vegetation Change in Boreal Forests of Alberta, Canada," *Ecosphere* 9, no. 3 (2018), https://doi.org/10.1002/ECS2.2156.

[65] Whitman et al., "Short-Interval Wildfire and Drought Overwhelm Boreal Forest Resilience"; Boucher et al., "How Climate Change Might Affect Tree Regeneration Following Fire at Northern Latitudes: A Review."

Climate change's increasing temperature and drought frequency could impair post-fire recruitment (regrowth) for important boreal tree species; for instance, black spruce is susceptible to drought.[66] In some areas of the boreal forest, deciduous species have been seen to have improved postfire recruitment at the expense of coniferous species.[67] Regeneration failures after fire are anticipated, which could lead to a change from a closed-canopy forest to open woodlands.[68] As areas frequently burn, young growth increases, which is less susceptible to fire, and some areas will become more deciduous dominated.[69] One study from Alberta concluded that increasing wildfire activity could result in the conversion of half of Alberta's upland mixedwood and conifer forest to deciduous woodland and grasslands by 2100.[70]

Vegetation changes that increase the proportion of deciduous trees relative to coniferous trees may result in wildfire fuel limitations (i.e., a decrease in vegetation susceptible to fire).[71] This suggests that while fire regimes are expected to increase in frequency and intensity in the short term, there is some uncertainty about how vegetation changes under climate change will impact the fire regime in the long term. However, another study focused on paleoecology found that the boreal forest has experienced significant changes to the fire regime in the past, and yet the boreal forest, and its species composition, has remained resilient to these changes. However, the uncertainty brought about by the cumulative effect of climate change may overwhelm this resiliency.[72]

1.4. Conclusion

The boreal forest's fire regime has been shaped by human activity for millennia, first through Indigenous burning practices, then through colonial fire suppression, and now through anthropogenic climate change. While this fire regime is essential to the healthy functioning of the boreal forest, the increased frequency of large fires and area burned has the potential to alter the ecosystem. Large fires driven by extreme fire weather conditions will burn more area, and increased fire severity may burn more deeply in peatlands, thereby affecting permafrost. Deciduous and mixedwood forests could become more prevalent as they replace coniferous forests impacted by drought and successive fires. Thus, an altered fire regime has the potential to change the structure and type of forest found in the northern regions of Manitoba as well as carbon absorption and storage capacity.

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[66] Jennifer L Baltzer et al., "Increasing Fire and the Decline of Fire Adapted Black Spruce in the Boreal Forest," 2021, 1–9, https://doi.org/10.1073/pnas.2024872118/-/DCSupplemental.Published.

[67] Boucher et al., "How Climate Change Might Affect Tree Regeneration Following Fire at Northern Latitudes: A Review."

[68] Sylvie Gauthier et al., "Climate Change Vulnerability and Adaptation in the Managed Canadian Boreal Forest1," *Environmental Reviews* 22, no. 3 (2014): 256–85, https://doi.org/10.1139/er-2013-0064.

[69] Stralberg et al., "Wildfire-Mediated Vegetation Change in Boreal Forests of Alberta, Canada"; Sarah J. Hart et al., "Examining Forest Resilience to Changing Fire Frequency in a Fire-Prone Region of Boreal Forest," *Global Change Biology* 25, no. 3 (2019): 869–84, https://doi.org/10.1111/gcb.14550.

[70] Stralberg et al., "Wildfire-Mediated Vegetation Change in Boreal Forests of Alberta, Canada."

[71] Stralberg et al.

[72] Martin P. Girardin, Adam A. Ali, and Christelle Hély, "Wildfires in Boreal Ecosystems: Past, Present and Some Emerging Trends," *International Journal of Wildland Fire* 19, no. 8 (2010): 991–95.

Chapter 2: Carbon and Wildfire in the Boreal Forest

Boreal forests have a global importance in carbon cycling, as these ecosystems are estimated to store one-third of the global terrestrial carbon (Zhao 2021). Kurz et al. (2013) estimated that Canada's managed boreal forest, which comprises 54% of the total boreal forest area, stores 28 Petagrams (i.e., 28 billion metric tons) of carbon in biomass, dead organic matter and soil pools. When considering options for forest carbon management, it is essential to understand the effects of wildfire and its changing patterns, caused by human-induced climate change, on carbon in the boreal forest. This chapter will first provide a brief overview of carbon dynamics and carbon stocks in the boreal forest, before focusing primarily on how fire affects carbon.

2.1. Carbon in the Boreal Forest

Carbon Balance

The carbon balance in the boreal forest is dynamic and primarily determined by the difference between two continuous processes: the uptake of CO_2 through **net primary production** (photosynthesis)[73] and the release of CO_2 during heterotrophic respiration (decomposition). Carbon is then stored in 3 main pools: 25% of carbon is stored in biomass (above- and below-ground), 35% in dead organic matter (snags, downed dead wood, fallen leaves, branches, litter, soil organic horizons), and 40% in organic carbon in mineral soil (below the soil organic horizons).[74] The carbon balance is further affected by carbon fluxes resulting from disturbances such as fire, insects and harvesting.[75]

At the forest **stand-level**[76], the difference between net primary production and heterotrophic respiration is called net ecosystem production (NEP), which is expressed through units of carbon per unit time. A positive NEP value indicates that the ecosystem is sequestering carbon, meaning that it is taking in more CO_2 through photosynthesis than it is releasing through respiration and decomposition. On the other hand, a negative NEP value indicates that the ecosystem is a net source of CO_2, meaning that it is releasing more CO_2 through respiration and decomposition than it is taking in through photosynthesis.

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[73] Net primary production is the carbon flux determined by total photosynthesis minus respiration of primary producers.

[74] W. A. Kurz et al., "Carbon in Canada's Boreal Forest-A Synthesis," *Environmental Reviews* (Canadian Science Publishing, 2013), https://doi.org/10.1139/er-2013-0041.

[75] Fire is the primary driver but not the only disturbance causing fluxes and impacting the carbon balance of the Boreal forest. Insect disturbances also play a role in tree mortality and adding to dead organic matter. Forest management activities affect the carbon budget through harvesting, site preparation, planting and the suppression of disturbances such as fire and insects. Harvesting transfers carbon from the forest to society through the provision of timber forest products. In the northern boreal forest Manitoba, much of the products are Kraft paper which has a shorter carbon lifespan comparative to other timber products.

[76] In forestry, stands are used to describe a unit in a particular area that can be identified by the species of trees present, the age and size of the trees, the presence of understory plants, and the overall structure within that unit.

NEP and carbon storage is affected by a variety of different factors including species composition, growth rate, and stand age. Species composition affects the NEP and carbon storage. For example, net primary productivity and carbon stocks have been found to be higher in mixedwood than in coniferous stands.[77] Growth rate generally affects NEP, with faster growth rates attributable to warmer growing conditions, resulting in an increased NEP. Age class affects NEP and carbon storage with young stands featuring increasing NEP, middle-aged stands are at their peak NEP, and old stands seeing a decline in NEP but reaching a maximum carbon storage level. Eventually, old stands exceed their carbon storage capacity, as dying trees contribute to dead organic matter and more decomposition occurs releasing carbon.[78]

Storage: Soils and Peatlands

The boreal forest is able to store significant amounts of carbon because of slow decomposition rates that are a result of cold and wet conditions. For this reason, the largest stores of carbon in the boreal forest are found in boreal soils and in wetlands/peatlands.[79] Boreal forest soils store a large amount of soil organic carbon, due to the extensive roots, woody biomass, and leaf litter which accumulate over time. Low temperatures mean that this organic carbon is slowly mineralized and the carbon in mineral soil, found below the organic horizons, remains relatively stable despite different stand characteristics and disturbance histories.[80] A study of jack pine and black spruce stands found an average carbon pool of 13.81 kg C/m^2 (kilograms of carbon per metre squared), with an average of 11.95 kg C/m^2 found in soil organic matter.[81]

It has been estimated that peatlands in the boreal forest store over half of Canada's soil carbon, while only comprising 12% of the land area.[82] Boreal peatlands are estimated to contain between 28.3-68.8 kg C/m^2, with the majority located in the soil organic layer (22.6-66.0 kg C/m^2).[83] Carbon is accumulated because the wet and cold conditions in these wetlands slows decomposition which allows for the organic matter (peat) to accumulate over extremely long time scales (millenniums).[84]

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[77] Payne et al., "Carbon Storage and Net Primary Productivity in Canadian Boreal Mixedwood Stands."

[78] Kurz et al., "Carbon in Canada's Boreal Forest-A Synthesis"; Payne et al., "Carbon Storage and Net Primary Productivity in Canadian Boreal Mixedwood Stands."

[79] Thomas H. DeLuca and Celine Boisvenue, "Boreal Forest Soil Carbon: Distribution, Function and Modelling," *Forestry* (Oxford University Press, 2012), https://doi.org/10.1093/forestry/cps003; Chun Lan Han et al., "Changes of Soil Organic Carbon after Wildfire in a Boreal Forest, Northeast China," *Agronomy* 11, no. 10 (October 1, 2021), https://doi.org/10.3390/agronomy11101925.

[80] DeLuca and Boisvenue, "Boreal Forest Soil Carbon: Distribution, Function and Modelling"; Payne et al., "Carbon Storage and Net Primary Productivity in Canadian Boreal Mixedwood Stands"; Han et al., "Changes of Soil Organic Carbon after Wildfire in a Boreal Forest, Northeast China."

[81] Xanthe J. Walker et al., *Cross-Scale Controls on Carbon Emissions from Boreal Forest Megafires*, *Global Change Biology*, vol. 24, 2018, https://doi.org/10.1111/gcb.14287.

[82] Nelson et al., "Peatland-Fire Interactions: A Review of Wildland Fire Feedbacks and Interactions in Canadian Boreal Peatlands."

[83] Joannie Beaulne et al., "Peat Deposits Store More Carbon than Trees in Forested Peatlands of the Boreal Biome," *Scientific Reports* 11, no. 1 (2021): 1–11, https://doi.org/10.1038/s41598-021-82004-x.

[84] Carlson et al., "Maintaining the Role of Canada's Forests and Peatlands in Climate Regulation."

Disturbances

Disturbances (e.g., fire, insects, harvesting, peat mining) in the boreal forest can lead to a brief intense flux (or burst) of CO_2 emissions, followed by a tail of increased decomposition as dead organic material decomposes. Over time, decomposition is offset by new growth which eventually overcomes the CO_2 release, resulting in increased net ecosystem production (more CO_2 is absorbed than released). Net ecosystem production is lowest in the years immediately following a disturbance and increases to a maximum for middle-aged stands.[85] Fire disturbance effects on carbon will be described in more detail in Chapter 2.2.

Landscape-level Carbon Balance

Determining the **landscape-level**[86] carbon balance requires accounting for the heterogeneity of the boreal forest landscape by adding together the differing stand-level NEP (based on species composition, age class and growth rates) and significant carbon stores (e.g. peatlands), and then subtracting emissions from disturbances.[87] Given that disturbance events occur rarely and sporadically at the stand-level, this landscape-level analysis is necessary when managing for disturbance events such as fire. Disturbances in the boreal affect the carbon cycle at a landscape-level; this poses a challenge for natural climate solutions for wildfire emissions, as forest management typically operates at a stand-level.

2.2. Wildfire Effects on Carbon Cycle and Carbon Balance

Describing and quantifying the effects of wildfire on the carbon cycle is a complex and rapidly evolving area of research. Differing models and research foci appear to draw conflicting conclusions regarding whether fire results in the forest becoming a carbon source[88] or sink.[89] Making these kinds of determinations requires accounting for the carbon emissions from wildfire, carbon legacies from fire, and post-fire recovery.[90] A further complicating factor within this is ecosystem heterogeneity, which means that different areas within the boreal forest will have different kinds of fires, emission rates, carbon legacies, and post-fire recovery.[91]

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[85] Kurz et al., “Carbon in Canada’s Boreal Forest-A Synthesis.”

[86] As described by Kurz et al. (2013) the boreal landscape is made up of various stands of trees with different ages, past disturbances, and species that grow in a variety of site conditions.

[87] Kurz et al., “Carbon in Canada’s Boreal Forest-A Synthesis.”

[88] Phillips et al., “Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management”; Zhao et al., “North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016.”

