WILDFIRE MITIGATION STRATEGIES FOR INCREASED WILDFIRE RESILIENCE IN WILDLAND-URBAN INTERFACE COMMUNITIES.

by

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ABSTRACT

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Historic wildfire management strategies across the North American boreal forest have resulted in fire deficit forests. These landscapes are characterized by an unnatural build-up of wildland fuel, forest densification and irregular age class distributions that lend to increased risk of wildfire disturbance to Wildland-Urban Interface communities. Under current climate projections wildfire frequency, intensity and area burned are projected to increase resulting in increased disruption to social and economic activity. Analyzed in this report were a variety of wildfire mitigation strategies designed to reduce wildfire behaviour. Fuel reduction treatment efficacy and longevity were explored in the context of increasing community resilience to wildfire disturbance. A special focus was given to remote communities disproportionately affected by wildfire disturbance events. Current barriers to application were explored to highlight areas within the Canadian wildfire management system that require further amendment to achieve increased mitigation efficacy and widespread application.

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I would like to give a big thank you to the many special teachers I have had the pleasure of learning from throughout my education career. The passion, dedication and support you have provided (and continue to provide) does not go unnoticed nor unappreciated. Thank you. A large thank you goes out to my family who have been my biggest supporters throughout this journey and continue to champion me every day – I couldn’t have done it without you! And finally, a thank you to my friends; both past and present who have provided unconditional love and support over the course of this journey. Thank you for the many laughs, hugs, and preservation of my sanity – you guys seriously rock.

1.0 INTRODUCTION

The boreal forest represents a fire driven and adapted ecosystem; wildfire serves as an important ecological process, maintaining landscape heterogeneity, biogeochemical cycles, disrupting pest cycles, while also acting as an important driver for stand succession (Jahan and Deacon 2018). Prior to the industrial revolution, fire behaviour was manipulated and utilized as a tool to manage the land; fire was applied to improve hunting and gathering success, land clearing and as a means to protect community values (Pausas and Keeley 2009). Post industrialization, land use and the primary management approach shifted, favouring instead practices that excluded fire from the landscape. Fire suppression - used to accommodate contemporary socio-economic values and demands - has resulted in an unnatural build-up of volatile, wildland fuel resulting in increased fire potential across the landscape. Fuel loading increases the likelihood of large, high intensity wildfires extremely hazardous to vulnerable areas such as the Wildland-Urban Interface (hereafter referred to as the WUI) (Jahan and Deacon 2018). In addition to changes made to landscape management, climate change is expected to increase wildfire frequency and severity across the landscape. Higher temperatures and erratic precipitation patterns are expected to further increase the frequency of extreme fire weather thus ignition and fire potential (Zhang et al. 2019).

Increased fuel loads and inputs from a warming climate paralleled with continued growth of the WUI suggests increasing pressures on suppression practices in efforts to reduce losses, damages, and disruptions to socially and economically significant areas (Peter and Wang 2006). Current demand placed on wildfire management systems has spurred increasing exploration into proactive wildfire mitigation practices such as fuel reduction treatments in efforts to curb wildfire behaviour prior to an ignition event (Blackwell 2019). Fuel reduction treatments offer land managers increased opportunity to control wildfire behaviour; reducing the rate of spread, fire intensity and likelihood of crown fire initiation in efforts to increase suppression efficiency and success in areas of high vulnerability (Kalabokidis 1998). Fuel continuity and structure represent the only element of the fire triangle managers have direct control over, where element inputs such as weather and topography remain beyond management control. The primary objective of fuel management is to reduce fuel homogeneity, increasing the distance between physical fuel elements in efforts to disrupt the fundamental wildfire combustion processes and manipulate wildfire behaviour (Beverly et al. 2020). Fuel treatments include but are not limited to; thinning, removal of understory vegetation and accumulated biomass while also increasing the vertical distance between surface and crown fuel (Beverly et al. 2020).