[89] C. Yue et al., “How Have Past Fire Disturbances Contributed to the Current Carbon Balance of Boreal Ecosystems?,” *Biogeosciences* 13, no. 3 (2016): 675–90, https://doi.org/10.5194/bg-13-675-2016; Simon P.K. Bowring et al., “Pyrogenic Carbon Decomposition Critical to Resolving Fire’s Role in the Earth System,” *Nature Geoscience* 15, no. 2 (2022): 135–42, https://doi.org/10.1038/s41561-021-00892-0.

[90] David M.J.S. Bowman et al., “Vegetation Fires in the Anthropocene,” *Nature Reviews Earth and Environment* 1, no. 10 (2020): 500–515, https://doi.org/10.1038/s43017-020-0085-3; Jeffrey E. Stenzel et al., “Fixing a Snag in Carbon Emissions Estimates from Wildfires,” *Global Change Biology* 25, no. 11 (2019): 3985–94.

[91] Walker et al., *Cross-Scale Controls on Carbon Emissions from Boreal Forest Megafires*; Guillermo Rein and Xinyan Huang, “Smouldering Wildfires in Peatlands, Forests and the Arctic: Challenges and Perspectives,” *Current Opinion in Environmental Science and Health* 24 (2021): 100296, https://doi.org/10.1016/j.coesh.2021.100296.

Wildfire Emissions

Following a wildfire in the boreal, there is an immediate release of carbon as biomass and organic matter is combusted. Estimates of the total amount of carbon emissions vary across models and time periods, but a recent study estimated direct carbon emissions from Canada between 1986-2016 was 49.9 Teragrams C/year.[92] This initial pulse of carbon is primarily composed of CO_2, though a variety of compounds, such as black carbon, are also emitted.[93] There is variation in how much carbon is released through combustion because of stand composition. Black spruce stands with intermediate drainage conditions contribute the most to carbon emissions through fire.[94] One way of estimating carbon emission loss is calculating the carbon emissions per metre square within burn areas, with models finding averages ranging from 1.3 kg C/m^2 to 3.35 kg C/m^2.[95] Some recent studies suggest that there appears to be a negligible effect of forest fires on methane (CH4) fluxes or a slight increase in the uptake of CH4 from soil organic matter.[96]

Burn severity plays a role in determining the primary source of combustion carbon emissions. Low severity fires result primarily in vegetation combustion with little soil organic matter combustion (living and dead plants on the surface of the ground will burn, but the fire does not burn deep). Severe fires result in emissions primarily through the combustion of soil organic matter (the accumulation of plant matter below the surface of the soil).[97] One thing to note is that emissions resulting from the combustion of the duff, litter, and small downed wood that make up soil organic matter, would likely have occurred as that matter decomposed, resulting in heterotrophic respiration. When fire burns duff it releases carbon immediately, as opposed to the slow release of carbon through decomposition.[98] Meanwhile fire does not appear to impact carbon stock in mineral soils found below the soil organic horizon significantly.[99]

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[92] Zhao et al., “North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016.”

[93] B.D. Amiro et al., “Direct Carbon Emissions from Canadian Forest Fires, 1959-1999,” *Canadian Journal of Forest Research* 31, no. 3 (2001): 512–25, https://doi.org/10.1139/cjfr-31-3-512; Phillips et al., “Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management.”

[94] Walker et al., *Cross-Scale Controls on Carbon Emissions from Boreal Forest Megafires*.

[95] W. A. Kurz et al., “The Carbon Budget of the Canadian Forest Sector: Phase I,” *Simulation*, 1993, https://doi.org/10.1177/003754979306100206; Amiro et al., “Direct Carbon Emissions from Canadian Forest Fires, 1959-1999”; Walker et al., *Cross-Scale Controls on Carbon Emissions from Boreal Forest Megafires*; Phillips et al., “Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management.”

[96] Christine Ribeiro-Kumara et al., “How Do Forest Fires Affect Soil Greenhouse Gas Emissions in Upland Boreal Forests? A Review,” *Environmental Research* 184 (May 1, 2020), https://doi.org/10.1016/j.envres.2020.109328.

[97] Han et al., “Changes of Soil Organic Carbon after Wildfire in a Boreal Forest, Northeast China”; Zhao et al., “North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016.”

[98] John Campbell et al., “Pyrogenic Carbon Emission from a Large Wildfire in Oregon, United States,” *Journal of Geophysical Research: Biogeosciences* 112, no. 4 (December 28, 2007), https://doi.org/10.1029/2007JG000451.

[99] M. Palviainen et al., “Decadal-Scale Recovery of Carbon Stocks After Wildfires Throughout the Boreal Forests,” *Global Biogeochemical Cycles* 34, no. 8 (2020): 10–15, https://doi.org/10.1029/2020GB006612.

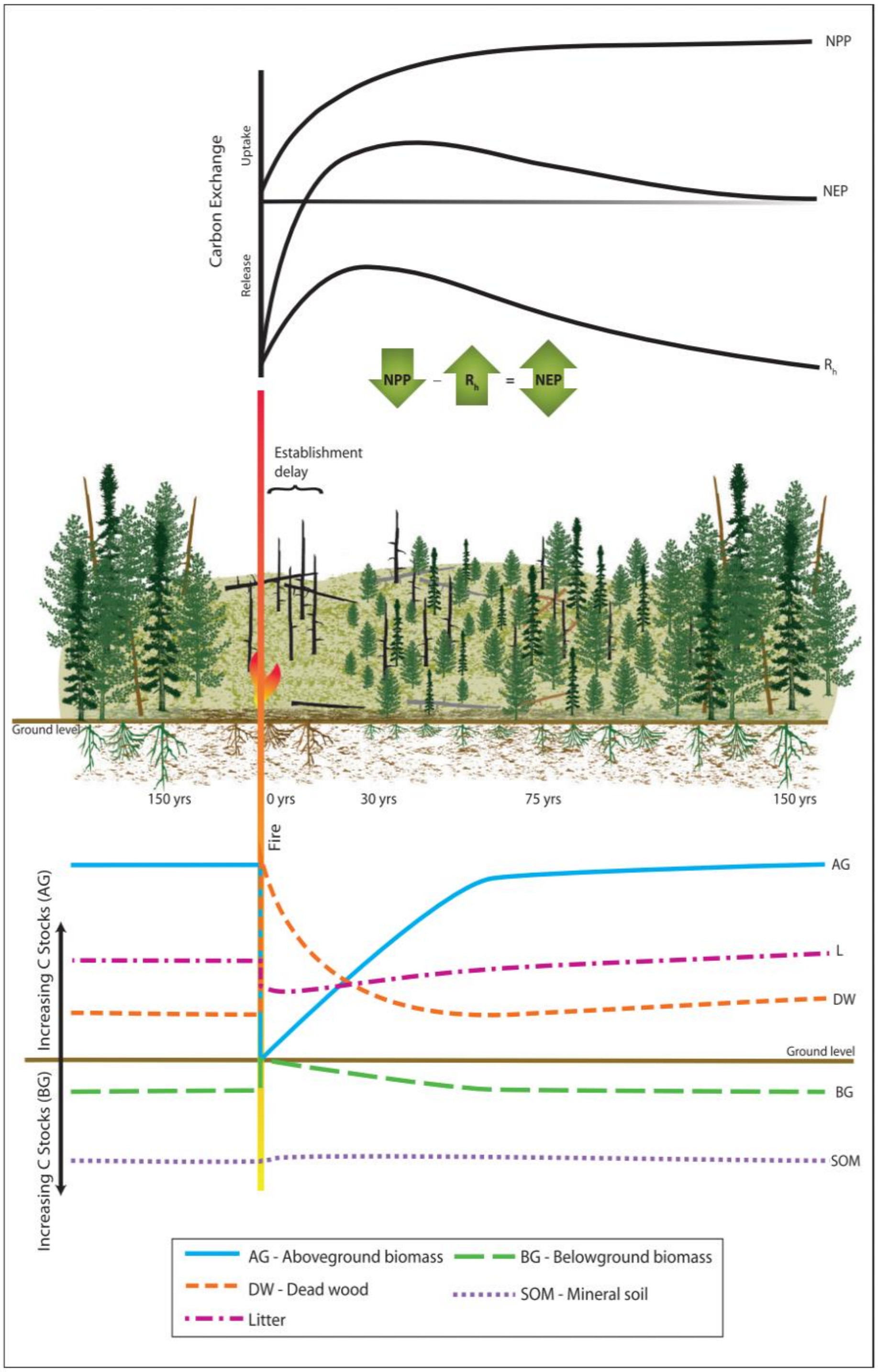

Figure 3: Generalized schematic of the carbon dynamics of boreal forest, including: fire disturbance; Net Primary Production (NPP); Net Ecosystem Production (NEP); Heterotrophic Respiration (R_h). From: Kurz et al., "Carbon in Canada's Boreal Forest- A Synthesis"

Despite the rapid release of carbon from combustion, the majority of carbon emissions has been thought to occur after a fire, as fire-killed vegetation decomposes and releases carbon through the heterotrophic and autotrophic respiration (i.e. decomposition).[100] However, this assumption is being challenged because the rate at which carbon is released through heterotrophic and autotrophic respiration is impacted by burn severity.[101] The rate of heterotrophic and autotrophic respiration has been found to decrease following a fire, as decomposition is slowed due to the fire effect on microbial activity.[102] This means that lower carbon emissions are expected from a recently burned site than an unburned site.[103]

Smouldering fires

To date, most wildfire science has focussed on analyzing and mitigating flaming wildfires (the large flaming fire fronts often shown in news broadcasts); however, there is evidence that smouldering wildfires are a significant contributor to carbon emissions.[104] Smouldering combustion is the slow, low temperature, and flameless burning of fuels, which can occur in peatlands and in remaining forest fuels after the flames of a forest fire have passed. Smouldering of solid forest fuels following a flaming wildfire could be responsible for consuming 50% of the biomass burned. Peatland smouldering fires are responsible for a significant amount of carbon loss, with some estimates suggesting that peat fires can release greenhouse gases equivalent to >15% of anthropogenic emissions.[105] It is estimated that the average emissions from peatland fires was 7.1 kg C/m^2 in 2015, which is expected to increase to 12.8 kg C/m^2 in 2050 and 27.2 kg C/m^2 in 2100 as climate change results in fires burning deeper in peatlands.[106] In addition to carbon emissions, peatland fires release significant amounts of carbon monoxide and methane as well as other emissions that are harmful to human health. In the boreal forest, bog peatlands are a significant store of carbon, including ancient carbon.[107]

There are additional factors that contribute to carbon loss from wildfires. Fires in the boreal forest combust biomass and soil. The degradation of organic soil results in less insulation, which causes

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[100] Kurz et al., "Carbon in Canada's Boreal Forest-A Synthesis."

[101] Caius Ribeiro-Kumara et al., "Short-to Medium-Term Effects of Crown and Surface Fires on Soil Respiration in a Canadian Boreal Forest," *Canadian Journal of Forest Research* 52, no. 4 (2022): 591–604, https://doi.org/10.1139/cjfr-2021-0354; Zhao et al., "North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016."

[102] Julia Kelly et al., "Boreal Forest Soil Carbon Fluxes One Year after a Wildfire: Effects of Burn Severity and Management," *Global Change Biology* 27, no. 17 (September 1, 2021): 4181–95, https://doi.org/10.1111/gcb.15721; Christine Ribeiro-Kumara et al., "Long-Term Effects of Forest Fires on Soil Greenhouse Gas Emissions and Extracellular Enzyme Activities in a Hemiboreal Forest," *Science of the Total Environment* 718 (May 20, 2020), https://doi.org/10.1016/j.scitotenv.2019.135291; Ribeiro-Kumara et al., "Short-to Medium-Term Effects of Crown and Surface Fires on Soil Respiration in a Canadian Boreal Forest."

[103] Ribeiro-Kumara et al., "How Do Forest Fires Affect Soil Greenhouse Gas Emissions in Upland Boreal Forests? A Review."

[104] Rein and Huang, "Smouldering Wildfires in Peatlands, Forests and the Arctic: Challenges and Perspectives."

[105] Rein and Huang.

[106] Shaorun Lin, Yanhui Liu, and Xinyan Huang, "Climate-Induced Arctic-Boreal Peatland Fire and Carbon Loss in the 21st Century," *Science of the Total Environment* 796, no. July (2021), https://doi.org/10.1016/j.scitotenv.2021.148924.

[107] Nelson et al., "Peatland-Fire Interactions: A Review of Wildland Fire Feedbacks and Interactions in Canadian Boreal Peatlands."

permafrost to thaw and release stored carbon.[108] Fires can increase soil temperature for several years due to reduced insulation (the loss of organic matter); increased solar radiation (shade removal); and decrease in surface albedo (decreased reflectivity of solar energy due to the blackening of ground and loss of plant material). In areas with permafrost, a fire will increase the depth of the active layer for 3-5 years before vegetation regenerates, allowing for a return to pre-fire conditions.[109]

Carbon Legacies

Wildfire carbon emissions are calculated using simulated models that often overestimate CO_2 emissions. A study of these models showed that they often failed to account for standing dead tree carbon pools (snags left behind after fires) and as a result, these models consistently overestimated the pulse of fire CO_2 emissions by 285%-486%. Thirty years post-fire, these models still exceeded the observation-based model by 39%-1010%. On average, most models overestimated emissions compared to an observation-based model by 150% to 130%.[110] The takeaway from these models and observations is that many estimates of wildfire carbon emissions have been exaggerated. The over-estimation of carbon emissions is partly a result of overlooking the carbon-based products of wildfire combustion. These products, known as pyrogenic carbon, result from biomass that chars, making it much more resistant to decomposition and oxidation.[111]

Pyrogenic carbon legacies following a fire include burnt snags, soil organic matter that does not fully combust, and charcoal. Burnt snags are considered to be of significant importance for calculating carbon emissions from wildfire, because while the bulk of wildfire emissions are attributed to post-fire decomposition, standing burnt snags decompose at a much slower rate than a fallen dead tree.[112] Soil organic matter that does not burn continues to accumulate, while incomplete combustion of some biomass can thermally alter some materials, making them significantly more resistant to decomposition, which lengthens the amount of time it would take for carbon to be released through heterotrophic respiration.[113] An example of pyrogenic material in soil is charcoal; about 10% of woody biomass is converted to charcoal in a fire. Charcoal is extremely stable and may resist decomposition for thousands of years, although it may be consumed by future fires if it has not had the time to mix into the mineral soil layer.[114] Shortened fire return intervals could result in increased combustion of charcoal, which impacts carbon accumulation.

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[108] Zhao et al., “North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016.”
[109] Ribeiro-Kumara et al., “Long-Term Effects of Forest Fires on Soil Greenhouse Gas Emissions and Extracellular Enzyme Activities in a Hemiboreal Forest.”
[110] Stenzel et al., “Fixing a Snag in Carbon Emissions Estimates from Wildfires.”
[111] Bowring et al., “Pyrogenic Carbon Decomposition Critical to Resolving Fire’s Role in the Earth System.”
[112] Stenzel et al., “Fixing a Snag in Carbon Emissions Estimates from Wildfires.”
[113] Ribeiro-Kumara et al., “How Do Forest Fires Affect Soil Greenhouse Gas Emissions in Upland Boreal Forests? A Review.”
[114] DeLuca and Boisvenue, “Boreal Forest Soil Carbon: Distribution, Function and Modelling.”

Rate of Carbon Recovery

Fires emit carbon and reduce carbon stocks in the short term; but, through post-fire regrowth, there is a gradual recovery of carbon stocks.[115] Many factors, such as fire intensity, stand composition, management history, amount of carbon combusted, and rate of reforestation, determine how quickly this carbon recovery can occur.[116] Fire severity can affect regeneration; in some cases high severity fires can prime the seed bed and lead to increased regrowth. In others, it can destroy organic matter and seeds; black spruce in particular are susceptible to regeneration failures.[117]

It is estimated that boreal forests recover their positive Net Ecosystem Productivity (where carbon uptake exceeds heterotrophic respiration) about 10 years after a fire, though some studies suggest this may take longer.[118] Some models suggested that ecosystem regrowth took 14 years post-fire to begin carbon sequestration, and took 150 years for carbon accumulation to roughly equal the initial pulse of wildfire emissions.[119] Another study found that in severe stand-replacing fires, carbon stocks declined by over 80%, but this was followed by fast accumulation for the following 50 years, with 90% of the ecosystem carbon maximum reached by 60 years.[120] A study in the boreal forest of China found that after wildfire, soil organic carbon stocks were reduced and had not recovered to original levels within 25 years, suggesting that the sequestration ability of soil was decreased following fire events. This was particularly pronounced in severe wildfires, where more of the surface level organic carbon was consumed.[121] What this means is that the boreal forest requires long fire return rates (between 80-150 years) in order to recover the carbon lost from high-severity fires.

Long-term Legacy of Fire-driven Ecosystem

The different processes that impact carbon during a fire event, and the subsequent recovery, balance the carbon emissions from fire, which contribute to the long-term carbon sink that exists in boreal forests.[122] Climate change may threaten the long-term viability of the boreal forest as a

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[115] Palviainen et al., “Decadal-Scale Recovery of Carbon Stocks After Wildfires Throughout the Boreal Forests.”

[116] Alana J. Clason, Ingrid Farnell, and Erica B. Lilles, “Carbon 5–60 Years After Fire: Planting Trees Does Not Compensate for Losses in Dead Wood Stores,” *Frontiers in Forests and Global Change* 5, no. June (2022): 1–18, https://doi.org/10.3389/ffgc.2022.868024.

[117] Baltzer et al., “Increasing Fire and the Decline of Fire Adapted Black Spruce in the Boreal Forest”; Dominic Cyr et al., “Mitigating Post-Fire Regeneration Failure in Boreal Landscapes with Reforestation and Variable Retention Harvesting: At What Cost?,” *Canadian Journal of Forest Research* 52, no. 4 (2022): 568–81, https://doi.org/10.1139/cjfr-2021-0180.

[118] Ribeiro-Kumara et al., “Short-to Medium-Term Effects of Crown and Surface Fires on Soil Respiration in a Canadian Boreal Forest”; Palviainen et al., “Decadal-Scale Recovery of Carbon Stocks After Wildfires Throughout the Boreal Forests.”

[119] Phillips et al., “Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management.”

[120] Palviainen et al., “Decadal-Scale Recovery of Carbon Stocks After Wildfires Throughout the Boreal Forests.”

[121] Han et al., “Changes of Soil Organic Carbon after Wildfire in a Boreal Forest, Northeast China.”

[122] Yue et al., “How Have Past Fire Disturbances Contributed to the Current Carbon Balance of Boreal Ecosystems?”; Ribeiro-Kumara et al., “How Do Forest Fires Affect Soil Greenhouse Gas Emissions in Upland Boreal Forests? A Review.”

carbon sink, as some studies suggest that emissions from wildfires in recent years have resulted in the boreal forest acting as a carbon source.[123]

2.3 Future Climate Change Wildfire and Carbon Emissions

As described in Chapter 1.3, climate change is already impacting the boreal forest's wildfire regime, resulting in a longer fire season, increasing wildfire occurrence, more severe fires, and more area burned. Climate change is also making important carbon pools (such as peatlands) more susceptible to wildfire, because of more frequent and extreme drought conditions. These changes to the wildfire regime will have an impact on the carbon balance of the boreal forest.

More active fire regimes are likely to result in increased fire emissions, with some estimates suggesting that fire emissions could double under a climate change scenario where CO_2 concentrations increase threefold.[124] Another study found that increasing the area burned by a factor of three (e.g., from 10% of the forest to 30% of the forest) only decreased the total amount of carbon stored in the forest by 6% over a 100-year period. However, the study also noted that having several years in a row with a lot of fires can significantly decrease the amount of carbon stored in the forest, and in some cases, even cause the forest to release more carbon into the atmosphere than it stores.[125] Increased burn severity will result in increased emissions from boreal soil, which could affect soil carbon storage.[126]

Climate change will result in increasing fire emissions from peatlands, with the emissions being dependent on the amount of warming that occurs. It was found that if the temperature in the boreal region continues to increase at a rate of 0.44°C per decade, the amount of carbon released by peat fires in this region is expected to increase from 143 Mt in 2015 to 544 Mt in 2100, for a total of 28 Gt over the course of the 21st century. Capping the warming rate at 0.3°C per decade would only result in 22 Gt of C lost to peat fires in the 21st century.[127] Emissions from peatland fires represent a significant risk to global climate change.

There is some uncertainty about how wildfire will affect climate warming or cooling. Wildfire emissions contribute to greenhouse gas concentrations in the atmosphere, which can contribute to warming. The removal of coniferous forest cover that results from fire can increase surface albedo effects, where snow reflects solar radiation resulting in a net-cooling effect.[128] Aerosols released

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[123] Zhao et al., "North American Boreal Forests Are a Large Carbon Source Due to Wildfires from 1986 to 2016"; Yue et al., "How Have Past Fire Disturbances Contributed to the Current Carbon Balance of Boreal Ecosystems?"

[124] Coogan et al., "Scientists' Warning on Wildfire — a Canadian Perspective"; Flannigan et al., "Implications of Changing Climate for Global Wildland Fire."

[125] Kurz et al., "The Carbon Budget of the Canadian Forest Sector: Phase I"; Amiro et al., "Direct Carbon Emissions from Canadian Forest Fires, 1959-1999."

[126] Flannigan et al., "Impacts of Climate Change on Fire Activity and Fire Management in the Circumboreal Forest."

[127] Lin, Liu, and Huang, "Climate-Induced Arctic-Boreal Peatland Fire and Carbon Loss in the 21st Century."

[128] T. C. Lemprière et al., "Canadian Boreal Forests and Climate Change Mitigation," *Environmental Reviews* 21, no. 4 (2013): 293–321, https://doi.org/10.1139/er-2013-0039.

by fires can contribute to the formation of clouds that can reflect solar radiation, resulting in net-cooling. It has been suggested that combined effects of boreal fire seems to result in climate warming shortly after fire, but then climate cooling 80-100 years post-fire.[129] However, identifying and combining all of the effects of fire on the climate is a difficult task that requires further research.

2.4 Conclusion

Wildfires are disturbances that play an important role in the carbon cycle and balance of the boreal forest. While some studies suggest that emissions from wildfires have shifted the boreal forest from a carbon sink to a carbon source, other studies suggest that direct (e.g., biomass combusted) and indirect (e.g., post-fire heterotrophic respiration) wildfire emissions have been overestimated in the past, which may mean that on a decadal timescale, post-fire regrowth will result in a net gain of carbon sequestered. Historically the wildfire regime has contributed to the enormous carbon balance that exists in the boreal forest by facilitating regrowth and adding pyrogenic carbon to soil carbon pools. However, climate change is resulting in decreasing fire intervals, increasing fire occurrences, area burned, and severity while also contributing to increased fire risk to peatlands. This suggests that it may be worth exploring options for reducing carbon emissions from wildfires.

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[129] Oris, F., Asselin, H., Ali, A. A., Finsinger, W., & Bergeron, Y. “Effect of increased fire activity on global warming in the boreal forest.” *Environmental Reviews*, *22*(3) (2014), 206–219. https://doi.org/10.1139/er-2013-0062

Chapter 3: Natural Climate Solutions For Wildfire Carbon Emissions

The role of fire in the boreal forest's carbon cycling is complex and still has areas of uncertainty. However, it does appear that with anthropogenic climate change resulting in a greater area burned and increased fire severity, there will be an increase in carbon emissions, particularly in the short to medium-term. From an emissions reductions management perspective, there are a few key challenges that have emerged from the literature:

1. Large fires (>200 ha) in the boreal forest are estimated to be about 2-3% of annual fires, but account for 97-98% of the area burned.
2. Large wildfires are infrequent occurrences that occur randomly across the landscape.
3. Extreme fire weather conditions result in the greatest area burned and most severe fire behaviour.
4. Boreal peatlands, and their massive store of legacy carbon, are increasingly vulnerable to wildfire as a result of climate change.

This chapter will provide an overview and evaluate some of the different options that may be pursued to reduce carbon emissions from wildfires. Reactive measures, like wildfire management (e.g., suppression), have been favoured in the past because of the uncertainty of fire occurrence over space and time (it is difficult to predict exactly when and where a fire will start). Proactive measures, such as fire-smart forest management and prescribed fire, may provide some potential for reducing fire risk and emissions.[130]

3.1. Wildfire Management (Suppression)

Wildfire Management in Manitoba

In Manitoba, the Natural Resources and Northern Development Wildfire Service is responsible for responding to wildfires. Their mandate is to "protect lives, property and other values at risk from wildfire, while also ensuring sustainable, healthy and resilient ecosystems are maintained." Under this mandate, the Wildfire Service has created Protection Zones, with the Primary Protection Zone and Observation Zone being relevant for the boreal forest area of Manitoba (Figure 4). Within the Primary Protection Zone, the Wildfire Service has High and Low priority areas, which are prioritized in the following order: 1. Life, 2. Property and community protection, 3. Remote values and infrastructure, 4. Forestry and other resource priorities. Forestry resources are prioritized based on commercial value. In the Observation Zone, only community protection zones are prioritized, which means most fires in the observation zone are allowed to burn unless they directly threaten a

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[130] Cyr et al., "Mitigating Post-Fire Regeneration Failure in Boreal Landscapes with Reforestation and Variable Retention Harvesting: At What Cost?"

community. Notably, the risk of carbon emissions is not currently included within Manitoba's fire management priority-setting considerations.