1.1 OBJECTIVES

The purpose of this thesis is to explore the feasibility of fuel management strategies as a mode to increase community resilience to wildfire while also reducing pressures on suppression resources. A variety of fuel management strategies will be analyzed for efficacy and treatment longevity to achieve and maintain increased landscape resilience and resistance to high intensity wildfire activity. The findings of this report will be analyzed in context to remote communities typically characterized by limited suppression resource availability and increased vulnerability to wildfire activity.

2.0 LITERATURE REVIEW

2.1 WILDLAND FIRE SUPPRESSION

Wildfire suppression is represented by a variety of firefighting strategies used to reduce or eliminate wildfire on the landscape. Fire exclusion strategies are applied in areas of high social and economic value in efforts to protect both public and private property from loss, damage and the disruption associated with high intensity wildfire. Aggressive suppression and fire exclusion strategies across North America are a product of highly damaging wildfire events that occurred during the early 20th century. The management focus became characterized by wildfire prevention through immediate suppression of natural starts and the elimination of traditional burn practices (Long et al. 2021).

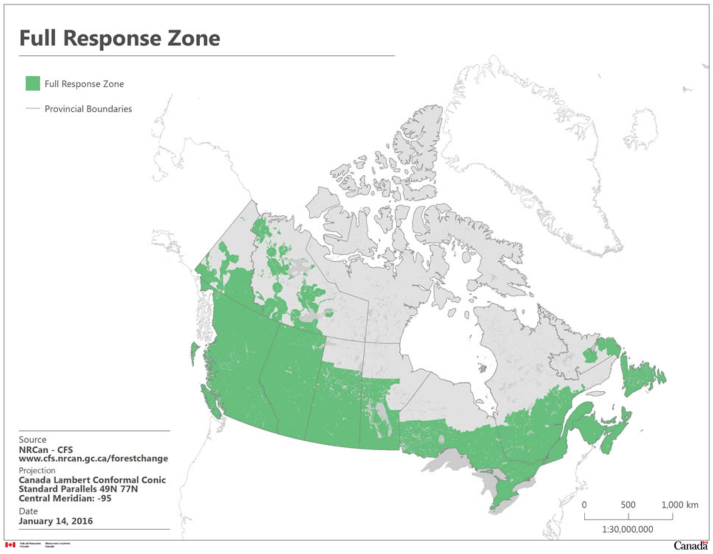

Figure 1. Full response zone in which all wildfires are actively suppressed (Natural Resources Canada (a) 2021).

Today, suppression is represented by rapid detection, response and extinguishment of wildfires linked to both timber resource and community protection objectives (Lake and Christianson 2019; Coogan et al. 2020). Figure 1 illustrates the provinces across Canada that practice full suppression systems as their primary wildfire management strategy in which all wildland fires are actively suppressed.

Suppression intensity is typically defined by the level of development present – where highly developed areas (such as the WUI) are assigned intensive suppression measures and remote, less populated areas are managed under an extensive suppression regime. Figure 2 illustrates the intensive and extensive fire management zones delineated for the province of Ontario. Management within these intensive wildfire management zones typically involves aggressive suppression efforts, rapid detection, and response to extinguish low to moderate intensity fires (Parisien et al. 2020).

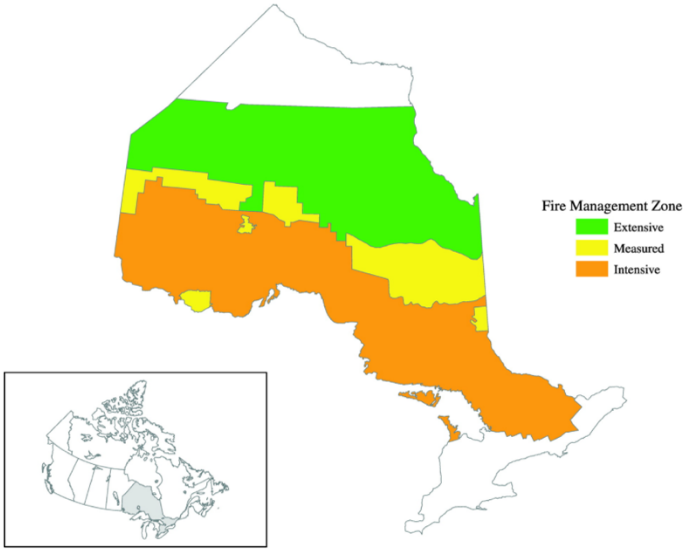

Figure 2. Fire management zones for the province of Ontario. Where full suppression efforts are applied within the orange, intensive zone (Martell and Sun 2008).