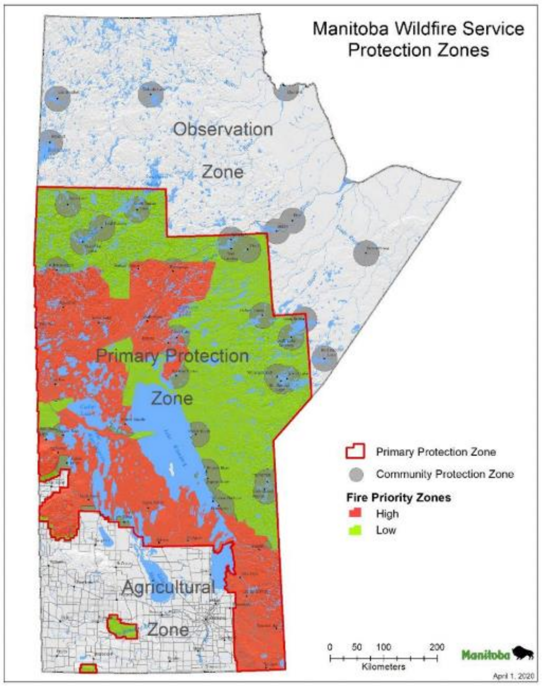

Figure 4: Manitoba Wildfire Service Protection Zones. From: Manitoba Wildfire Services, "Manitoba Wildfire Service: Who we are and What we do!"

History of wildfire management

Wildfire management in Canada has a complex history, with Indigenous Nations practicing fire management for millennia. However, colonial policing in Canada often prohibited the setting of bushfires.[131] Wildfire suppression was used to protect forest resources from fire. This led to unintended consequences in some forested regions of North America, where fire suppression contributed to the build-up of fuels, resulting in increased fire risk; however, this fuel build-up effect is unlikely to be a significant factor in the closed-canopy of the boreal forest and its stand-replacing fire regime.[132] Fire suppression has likely also contributed to increased insect disturbances.[133] These types of effects (perceived and otherwise) coupled with a greater appreciation for the ecosystem benefits of fire, and increasing suppression costs, has led to modified or limited suppression responses to wildfire in some regions of the boreal forest. Informally, the decision to limit fire suppression activities in certain areas to enable fire reintegration have been called "let it burn" policies.

Indigenous Fire Management

"Let it burn" policies, which allow wildfires to burn without intervention, have been criticized by some First Nations. This is because "let it burn" policies continue colonial governance arrangements related to fire management by failing to consider the landscape values, perspectives, and traditional fire management practices of First Nations. Fire suppression originally disrupted Indigenous burning practices in order to protect the forest resources, and now "let it burn" policies are again making decisions based on a different set of values on the landscape that do not necessarily align with Indigenous values (e.g., cultural sites, traplines).[134]

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[131] Christianson, "Social Science Research on Indigenous Wildfire Management in the 21st Century and Future Research Needs."

[132] Miyanishi, Bridge, and Johnson, "Wildfire Regime in the Boreal Forest and the Idea of Suppression and Fuel Buildup."

[133] Carlson et al., "Maintaining the Role of Canada's Forests and Peatlands in Climate Regulation."

[134] Zahara, "Breathing Fire into Landscapes That Burn: Wildfire Management in a Time of Alterlife."

Indigenous firefighters have played a significant role in wildfire management for generations, which represented a way to use and maintain fire knowledge and became an important work opportunity in the north.[135] There are a large number of Indigenous communities, as well as a wide array Indigenous values and cultural sites, located in the fire-prone boreal forest region of Manitoba. Therefore, it may be valuable to explore wildfire management strategies for carbon emissions that include First Nations' leadership and consider the impacts on Indigenous values and practices.

Efficacy of Fire Suppression

Wildfire suppression can be responsive temporally and spatially to fire risk and occurrence on the landscape. This differentiates this management option compared to fuel treatments (i.e., thinning, harvesting and prescribed fire), which must anticipate when and where fire will occur on the landscape. This responsiveness gives fire suppression the flexibility to respond to interannual changes in fire conditions or to protect carbon values on the landscape as needed.

Fire suppression costs are rising at a significant rate, and these costs have led to the curtailment of fire suppression activities in Manitoba and Canada.[136] However, it has been argued that fire suppression efforts may be a cost-effective way to reduce carbon emissions from wildfire in the boreal forest. A model analyzing wildfire suppression in North American boreal forests calculated the average cost of wildfire suppression to avoid 1 metric ton of CO_2 emissions from wildfire to be $12.63USD.[137] Fire suppression can be effective at reducing carbon emissions from wildfire in the short term. By extinguishing fires quickly, the amount of carbon released into the atmosphere is reduced. Fire suppression in Canada has been effective, with fire agencies controlling 97% of fires before they reach 200 ha in size; however, the 3% that are not controlled are responsible for nearly 97% of the area burned.[138] An analysis of fire suppression in Ontario found that wildfire suppression was effective at preventing small fires from growing into large fires, which reduced the overall area disturbed by fire, and maintained older age-classes in areas protected by suppression activities.[139]

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[135] Christianson, “Social Science Research on Indigenous Wildfire Management in the 21st Century and Future Research Needs”; Zahara, “Breathing Fire into Landscapes That Burn: Wildfire Management in a Time of Alterlife.”

[136] Cordy Tymstra et al., “Wildfire Management in Canada: Review, Challenges and Opportunities,” *Progress in Disaster Science* 5 (2020): 100045, https://doi.org/10.1016/j.pdisas.2019.100045; Emily S. Hope et al., “Wildfire Suppression Costs for Canada under a Changing Climate,” *PLoS ONE* 11, no. 8 (2016): 1–19, https://doi.org/10.1371/journal.pone.0157425.

[137] Phillips et al., “Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management.”

[138] Flannigan et al., “Impacts of Climate Change on Fire Activity and Fire Management in the Circumboreal Forest.”

[139] P C Ward, A G Tithecott, and B M Wotton, “Reply: A Re-Examination of the Effects of Fire Suppression in the Boreal Forest,” *Canadian Journal of Forest Research* 31, no. 8 (2011): 1467–80, https://doi.org/10.1139/x01-074.

Peatlands Wildfire Suppression

In order to reduce their outsized contribution to wildfire carbon emission, priority could be given to targeting fire management operations for protection of high carbon values, such as peatlands. Managing peatland fires is a significant challenge for a number of reasons. Due to the fact that they can burn underground, peat fires are difficult to detect using satellite sensing. Fire suppression of peat fires also pose unique challenges; once detected, peat fires are difficult to extinguish and can persist for long periods of time. In some cases, trenches can be used to limit the spread of peat fires, but this approach is impractical in large fires. Likewise, suppression using water is only possible for small fires, and large peat fires require partial flooding or removal of significant amounts of fuel, which is impractical and difficult in remote areas.[140] It has been suggested that prevention is the best-known means of mitigating peat fires. Prevention, in this context, involves limiting potential ignition sources near dry peatlands and avoiding activities that could result in drainage and drying of peatlands.[141] Peat fires are an emerging issue and research is nascent on this subject. More research is needed to understand the impacts and mitigation options of peat fires in the boreal forest of Canada.

Challenges

The remoteness of the boreal forest in Northern Manitoba, and the randomness of where lightning fires occur, pose a challenge to effective wildfire management. Suppression efforts are already substantial, so some researchers think it would be difficult for additional suppression to have a significant impact on carbon emissions.[142] Additionally, the interannual drought cycles that bring about extreme fire seasons and result in the largest fires mean that firefighting effort and expenses may not be constant every year. With just 3% of wildfires accounting for about 97% of the area burned, suppressing the large fires will lead to the greatest reduction in area burned. However large fires occur under extreme fire conditions, which means these are the fires that are most likely to escape control, and the most difficult to suppress.

Conclusion

Wildfire suppression has been very effective at catching and extinguishing small fires before they become large fires. This efficacy may be tested by a more active fire regime under climate change. The increased fire suppression activity that would be required to reduce wildfire emissions would be costly, though it may be somewhat cost-effective given the responsiveness of wildfire services and could present employment opportunities for Indigenous firefighters in Northern Manitoba. Fire management is focused on community and values protection, which presently does not consider carbon values on the landscape. To identify high value carbon pools, like peatlands, as

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[140] Rein and Huang, "Smouldering Wildfires in Peatlands, Forests and the Arctic: Challenges and Perspectives."

[141] WCS Canada, "Protecting Northern Peatlands: A Vital Cost-Effective Approach to Curbing Canada's Climate Impact," *Smart Prosperity Institute*, 2021, https://doi.org/10.1002/fee.2437; Lorna I. Harris et al., "The Essential Carbon Service Provided by Northern Peatlands," *Frontiers in Ecology and the Environment* 20, no. 4 (2022): 222–30, https://doi.org/10.1002/fee.2437.

[142] Amiro et al., "Direct Carbon Emissions from Canadian Forest Fires, 1959-1999."

values-at-risk within Manitoba, would require a shift in policy. Even with this policy, further research and wildfire strategies would need to be developed to fight complex fires like large fires and smouldering fires. Fire suppression may benefit from collaboration with forest management that incorporates fire risk reduction strategies.

3.2. Forest Management

Forest management in Manitoba

In Manitoba, there are a small number of forest companies and management tenures that cover a large area of Manitoba's boreal forest. Forest management planning occurs at the strategic level, through the development of 20-year forest management plans, and operationally, through 2-year operational plans. Strategic planning includes a focus on maintaining natural climate cycles and carbon modelling; monitoring and reporting is done through the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). Disturbances (such as fire) that cause carbon losses are accounted for through adjustments to the wood supply, and annual allowable cut limits, to ensure sustainable harvesting and carbon stocks.

The province of Manitoba is responsible for fire protection services, though tenure holders cooperate and support fire protection actions through prevention, detection, and suppression. Manitoba forest companies seek to emulate fire disturbance in their cut block layout. At present, there does not appear to be a proactive strategy for reducing fire-related carbon emissions or fire risk, through either harvesting or silvicultural prescriptions. There have been occasions where operational planning has sought to mitigate fire risk to communities.[143]

Given the large area under forest management, it is important to consider how forest management decisions and activities could affect wildfire and resultant emissions. There are two main approaches for managing forests for carbon emissions: harvesting/thinning treatments and silviculture. While each of these areas has the potential to reduce fire activity, there are risks and limiting factors for both approaches.

Harvesting and Thinning

There are two common, closely linked perceptions related to forest management and wildfire: 1) wildfire is going to burn up all the trees (which will release the carbon) so trees should be cut down to sequester the carbon in forest wood products; and 2) cutting down trees will reduce fire risk.[144]

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[143] Nisokapawino Forestry Management Corporation, "NFMC Forest Management Operating Plan 2021-2023," no. 1 (2021): 88–100. NFMC Operational plans for FML-2 identified increased fire risk in jack pine budworm affected stands as reason for pursuing salvage logging. Though it is unclear if jack pine budworm affected stands result in increased fire risk.

[144] Personal observation. See also: Zinke, R. "Wildfires Seem Unstoppable, but They Can Be Prevented. Here's How, Opinion." *USA TODAY*, 2018.

Upon analysis these perceptions prove to be faulty, as this fails to acknowledge the carbon cost of harvesting, and how forest management can contribute to fire risk.[145]

Fire risk

Harvesting and associated activities, such as site preparation and road building, can have the unintended effect of increasing wildfire risk. Harvest by-products that are left untreated post-harvest can be a significant surface fuel. With the removal of the overstory, surface fuels are more prone to drying, increasing their flammability under severe fire weather conditions. It has been found that harvesting can increase subsequent fire severity.[146] While forestry in the boreal often seeks to emulate fire patterns, it has been found that recently harvested sites have an increased probability of fire initiation that may last for 30 years, whereas fire initiation decreased on recently burned sites.[147] Forestry and road development are also a significant reason that peatlands are drained or disturbed, which has been found to increase fire risk and burn depth.[148] This suggests that fire risk reductions should not be an assumed result of harvesting-associated activities.

Harvesting effects on carbon

Forest harvesting, which most often takes the form of clear-cutting in the boreal forest to emulate stand-replacing wildfire, has its own carbon effects. Forest harvesting removes the carbon from the landscape in the form of mature tree stems. The storage capacity (or duration) of this carbon will depend on the type of forest product being used. Larger products, like timber, hold carbon for longer than paper products, which have a shorter decomposition time.[149] Harvesting results in greater tree mortality than wildfire, because the spatial pattern of wildfire means that mature trees can survive a wildfire.[150] Large mature trees also have the potential to become standing snags, which have a slower rate of decomposition as a pyrogenic carbon legacy (i.e. they will hold carbon and release it at a slow rate).[151] Coarse and fine woody debris is a by-product of harvesting that is either left on site or disposed of through broadcast burning or slash pile burning.[152] Burning these by-products results in similar emissions to wildfire, as they would likely be consumed in a fire.

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[145] Carter Stone, Andrew Hudak, and Penelope Morgan, "Forest Harvest Can Increase Subsequent Forest Fire Severity," *Proceedings of the Second International Symposium on Fire Economics, Planning, and Policy: A Global View and Policy: A Global View*, 2004, 525–34, http://www.fireplan.gov/content/home/.

[146] Stone, Hudak, and Morgan; Jacob I. Levine et al., "Higher Incidence of High-Severity Fire in and near Industrially Managed Forests," *Frontiers in Ecology and the Environment* 20, no. 7 (2022): 397–404, https://doi.org/10.1002/fee.2499.

[147] Meg A. Krawchuk and Steve G. Cumming, "Disturbance History Affects Lightning Fire Initiation in the Mixedwood Boreal Forest: Observations and Simulations," *Forest Ecology and Management* 257, no. 7 (2009): 1613–22, https://doi.org/10.1016/j.foreco.2009.01.019.

[148] Nelson et al., "Peatland-Fire Interactions: A Review of Wildland Fire Feedbacks and Interactions in Canadian Boreal Peatlands."

[149] DeLuca and Boisvenue, "Boreal Forest Soil Carbon: Distribution, Function and Modelling"; Kurz et al., "Carbon in Canada's Boreal Forest-A Synthesis."

[150] Kristina J. Bartowitz et al., "Forest Carbon Emission Sources Are Not Equal: Putting Fire, Harvest, and Fossil Fuel Emissions in Context," *Frontiers in Forests and Global Change* 5, no. May (2022): 1–11, https://doi.org/10.3389/ffgc.2022.867112.

[151] Stenzel et al., "Fixing a Snag in Carbon Emissions Estimates from Wildfires."

[152] Carlson et al., "Maintaining the Role of Canada's Forests and Peatlands in Climate Regulation."

Whereas those biomass by-products that are left on site are subject to decomposition, which results in emissions from heterotrophic respiration. Decomposition of biomass that remains post-harvest or post-fire (e.g., roots) decompose at a faster rate in harvested stands, because of the impact fire has on microbial communities.

A study in the western United States that analyzed harvested areas and burned areas calculated an average carbon loss per unit area and found that any type of logging resulted in a loss of carbon storage and emitted more carbon per unit area than wildfire. This included an analysis of commercial fuel treatments, which specifically seek to reduce wildfire risk.[153] A different report found that clear-cutting released 1.8 - 2.75 kg C/m^2 over a period of 13 years in jack pine-dominated forest, and 27 years in black spruce-dominated forest,[154] which would mean there was slightly less emissions compared to the average burn emissions of 1.35 - 3.35 kg C/m^2 from similar sites.[155] A study from the boreal forest in Ontario found that clear cut harvesting would decrease carbon storage compared to wildfire. This decrease in storage capacity would be compounded with shorter (80-100) year harvest rotations and longer fire intervals.[156] Harvesting of mature and productive stands leads to a significant decrease in average primary production at the landscape and stand levels.[157]

Thinning treatments

Mechanical thinning treatments are often used in wildfire risk reduction programs because thinning, removing ladder fuels, and isolating fuels has been shown to reduce fire intensity and severity.[158] Fuel treatments in other geographic areas (e.g., Western United States) are particularly well known and developed to restore forests to the fire-resistant state that existed before firefighting activities began and Indigenous practices were suppressed. However, the conifers of the boreal forest are not fire resistant, so changing their structure is not a restoration but an alteration of the natural stand composition. Stand-level thinning treatments in the boreal forest have been found to be effective at reducing fire behaviour and limiting crown-fire development under low to moderate fire weather conditions; however, in high and extreme fire weather conditions these interventions may not be sufficient to slow fire spread or crown fires. An

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[153] Bartowitz et al., “Forest Carbon Emission Sources Are Not Equal: Putting Fire, Harvest, and Fossil Fuel Emissions in Context.”

[154] NRDC, “Pandora’s Box: Clearcutting in the Canadian Boreal Unleashes Millions of Tons of Previously Uncounted Carbon Dioxide Emissions,” *Nrdc*, no. March (2018): 1–15, www.facebook.com/nrdc.org.

[155] Amiro et al., “Direct Carbon Emissions from Canadian Forest Fires, 1959-1999”; Walker et al., *Cross-Scale Controls on Carbon Emissions from Boreal Forest Megafires*.

[156] Jay R. Malcolm, Bjart Holtsmark, and Paul W. Piascik, “Forest Harvesting and the Carbon Debt in Boreal East-Central Canada,” *Climatic Change* 161, no. 3 (2020): 433–49, https://doi.org/10.1007/s10584-020-02711-8.

[157] Cyr et al., “Mitigating Post-Fire Regeneration Failure in Boreal Landscapes with Reforestation and Variable Retention Harvesting: At What Cost?”

[158] Larissa L. Yocom Kent et al., “Interactions of Fuel Treatments, Wildfire Severity, and Carbon Dynamics in Dry Conifer Forests,” *Forest Ecology and Management* 349 (2015): 66–72, https://doi.org/10.1016/j.foreco.2015.04.004; S. S. Rabin, F. N. Gérard, and A. Arneth, “The Influence of Thinning and Prescribed Burning on Future Forest Fires in Fire-Prone Regions of Europe,” *Environmental Research Letters* 17, no. 5 (2022), https://doi.org/10.1088/1748-9326/ac6312.

additional challenge to using some fuel treatments are the physical limitations to the amount of thinning that can be accomplished in boreal conifer stands before the stand health is compromised, either by increased susceptibility to leaning or by windthrow.[159]

Mechanical thinning produces large amounts of unmerchantable biomass or treatment residue that is typically disposed of by piling and burning, or mastication and spreading. There is the potential in some situations for this residue to be utilized, thereby providing an economic incentive for these treatments.[160] The removal and use of this biomass has its own carbon emission cost, which may limit the total carbon emissions reduction potential, even if the treatment would result in a less intense or severe fire.[161]

Silviculture

Silvicultural or reforestation practices may be able to contribute positively or negatively to fire emissions. The effects depend on reforestation that takes place post-harvest or post-fire, the planting spatial arrangement, and species mix.

Research has found that industrially managed forests in Western United States resulted in increased fire severity to a greater extent than fire exclusion in old stands of publicly managed forest land. This is due to the young stand density, homogenous stand structure, and spacing, which resulted in high fuel continuity in the planted forest.[162] Increasing the age, and promoting spatial heterogeneity of stands and fuels, is a means of reducing fire severity. Furthermore, fuel reduction treatments in plantations are important, though expensive. Thus, there is a limitation due to economics of conducting fuel treatments in planted stands. Reducing fire risk in planted stands is important because successive disturbances have a compounding effect and are more likely to result in regeneration failures by disrupting seed beds.[163] Variable retention harvesting, where cone-bearing seed trees (e.g., Jack pine) are retained during harvest, provides some mitigation potential

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[159] Jennifer L. Beverly et al., "Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests," *Fire* 3, no. 3 (2020): 1–23, https://doi.org/10.3390/fire3030035; Susan J. Prichard et al., "Adapting Western North American Forests to Climate Change and Wildfires: 10 Common Questions," *Ecological Applications* 31, no. 8 (December 1, 2021), https://doi.org/10.1002/eap.2433.

[160] Robert M. Campbell and Nathaniel M. Anderson, "Comprehensive Comparative Economic Evaluation of Woody Biomass Energy from Silvicultural Fuel Treatments," *Journal of Environmental Management* 250, no. July (2019): 109422, https://doi.org/10.1016/j.jenvman.2019.109422.

[161] Yocom Kent et al., "Interactions of Fuel Treatments, Wildfire Severity, and Carbon Dynamics in Dry Conifer Forests."

[162] Levine et al., "Higher Incidence of High-Severity Fire in and near Industrially Managed Forests"; Harold S.J. Zald and Christopher J. Dunn, "Severe Fire Weather and Intensive Forest Management Increase Fire Severity in a Multi-Ownership Landscape," *Ecological Applications* 28, no. 4 (2018): 1068–80, https://doi.org/10.1002/eap.1710.

[163] Krawchuk and Cumming, "Disturbance History Affects Lightning Fire Initiation in the Mixedwood Boreal Forest: Observations and Simulations"; Cyr et al., "Mitigating Post-Fire Regeneration Failure in Boreal Landscapes with Reforestation and Variable Retention Harvesting: At What Cost?"

against the risk of regeneration failure resulting from fire by maintaining an aerial seed bank within the stand.[164]

Reforestation following wildfire events is increasingly used as a natural climate solution to mitigate carbon lost to fire.[165] While this may speed up regrowth following a wildfire, there are some drawbacks. Namely, there is a carbon consequence to replanting after wildfire. This can include removal of biomass through salvage logging or site preparation (removal of snags to make area safer for planters), or pile burning any remaining biomass. In British Columbia, a study that modelled carbon effects of replanting or not planting in burned areas, found that after 60 years stands that were not planted contained a greater amount of carbon, which was largely attributed to the greater abundance of dead wood in non-planted sites.[166] Reforestation through tree planting may be an option on specific occasions when a young forest (planted or regrowth from previous fire) has burned before the regrowth can replenish seed beds.[167,168]

Silvicultural decisions about what species to plant could make an impact on carbon sequestration and/or reducing fire risk. Densely packed, fast growing conifer plantations could potentially reach positive net ecosystem productivity quickly and result in harvestable merchantable timber within fire return intervals. However, these types of plantations may be susceptible to fire occurrence and increased fire intensity.[169]

Fuel conversion (or preventative silviculture) seeks to shift the fuel type in a general area from highly flammable conifers to deciduous species. This could reduce landscape flammability and fire spread.[170] As described above (Chapter 1.3), some fuel conversion is anticipated to occur with the changing climate, but converting conifer stands into deciduous or mixedwood stands could be achieved through forest management. Mixedwood and deciduous trees may effectively sequester carbon and are less flammable than pure conifer stands, but may not produce the same value of

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[164] Cyr et al., “Mitigating Post-Fire Regeneration Failure in Boreal Landscapes with Reforestation and Variable Retention Harvesting: At What Cost?”

[165] Bowman et al., “Vegetation Fires in the Anthropocene.”

[166] Clason, Farnell, and Lilles, “Carbon 5–60 Years After Fire: Planting Trees Does Not Compensate for Losses in Dead Wood Stores.”

[167] Cyr et al., “Mitigating Post-Fire Regeneration Failure in Boreal Landscapes with Reforestation and Variable Retention Harvesting: At What Cost?”

[168] In personal communication with silviculturist operating in Northern Manitoba, it was noted that planted stands that burn prior to “free to grow” standing are not the responsibility of the forest company to replant but fall under provincial regulations. This suggests that post-fire planting opportunities and activities may fall under the jurisdiction of the provincial government and may not be an activity undertaken by private forest management companies.

[169] Girardin et al., “Fire in Managed Forests of Eastern Canada: Risks and Options.”