The boreal forest represents a fire prone ecosystem where stand succession and biodiversity values are shaped and driven by frequent, stand replacing wildfire disturbances (Schroeder 2010). Exclusion of fire across this landscape has resulted in alterations to the natural age class distribution, stand composition, structure, and an unnatural fuel load accumulation across the landscape. These alterations have resulted in landscapes more conducive to uncontrollable, highly damaging wildfire activity (Graham et al. 1999; Fernandes and Botelho 2003; Ager et al. 2006; Jahan and Deacon 2018).

Ager et al. (2006) suggest that suppression results in the unnatural densification of boreal stands than would be maintained under a natural fire regime. Unnaturally high stocking in stands results in increased vulnerability to pathogen and insect disturbance further decreasing a stand's resilience to wildfire (Ager et al. 2006; Parker et al. 2006). Parisien et al. (2020) suggests current wildfire management strategies result in fire deficit forests directly surrounding WUI communities. Recently burned forests - defined by Parisien et al. (2020) as forests burned within the last 30 years - provide an increased level of wildfire resilience as fine and coarse fuels are reduced, decreasing the probability of high intensity wildfire development (Tolhurst and McCarthy 2016; Lake and Christianson 2019; Parisien et al. 2020). Figure 3 depicts the relative abundance of recently burned forests within proximity to communities across Canada.

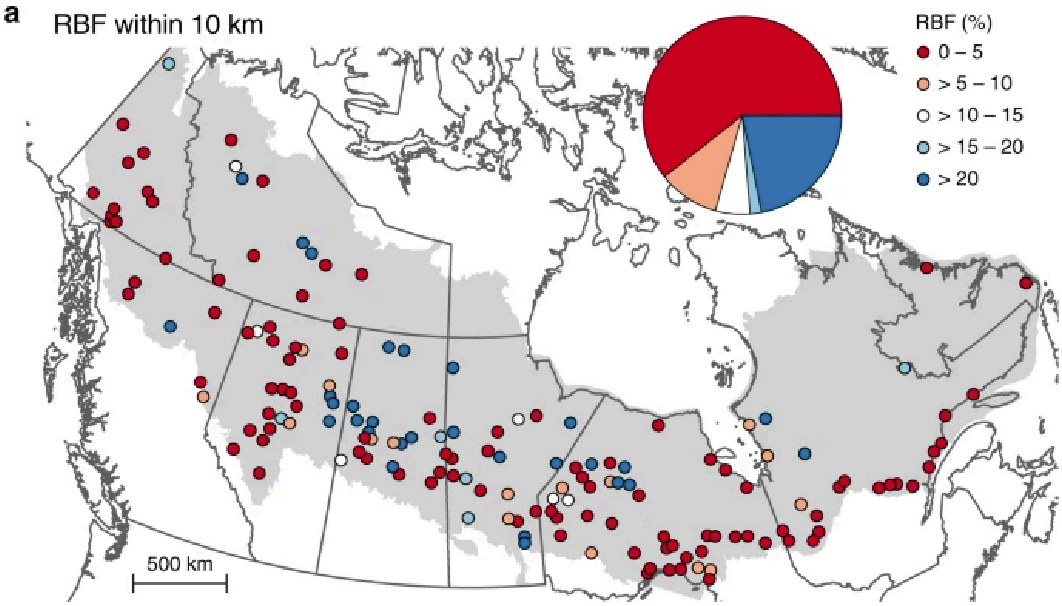

Figure 3. WUI communities buffered at 10 kilometers with a focus on surrounding forests inventoried for Recently Burned Forest (RBF) components (Parisien et al. 2020).