[170] B. D. Amiro et al., “Fire, Climate Change, Carbon and Fuel Management in the Canadian Boreal Forest,” *International Journal of Wildland Fire* 10, no. 3–4 (2001): 405–13, https://doi.org/10.1071/wf01038; Marc André Parisien et al., “Spatial Patterns of Forest Fires in Canada, 1980-1999,” *International Journal of Wildland Fire* 15, no. 3 (2006): 361–74, https://doi.org/10.1071/WF06009.

merchantable timber.[171] It is thought that fuel conversion on large scales could be effective, because it does not require ongoing maintenance to reduce fire behaviour potential.[172]

Fuel conversion at a landscape-level would likely be limited by the potential economic value of deciduous forests comparative to coniferous species, the ecological impact of shifting ecosystem composition, and whether site conditions are suitable for deciduous species (e.g. low-lying areas are more suited for black spruce and sandy or rocky ridges are preferred by pines).[173] On a more limited scale, preventative silviculture can be used as a fuel break to provide area-wide protection. These can be located in areas of high fire risk, on fire paths, according to predominant wind direction, topography, near ignition sources, or according to simulations models.[174]

Fire-smart Forest Management

"Fire-smart forest management" is a proactive and integrated approach that incorporates fuel treatments as a goal into forest management.[175] In the boreal forest of Canada, fuel treatments are typically done at a stand-level to protect particular values (i.e. populated areas), but on a landscape-level, fuel management is about creating a mosaic that breaks up fuel continuity through land conversion or harvesting to reduce flammability.[176] Integrated approaches to fuel and forest management through harvest scheduling and locations could be used to alter the landscape in order to decrease the number and size of fires. One study developed a methodology for locating cut-blocks, to maximize their ability to reduce landscape flammability and protect values. This analysis revealed the most effective cut blocks interrupted fuel continuity by being situated in flammable vegetation on, or near, critical paths between areas where fires were likely to occur, and where values were located.[177] One potential negative side-effect of disrupting fuel continuity is that it results in habitat fragmentation and could have an impact on wildlife.[178]

There have been different models developed to help plan the optimal spatial arrangement for fuel treatments and harvesting to reduce fire risk to forest values. One model focused on the probability of fire and economic conditions (i.e., value of harvested stands), to determine the spatial

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[171] T. C. Lemprière et al., "Canadian Boreal Forests and Climate Change Mitigation," *Environmental Reviews* 21, no. 4 (2013): 293–321, https://doi.org/10.1139/er-2013-0039.

[172] Marc André Parisien, David R Junor, and Victor G Kafka, "Using Landscape-Based Decision Rules To Prioritize Locations for Placement of Fuel Treatments in the Boreal Mixedwood of Western Canada," no. March (2006): 1–29.

[173] Amiro et al., "Fire, Climate Change, Carbon and Fuel Management in the Canadian Boreal Forest."

[174] Constantinos Siettos, "Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires," *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*, no. September (2020), https://doi.org/10.1007/978-3-319-51727-8.

[175] K. Hirsch et al., "Fire-Smart Forest Management: A Pragmatic Approach to Sustainable Forest Management in Fire-Dominated Ecosystems," *Forestry Chronicle* 77, no. 2 (2001): 357–63, https://doi.org/10.5558/tfc77357-2.

[176] Hirsch et al.; Beverly et al., "Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests."

[177] Cristian D. Palma et al., "Assessing the Impact of Stand-Level Harvests on the Flammability of Forest Landscapes," *International Journal of Wildland Fire* 16, no. 5 (2007): 584–92, https://doi.org/10.1071/WF06116.

[178] Mauricio A. Acuna et al., "Integrated Spatial Fire and Forest Management Planning," *Canadian Journal of Forest Research* 40, no. 12 (2010): 2370–83, https://doi.org/10.1139/X10-151.

arrangement of these treatments.[179] Another focused on trying to overcome spatial and temporal challenges associated with fuel management for fire, by considering changes to forest dynamics, fire behaviour and spread, values at risk, and feasibility. [180]

A study in northern Saskatchewan considered how fuel management and preventative silvicultural treatments could be used together to reduce wildfire risk, by modelling burn probability on the landscape using the BURN-P3 simulation model. This study emphasized the importance of treatment intensities (i.e., size of the treatment relative to the area) and strategically locating fuel treatments. At a spatially smaller scale, clumping treatments (thereby increasing treatment intensity) was effective at limiting burn probability. On a larger scale, where the relative treatment intensity required may not be desirable (e.g., ecologically), locating treatment options in conjunction with natural fuel breaks (e.g., lakes) were more effective for limiting burn probability.[181]

Integrating fire suppression and fire-smart forest management planning at a landscape-level could maximize the potential effectiveness of both efforts. Harvested cut-blocks and fuel breaks provide safer opportunities for wildfire agencies to control wildfire, because the reduced fuel loads can result in reduced fire behaviour (rate of spread, intensity and severity). Forestry infrastructure, such as roads, provide increased access that may aid initial-attack efforts to halt a fire quickly. One study developed a methodology for integrating fire suppression with fire-smart forest management, to protect forest values in a forest landscape in Alberta. Their methodology used a burn probability and fire spread model to help determine a spatial management plan. By combining wildfire suppression, harvest scheduling, and locating cut-blocks to reduce fire spread and act as fuel breaks, they found that their strategy would result in an increased forest harvest of 8.1% over a non-fire-smart forest management strategy. While this study focused on protecting timber values, it suggests that this integrated approach could be applied to other values on the landscape.[182]

There are challenges to the potential efficacy of fire-smart forest management, including the uncertainty of the temporal and spatial occurrence of wildfire (when and where fires will occur); the scale of the area burned compared to the limited area that may be treated; the duration of some fuel treatment effects (due to the nature of regrowth, fuel treatment effectiveness decreases over time); and the ecological and economic effects of some treatments (i.e. effect of thinning on stand-health and fuel conversion on ecosystem).

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[179] Masashi Konoshima et al., "Optimal Spatial Patterns of Fuel Management and Timber Harvest with Fire Risk," *Canadian Journal of Forest Research* 40, no. 1 (2010): 95–108, https://doi.org/10.1139/X09-176.

[180] Woodam Chung et al., "Optimising Fuel Treatments over Time and Space," *International Journal of Wildland Fire* 22, no. 8 (2013): 1118–33, https://doi.org/10.1071/WF12138.

[181] Parisien, Junor, and Kafka, "Using Landscape-Based Decision Rules To Prioritize Locations for Placement of Fuel Treatments in the Boreal Mixedwood of Western Canada."

[182] Acuna et al., "Integrated Spatial Fire and Forest Management Planning."

Conclusion

Proactive and integrated fire-smart forest management has the potential to impact fire intensity, severity and spread at the landscape-level. This requires the inclusion of fire-risk planning as part of forest management strategic and operational planning for the spatial location and shape of cut-blocks and other forest developments (i.e., roads), timing of harvesting activities, and the silviculture practised within cut blocks. In order for this fire-smart forest management to reduce wildfire emissions, it is essential that harvesting and silviculture emissions, carbon storage, and fire risk impacts must be understood and accounted for. Further research and modelling are required to further investigate and integrate fire-smart forest management that incorporates wildfire emissions reductions as an objective at a landscape-level. One area of potential is for using fire-smart forest management at a landscape-level to break up fuel continuity and as a protection strategy for significant carbon storage pools (e.g., peatlands). This type of strategy can also be used to reduce fire risk to communities and other values on the landscape.

3.3. Prescribed Fire

Recent years have seen an increasing recognition of the importance and potential for the use of prescribed fire as a tool for reducing wildland fire extent and intensity. Prescribed fire is being used to reduce fuel loads by using low-intensity fires to burn accumulated fine and coarse fuels and flammable vegetation in a controlled manner. This can reduce the risk of high-intensity fires which are more likely to burn out of control and ladder into the canopy resulting in crown fires. [183]

Many prescribed fire programs focus on restoring cultural burning practices or reducing the fire danger risk to people and properties; however, there is a growing emphasis on using prescribed fire to reduce carbon emissions. A study from the western United States noted that while prescribed burning does not eliminate the occurrence of wildfire, treating fuels limited wildfire severity, and prescribed burning could reduce CO_2 and other emissions from fires in dry forest types by 52-68%.[184]

Prescribed Fire and Carbon Offsets

Programs that use prescribed fires for emissions reductions have predominantly been located in Australia (though there are programs in Brazil, South Africa and Western United States[185]) and are tied to the restoration of cultural burning practices and Indigenous fire and land stewardship. One of the more promising elements of this type of program is that they may be funded through a

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[183] Molly E. Hunter and Marcos D. Robles, “Tamm Review: The Effects of Prescribed Fire on Wildfire Regimes and Impacts: A Framework for Comparison,” *Forest Ecology and Management* 475, no. July (2020), https://doi.org/10.1016/j.foreco.2020.118435.

[184] Matthew D. Hurteau and Christine Wiedinmyer, “Response to Comment on ‘Prescribed Fire as a Means of Reducing Forest Carbon Emissions in the Western United States,’” *Environmental Science and Technology* 44, no. 16 (2010): 6521, https://doi.org/10.1021/es102186b.

[185] Veiga Nikoklais 2022

voluntary carbon offset program, where carbon credits are purchased in the offsets market which then funds the burn program.

The success of the Australian carbon offsets programs offers an interesting case study to consider the opportunities and limitations for natural climate solutions focused on wildfire emissions in the boreal forest of Manitoba. These programs emerged out of an ongoing project that was re-introducing Indigenous Fire Management to northern Australia, with the goals of mitigating catastrophic wildfires, creating a mosaic landscape, benefiting biodiversity, maintaining habitats protected from fire, and supporting fire dependent species. Through the development of a carbon measurement system, this program was able to sell carbon-offsets based on the efficacy of these prescribed fires. This contributed socio-economic benefits alongside the other benefits of the prescribed fire program.[186]

The basic principle of these carbon offset programs is that carbon savings are possible by re-introducing prescribed fire in the early dry season which is critical in mitigating catastrophic late dry season wildfires. Emission reductions occur because of reduced burn areas and altered fire frequency and intensity.[187] The carbon-savings are determined by calculating the net difference in carbon emissions between early dry season and late dry season fires, with evidence showing that early dry season fires emit only 48% of the carbon emissions of late dry season fires.[188]

One potential critique of a prescribed fire program for reducing wildfire emissions is the total effect of a prescribed fire regime on the total emissions and carbon balance of the forest. In Australia, a study was conducted that considered the impact of prescribed fire's effect on emissions and the total ecosystem carbon balance (e.g., the amount of carbon stored) compared to a wildfire regime without prescribed fire. By comparing frequent fire regimes (prescribed fire) and infrequent fire regimes, the difference in the carbon balance was almost negligible over the long-term. However, they did find that wildfire risk (intensity and extent of wildfires) was reduced through prescribed fire management.[189] In this case, prescribed fire was not achieving

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[186] William Nikolakis et al., "Goal Setting and Indigenous Fire Management: A Holistic Perspective," *International Journal of Wildland Fire* 29, no. 11 (November 1, 2020): 974–82, https://doi.org/10.1071/WF20007; Nikolakis and Roberts, "Indigenous Fire Management: A Conceptual Model from Literature"; William Nikolakis, Clive Welham, and Gregory Greene, "Diffusion of Indigenous Fire Management and Carbon-Credit Programs: Opportunities and Challenges for 'Scaling-up' to Temperate Ecosystems," *Frontiers in Forests and Global Change* 5 (September 16, 2022), https://doi.org/10.3389/ffgc.2022.967653.

[187] Renata Moura da Veiga and William Nikolakis, "Fire Management and Carbon Programs: A Systematic Literature Review and Case Study Analysis," *Society and Natural Resources* (Routledge, 2022), https://doi.org/10.1080/08941920.2022.2053618.

[188] Jeremy Russell-Smith et al., "Managing Fire Regimes in North Australian Savannas: Applying Aboriginal Approaches to Contemporary Global Problems," *Frontiers in Ecology and the Environment* 11, no. SUPPL. 1 (2013), https://doi.org/10.1890/120251.