Parisien et al.'s (2020) findings suggest that the exclusion of fire on the landscape has resulted in forest matrices with increased flammability characteristics in direct proximity to highly developed areas.

2.2 CLIMATE CHANGE

Current climate projections indicate that increase to the mean annual temperatures are expected to increase the frequency, severity and total area burned annually across the boreal landscape (Wotton et al. 2005; Bush and Lemmen 2019; Coogan et al. 2020). The projected climate forecast suggests the current fire season may be lengthened by as much as 30 days (Hope et al. 2016) while increased frequency of fire weather is expected to further increase ignition potential (Coogan et al. 2020).

The total number of wildfires that occur in Ontario are projected to increase by 15 percent by 2040 and by 50 percent by the end of the century (Wotton et al. 2005). As a result, the total annual area burned is expected to increase by a multiplier of 1.5 to 4 times the current area burned across the boreal (Hope et al. 2016). Figure 4 illustrates how the current fire return intervals across the Canadian WUI are expected to change over time through the influence of a warming climate.

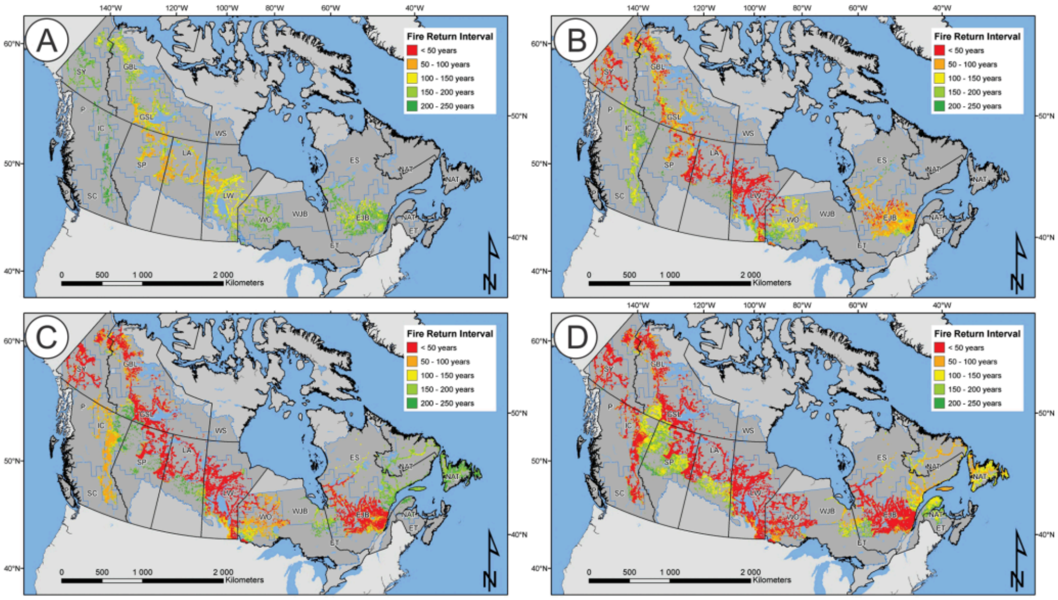

Figure 4. Location and exposure of WUI areas exposed to fire return intervals of FRI ≤ 250 years over four time periods. A) Current conditions 1961 - 1990; B) future conditions in 2010 - 2040; C) future conditions in 2041 -2070; and D) future conditions in 2071 - 2100. All projections modelled under a Representative Concentration Pathway (RCP) scenario of 8.5 (Erni et al. 2021)

Figure 4 represents a model run under the assumption current CO_2 emissions will remain unchanged and no significant climate change policy or legislation be enacted. Under this climate scenario a majority of the WUI is expected to see a fire return interval of less than 50 years by the turn of the century. Although this scenario represents the worst-case scenario it highlights the effect a warming climate is liable to have on wildfire frequency and behaviour and the implications this has for WUI communities and developments.