[189] Liubov Volkova, Stephen H. Roxburgh, and Christopher J. Weston, "Effects of Prescribed Fire Frequency on Wildfire Emissions and Carbon Sequestration in a Fire Adapted Ecosystem Using a Comprehensive Carbon Model," *Journal of Environmental Management* 290, no. April (2021): 112673, https://doi.org/10.1016/j.jenvman.2021.112673.

emission abatement, but fire management for other purposes might have been useful. This is similar to findings from other studies which suggest that the implications of prescribed fire on emissions and ecosystem carbon are unclear, with some suggesting that increased rates of fire through prescribed burns result in increased emissions.[190]

Prescribed Fire Potential in Canada

Although the vast majority of fire management carbon offset programs occur in Australia, there is an Indigenous Fire Management program in development involving the Yunesit'in and Xeni Gwet'in First Nations in central British Columbia, Canada (the Chilcotin). This project is drawing direct inspiration from the Australian Indigenous Fire Management programs that have successfully incorporated carbon-credits into their programs to fund the work that they are doing.[191]

Nikolakis et al. (2022) has documented some of the work that is being done to develop this program, including some of the considerations for a carbon offset program. Development of a methodology for determining carbon stocks, carbon emissions from prescribed fire, estimated emissions from a wildfire, and the governance of this program are vital pieces that are still in development. The potential for a carbon offset program working is going to require site-specific measurements and carbon analysis.[192]

In addition to the potential issue with the efficacy of prescribed fire programs resulting in reduced carbon emissions is that the boreal forest is a difficult context for prescribed fire. The boreal forest's stand-replacing fire regime means that there may be more risk to the application of prescribed fire, even at low intensities. Boreal conifers, like black spruce, have thin bark which means that they have minimal fire resistance, so even low intensity prescribed fires are likely to lead to tree mortality.[193] Burning operations would also have a very limited window given the weather conditions required for burning surface fuels without risking a crown-fire developing.

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[190] Hunter and Robles, "Tamm Review: The Effects of Prescribed Fire on Wildfire Regimes and Impacts: A Framework for Comparison."

[191] William Nikolakis and Russell Myers Ross, " Rebuilding Yunesit'in Fire (Qwen) Stewardship: Learnings from the Land ," *The Forestry Chronicle*, August 12, 2022, 1–8, https://doi.org/10.5558/tfc2022-001.

[192] Nikolakis and Ross; da Veiga and Nikolakis, "Fire Management and Carbon Programs: A Systematic Literature Review and Case Study Analysis."

[193] Beverly et al., "Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests"; Ribeiro-Kumara et al., "Short-to Medium-Term Effects of Crown and Surface Fires on Soil Respiration in a Canadian Boreal Forest."

Criteria for Carbon Offsets Program:
Should a prescribed fire carbon offset program be considered a possibility in northern Manitoba, it would need to be assessed according to a set of criteria to determine the validity of the project as a carbon offset. The recently launched Federal Greenhouse Gas Offset Credit System provides a good description of carbon offset project criteria:

- Real: Requires a specific activity that will result in greenhouse gas (GHG) reductions.
- Additional: GHG reduction must occur because of the project activities, reductions that occur without the project would not be additional.
- Quantifiable: GHG reductions must be accurately accounted for, which means a proven method and measurement system is required to calculate reductions.
- Unique: The offset can only be registered under one offset program.
- Verifiable: Information about project must be recorded so that it can be reviewed and confirmed by a qualified, independent third party.
- Permanent: Project must ensure the permanence of GHG emissions reductions for a required period of time. E.g., A forested area that is treated with prescribed fire to reduce carbon emissions from high severity fire cannot be harvested at a later date within the required period of time, as this would negate the permanence of the reduced emissions.

There are some issues around the comparative measurement mechanism that may limit the relevance of the use of prescribed fire for carbon offsets in the boreal forest: 1) Most of the fire management programs with a carbon focus are located in savanna landscapes, which feature short and predictable fire intervals thus making it easier to calculate emissions reductions. This is significantly different from the long and unpredictable fire intervals in the boreal forest, which makes calculating emissions savings more complex; 2) The type of fires that occur in savanna ecosystems feature clear differences between early and late dry season fires that reduce complexity in anticipating results of prescribed fire. The boreal forest's fire regime does not have the predictability between different seasonal fires; and 3) The fuel structure of savanna ecosystems makes prescribed fire control and outcomes more predictable, as compared to the closed-canopy fuel structure and stand-replacing characteristics of the boreal forest, which make fire control more difficult and the outcomes less predictable.[194]

Another challenge to the use of prescribed fire is the uncertainty of where and when wildfires will occur in the boreal forest. Emissions reductions possible from prescribed fire are dependent on wildfires encountering areas that have been treated with prescribed fire during the lifespan of its effectiveness.[195] Given the long fire intervals of the boreal forest, it is difficult to anticipate if the carbon emissions benefits of prescribed fire treatment would be realised.

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[194] Nikolakis and Ross, " Rebuilding Yunesit'in Fire (Qwen) Stewardship: Learnings from the Land "; Nikolakis, Welham, and Greene, "Diffusion of Indigenous Fire Management and Carbon-Credit Programs: Opportunities and Challenges for 'Scaling-up' to Temperate Ecosystems."

[195] Molly E. Hunter and Marcos D. Robles, "Tamm Review: The Effects of Prescribed Fire on Wildfire Regimes and Impacts: A Framework for Comparison"

Combining with Forest Management

Combining prescribed fire with fuel management has the potential to reduce emissions from wildfire. A model in the dry-forest type of western United States found that using an optimized mix of thinning treatments and prescribed fire to reduce emissions was found to reduce wildfire severity by 29%, and reduced carbon emissions from wildfire and resulted in a net 5.9 Mg C ha^{-1} over 50 years.[196] This simulation took place in a forest-type where fire exclusion has resulted in fuel build-up, and treatment options were aimed to restore the forest to a more fire resistant state. Potential carbon emissions reductions in the boreal would likely be different; however, this does suggest that integrating prescribed fire and thinning treatments could be used in an integrated manner to reduce wildfire emissions, if incorporated into forest management planning.

Conclusion

Prescribed fire is being used to reduce emissions from wildfires in savanna ecosystems, which has created opportunities for carbon-credit programs. Transposing this strategy into the boreal forest of Manitoba contains many challenges and uncertainties. One opportunity to learn more about the potential for prescribed fire will be through the experience of the Chilcotin fire management program that is being developed in British Columbia. It is worth noting that this program's primary motivation is re-establishing Indigenous fire management, with carbon reductions being a supplementary objective due to the potential for funding through a carbon-credits program. This is important because there are concerns about this type of programming becoming to "carbon-centric."[197] The applicability of prescribed fire to the boreal region of Manitoba will require further research to better understand the potential for the reduction of carbon emissions.

3.4 Peatland Fire Management

Peatlands are recognized as an important store of global carbon, and as such there is a growing body of literature focusing on peatland preservation and management as a natural climate solution.[198] While peatlands have been fire-resistant given their high moisture content, they are becoming more fire-prone as a result of conversion, drainage that occurs due to resource development, and climate change.[199] Reducing fire risk to boreal peatlands could be an important natural climate solution for reducing boreal emissions resulting from wildfire.

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[196] D. J. Krofcheck et al., "Optimizing Forest Management Stabilizes Carbon Under Projected Climate and Wildfires," *Journal of Geophysical Research: Biogeosciences* 124, no. 10 (October 1, 2019): 3075–87, https://doi.org/10.1029/2019JG005206.

[197] Nikolakis, Welham, and Greene, "Diffusion of Indigenous Fire Management and Carbon-Credit Programs: Opportunities and Challenges for 'Scaling-up' to Temperate Ecosystems."

[198] C. Ronnie Drever et al., "Natural Climate Solutions for Canada," *Science Advances* 7, no. 23 (2021): 1–14, https://doi.org/10.1126/sciadv.abd6034; Harris et al., "The Essential Carbon Service Provided by Northern Peatlands."

[199] Turetsky et al., "Global Vulnerability of Peatlands to Fire and Carbon Loss."

Some management options, such as suppressing fires in peatlands (3.1 Fire Management) and reducing fuel continuity leading to peatlands (3.2 Forest Management) have been discussed above. However, peatland protection management options, and their challenges, are more extensive than what could be included within the scope of this report. Significant work has been done to identify peatland protection options. Notably, the Wild Conservation Society of Canada (WCS Canada) has written a policy brief that identifies a number of policy gaps, challenges, and opportunities for protecting peatlands.[200]

Of relevance to this report are the potential ways that peatland protection could be incentivized. The WCS Canada's policy brief highlights the need for incentivizing peatland protection through support to Indigenous-led Conservation and Guardians Programs, carbon tenures, and credit programs. With regards to carbon offset programs, it is unclear how fire risk reduction and the issue of additionality could be addressed to provide financial support to peatland protection though this may change as payment for ecosystem services programs develop. Since peatland protection as a natural climate solution is significantly linked to fire risk reduction in these ecosystems, these incentives could be opportunities to support wildfire-related emissions reductions in the boreal region of Manitoba.

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[200] WCS Canada, "Protecting Northern Peatlands: A Vital Cost-Effective Approach to Curbing Canada's Climate Impact."

Chapter 4: Key Findings and Recommendations

Key Findings

The findings of this review show that the range of potential options or possibilities for reducing carbon emissions related to wildfire will require additional research. With the boreal forest being a complex fire-driven landscape, there are social, economic, biological, and ecological feedbacks that could result from any interventions in the wildfire regime of the boreal forest. Determining potential emissions reductions based on different treatment options is challenging at a landscape-level, particularly given that most treatment options for reducing wildfire emissions at the scale required for landscape-level reductions are limited and are reliant on wildfires encountering treated areas, which is uncertain. This chapter will present some of the key findings from the literature.

Key Finding 1: Wildfire is an essential component within the biology, ecology, carbon-cycle, and cultures of the boreal landscape.

- **Fire disturbance plays an important role in regenerating the boreal forest**. Boreal vegetation has evolved to encourage and is adapted to stand-replacing fires. A small number of large (>200 ha), stand-replacing fires (3% of all fires) result in the vast majority of area burned (97% of area burned). These infrequent large fires (average fire interval of 80 years) generally occur under extreme fire weather conditions (high temperatures, high winds, low humidities). Fire shapes the landscape mosaic of different ecosystems, species and stand age-classes.
- The carbon cycle of the boreal forest is impacted by the release of carbon that accompanies a fire and then the subsequent recovery of carbon through regrowth. **The boreal forest's vast carbon stores have been accumulated over time in spite, or because of, its fire-disturbance regime.**
- There is a complex relationship between fire, the boreal landscape and Indigenous peoples that has been altered through colonization and wildfire suppression activities. Indigenous knowledge of fire in the boreal forest has largely been excluded in the field of wildfire science and research, though this is increasingly being challenged.

Key Finding 2: Climate change is altering the wildfire regime by increasing wildfire occurrence, behaviour, and the area burned, resulting in increased combustion emissions and increased risk for carbon stores in soils and peatlands.

- **Climate change is already impacting the fire regime through longer fire seasons, increasing occurrence of extreme fire weather events, and increased frequency of droughts**. The altered fire climate is resulting in an increase in fire occurrence, extreme fire behaviour (high rates of spread, intensity and severity), and the area burned. Increasing drought conditions are also making historically fire-resistant peatlands more vulnerable to fire.

- Increases to the area burned result in increased emissions from combustible biomass. Increasing conditions for extreme wildfire behaviour, especially burn severity, will result in increased emissions from carbon stored in soils and peatlands.

Key Finding 3: Quantifying wildfire carbon emissions and impact on storage is complex, and has some uncertainties. Therefore, quantifying the effectiveness of wildfire management options for reducing wildfire-related carbon emissions is challenging and requires site-specific (stand-level) analysis.

- **The boreal forest carbon cycle is dynamic**. Carbon sequestration, emission, and storage varies depending on stand characteristics such as: age-class, species composition, rate of growth, and site conditions. The majority of carbon is stored in boreal soils particularly in peatlands, which contain vast stores of ancient carbon.
- **Wildfire results in an immediate release of large amounts of direct emissions** through the combustion of biomass and organic matter in the soil organic layers. Combustion emissions are determined by stand composition and burn severity. Peatland combustion could emit vast quantities of CO_2 and other GHGs.
- **Models for estimating wildfire-related carbon emissions often overestimate emissions** because they do not take into account post-fire carbon legacies. Fire disrupts microbial communities, which slows decomposition related emissions. Incomplete combustion of biomass on the landscape results in pyrogenic carbon (e.g., standing snags, carbon) that is resistant to decomposition.
- **Carbon emitted from wildfires is recovered through post-fire regrowth.** Initial carbon-recovery post-fire is slow, but within 10-25 years net ecosystem productivity will return (carbon uptake exceeds decomposition emissions). Carbon stocks recovery occurs on a longer timescale, requiring longer than 60 years to fully recover the carbon lost from a fire. Shortened fire return intervals (<60 years) threaten long-term carbon sequestration potential.
- **Quantifying net wildfire emissions** requires accounting for different carbon pools at the stand level, determining emissions based on fuel consumption, identifying any pyrogenic carbon legacies (pyrogenic carbon) that remains after the fire, and then subtracting any carbon that is subsequently recovered through regrowth after the fire.
- **Quantifying wildfire emissions reductions** through wildfire management requires calculating carbon sequestration and storage for management area, subtracting emissions related to management options (e.g., harvest emissions), and then determining the difference between the hypothetical potential net wildfire emissions for the area with no management.

Table 1: Carbon Storage and Emissions Comparison for Jack Pine & Black Spruce Stands and Boreal Peatlands

	Jack Pine & Black Spruce Stands	**Boreal Peatlands**
Average Carbon Storage (kg C/m^2)	13.81	28.3-68.8
Average Carbon in Soil Organic Layer (kg C/m^2)	11.95	22.6-66.0
Average Burn Emissions (kg C/m^2)	1.35-3.35	2015 - 7.1; 2050 - 12.8; 2100 - 27.2
Harvest Emissions (kg C/m^2)	1.8-2.75	N/A

Key Finding 4: Wildfire management options can reduce wildfire risk, spread, intensity, and severity.

- **Wildfire suppression** has been proven to be effective at controlling wildland fires, with fire agencies controlling 97% of fires before they reach 200 ha in size. Wildfire suppression can be responsive temporally and spatially to fire risk and occurrence on the landscape.
- **Forest management** plays a significant role in the boreal forest because of its scope and through the treatment activities of harvesting, thinning, and preventative silviculture. Harvesting and thinning can reduce flammability and fire intensity in particular areas by reducing fuel loads and disrupting fuel continuity (Fire-smart forest management). By planting less-flammable trees (e.g., deciduous trees), preventative silviculture can reduce stand flammability and if located appropriately can act as a fuel break by disrupting fuel continuity.
- **Prescribed fire** uses low-intensity fire to burn fine and coarse fuels during appropriate seasonal conditions to reduce fuel loads. This reduces the risk of high-intensity fires that might occur under high or extreme fire weather conditions. Prescribed fire has been practised by Indigenous peoples throughout the world to reduce fire risk and achieve other objectives on the landscape.
- **Peatland protection** maintains the fire-resistance of these ecosystems by reducing peatland conversion and drainage.

Key Finding 5: Wildfire management options as natural climate solutions have limitations and drawbacks in the boreal forest of Manitoba.

- **Fire suppression** has had unintended effects such as increasing insect disturbances and disrupting ecologically significant disturbance cycles. At present, policies in Manitoba do not prioritize reducing carbon emissions or protecting carbon pools. Prioritizing carbon emission reductions and carbon pool protection may require controlling fires in low-priority and observation zones. Fire suppression activities are already extensive and expensive. Actioning fires in remote, low-priority, and observation zones would stretch fire agency resources and capacity.

- **Forest management** activities have a number of limitations and drawbacks.
    - *Emissions*: Harvesting impacts carbon sequestration by removing mature stands in peak production and results in emissions similar to fire emissions because of high tree mortality, and the decomposition or burning of biomass by-products.
    - *Fire Risk*: Forest management activities may result in increased fire risk. Harvest by-products (slash) are prone to drying and may result in increased fire ignitions and burn severely. Dense, homogenous planted stands are linked to increased fire severity and fire risk. Forestry has been linked to peatland drainage and disruption, thereby increasing burn risk.
    - *Treatment duration*: Harvesting and thinning treatments have a duration of effectiveness that may not correspond with fire occurrence given the uncertainty of when and where wildfires will occur.
    - *Ecosystem composition and health*: Boreal conifer-forest stands do not have a natural fire-resistant state that can be restored through treatments. Mechanical thinning in the boreal forest can impact stand-health by increasing risk of windthrow and leaning. Using harvested cut blocks to limit fire pathways could result in habitat fragmentation and have impacts on wildlife. Successive disturbances (by harvesting and fire) have a compounding effect on ecosystem health that could affect regeneration. Converting more flammable conifer stands to deciduous stands may have ecological impacts or be limited by site conditions.
    - *Economic*: Forestry activities are costly and maximizing the reduction of fire risk to impact wildfire emissions must be balanced with economic considerations. Locating cut-blocks for reducing fuel risk and continuity may not correspond with the most economically preferable option. Thinning treatments are costly and most of the by-products are not merchantable and must be disposed of. Planting deciduous trees to reduce fire risk may have an economic trade-off as these may be less valuable in the future.
    - *Responsibility*: The Manitoba provincial government is responsible for fire protection even in forest management license areas. Forest companies cooperate and support provincial fire protection actions. Forest companies are not required or responsible for reducing fire risk, except for taking steps to reduce direct fire ignitions from harvesting operations.
- **Prescribed fire** efficacy and potential as a natural climate solution in the boreal forest is uncertain.
    - *Methodological challenge*: Most prescribed fire programs that feature carbon emissions reductions take place in savanna ecosystems that feature short and

  predictable fire intervals with clear distinctions between early and late season fires. This has enabled the development of a clear methodology for calculating emissions reductions. Boreal forest wildfires occur on longer intervals and are stand-replacing events, which poses difficulties for developing a methodology for calculating emissions reductions.
  - *Treatment duration:* There is a duration of effectiveness following prescribed burns that may not correspond with fire occurrence given the uncertainty of when and where wildfires will occur.
  - *Efficacy for emissions reduction*: Even in a savanna context with a developed methodology there is some uncertainty about what carbon emission reductions are possible.
  - *Risk*: Boreal forest fuel structure makes prescribed fire control more difficult and less predictable.
  - *Lack of prescribed burn programs in Manitoba*: Prescribed burn programs have developed, or are developing, a carbon offsets component to support their existing program and its objectives. There is a dearth of prescribed burn programs in the boreal region of Manitoba.

Recommendations

There is an inherent difficulty in quantifying potential wildfire carbon emissions reductions in Manitoba’s boreal forest, given the scale of fire and forest management activities within the boreal forest. We know that the different fire management tools described can impact fire risk, fire spread, intensity, and severity. Therefore, we can be relatively confident that these interventions can result in reductions in emissions. However, these interventions have not been utilized with a goal to reduce emissions in a boreal context and so determining the actual emissions result possible is beyond the scope of this paper. Significant modelling is required to understand the full potential for application on the landscape. To use these interventions effectively to manage emissions from wildfires requires a landscape-level strategy focused on reducing wildfire related emissions in an integrated way. This chapter presents recommendations for pursuing natural climate solutions targeting wildfire carbon emissions.

Recommendation 1: Develop system for researching, monitoring and evaluating the effect of climate change on carbon dynamics and wildfire risk in the boreal region of Manitoba

- While this review has grappled with the complexity of wildfire, climate change, and carbon dynamics in the boreal forest at a coarse scale, some uncertainties remain and there is still a need for finer detail and geographic specific analysis. The full effect of wildfire on emissions and the effect of wildfire on climate change are still not fully understood. Meanwhile the finer details required to prescribe, and estimate costs for, specific localized management treatments need to be identified, monitored, and evaluated in a systematic way.

- Quantifying and locating carbon sequestration, emissions, and stocks in the boreal region[201] cross-referenced with wildfire risk modelling[202] could allow for the identification of carbon values-at-risk, and protection strategies on the landscape.
- Monitoring wildfire occurrences and carbon may allow for the identification of sites where successive disturbances have occurred and impacted regeneration. This may allow for the identification of sites where reforestation activities may be desirable.

Recommendation 2: Advocate for the development of an integrated and proactive Fire-smart forest management approach in Manitoba's forest management license areas (FMLAs)

- The scale at which wildfire occurs on the landscape is vast. For example, in 1989, Manitoba's most severe season, 1147 fires occurred burning 3.28 million ha, which accounted for about 9% of the province's forested area.[203] Because of this scale, it is essential for wildfire management to occur on a landscape-level in an integrated and proactive manner.
- An integrated and proactive Fire-smart forest management approach can incorporate objectives (e.g., reduced wildfire emissions), different values-at-risk (e.g., carbon stocks), and different management options (e.g., fuel breaks, preventative silviculture, fire suppression) into strategic planning and modelling processes. This could lead to the identification of harvest scheduling and cut block/fuel break locations that can minimize wildfire risk. In an integrated process fire risk planning also balances these treatment options with other values and objectives.
- Forest management companies have access to carbon pool data (located in CBSM-CFS3) and could plan forest activities that lower fire risk to high value carbon pools, rather than just limiting any forestry impacts to those pools. This could be done by incorporating a fire susceptibility simulation model such as BURN-P3.[204]
- An opportunity exists in Manitoba for the development of an integrated FireSmart forest management approach to the changing wildfire regime and its resultant emissions. FML-2, the largest forest tenure in North America, is presently developing a strategic 20-year Forest Management Plan. There is an opportunity to advocate for the inclusion of wildfire risk management objectives and carbon value protection into the Forest Management Plan at a strategic level.
- Challenges and limitations:

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[201] Potentially available within the Carbon Budget Model for the Canadian Forest Sector (CBSM-CFS3).

[202] Potentially available through the Burn-P3 Simulation Model. See: Parisien, M. A., Kafka, V. G., Hirsch, K. G., Todd, J. B., Lavoie, S. G., Maczek, P. D. *Mapping Wildfire Susceptibility With the Burn-P3 Simulation Model*. (2005). Canadian Forest Service, Northern Forestry Centre.

[203] Hirsch, K. G. "A chronological overview of the 1989 fire season in Manitoba."

[204] Parisien, M. A., et al., *Mapping Wildfire Susceptibility With the Burn-P3 Simulation Model*.

  - Requires willing participation and cooperation of Nisokapawino Forest Management Corporation and Manitoba Wildfire Service.
  - Introducing reduced fire risk and carbon emissions as objectives or values represents added complexity within the planning and modelling process and potentially a policy hurdle for the Wildfire Service.
  - If integrated into the planning process, these objectives or values will need to be balanced with other objectives, values, and considerations, which might limit the overall efficacy of the emergent carbon-related management options.

Recommendation 3: Investigate potential for existing or new programs to integrate wildfire emissions reductions as an additional outcome or benefit

- A critique of programs focused primarily on carbon emissions reductions is that land and fire stewardship are too "carbon-centric", which lose sight of Indigenous values and other ecological processes on the landscape.[205] It has been suggested that managing fires or forests for carbon might not align with Indigenous values in the landscape.[206] Given this critique, it may be important to investigate existing programs that already exist to see if wildfire emissions reductions could be an additional outcome or benefit, without becoming the sole focus of the program.
- As an example, WCS Canada identified Indigenous-led Conservation and Guardians Programs that work in the boreal peatlands as opportunities to monitor and protect peatlands.[207] As peatland fire risk could have a significant impact on overall wildfire carbon emissions, it is worth investigating to see whether fire risk reduction outcomes are possible or whether payment for ecosystem services (PES) or funding though carbon offsets could support these programs.
- Further research is needed to determine the potential for prescribed fire programs to impact wildfire emissions in the boreal forest. Learning from the Chilcotin program in British Columbia will be essential, should there be interest in pursuing a prescribed fire program in northern Manitoba.

Recommendation 4: Pursue climate change mitigation activities that reduce greenhouse gas emissions.

- Fire disturbance is a natural and integral dynamic of the boreal ecosystem and its carbon cycle. **Anthropogenic climate change is the most significant driver of increased fire activity** and the resulting increase in carbon emissions. As such, policies and actions that focus on the root causes of climate change, anthropogenic greenhouse gas emissions, are the most important mechanisms for reducing carbon emissions from wildfire now and in

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[205] Nikolakis, Welham, and Greene, "Diffusion of Indigenous Fire Management and Carbon-Credit Programs: Opportunities and Challenges for 'Scaling-up' to Temperate Ecosystems."

[206] Zahara, "Breathing Fire into Landscapes That Burn: Wildfire Management in a Time of Alterlife"

[207] WCS Canada, "Protecting Northern Peatlands: A Vital Cost-Effective Approach to Curbing Canada's Climate Impact."

the future. An analysis in the western United States, which has experienced several years of large fires and has more extensive timber harvest and fire suppression resources than the boreal forest, found that fossil fuel emissions in that area were 7 times greater than from fire and timber harvest combined.[208] This, combined with the uncertainty of how wildfire interacts with climate change, suggests that reducing anthropogenic GHG emissions is the primary mechanism for slowing climate change.

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[208] Bartowitz et al., "Forest Carbon Emission Sources Are Not Equal: Putting Fire, Harvest, and Fossil Fuel Emissions in Context."

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