2.3 WILDLAND-URBAN INTERFACE

The WUI represents areas of high complexity where communities and developments overlap with wildland vegetation resulting in increased hazard exposure to wildfire (Johnston and Flannigan 2018; Beverly 2022). The Wildland Human Interface (WHI) encompasses the WUI, the Wildland-Industrial Interface (WII) as well as the Wildland-

Infrastructure Interface (INF); encompassing all anthropogenic engineering and developments. The WHI represents 17.3 percent of the total forested land base across Canada (Erni et al. 2021) while the residential WUI represents 3.8 percent measuring a total of 32.3 million hectares in size (Johnston and Flannigan 2018). Figure 5a) illustrates the WHI across Canada - visualising the overlap between the urban, industrial and infrastructure interfaces. Figure 5b) illustrates the WUI expanse across Ontario adjusted to represent WUI areas in proximity to hazardous wildland fuels.

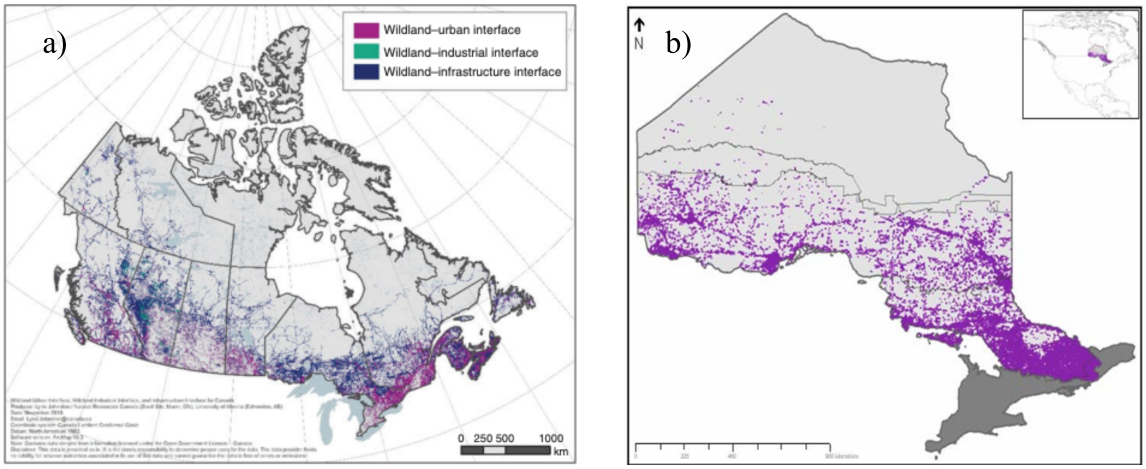

Figure 5. a) Illustration of the Wildland-Human Interface – A combination of the Wildland-Urban Interface with both the industrial and infrastructure interfaces. Johnston and Flannigan 2018. b) Ontario's mapped Wildland-Urban Interface – where purple areas have been corrected to represent high risk forest fuel material and development overlap (Bowman 2012).

Table 1 outlines the total Wildland Human Interface (WHI) across the province of Ontario, delineating the percent area defined by each interface.

Table 1. Total percent WHI area within the Western Ontario Homogenous Fire Regime (HFR) zone - where the WHI consists of the Wildland-Urban Interface (WUI), the Wildland-Industrial Interface (WII) and the Wildland-Infrastructure Interface (INF).

Area (km^2)	WUI	WII	INF	WHI
211 585	1.68	0.65	16.93	17.25

(Erni et al. 2021).

As the Canadian population continues to grow at a rate of one percent annually (Erni et al. 2021), so grows the WUI, effectively increasing the area required to be monitored, managed, and actioned in the event of ignition. Currently, 12.4 percent of Canada's population live within the WUI are expected to be increasingly impacted as wildfire frequency and area burned increase (Erni et al. 2021). The direct and indirect effects of wildfire in proximity to these areas result in economic and social disruption, damages and loss. Climate influenced projections suggest increases to destructive interface events further increasing the demand on suppression resources (Peter and Wang 2006; Johnston and Flannigan 2018).

2.3.1 Remote Communities

The WUI represented by remote communities are of special concern as these developments often intersect with forested areas susceptible to frequent, high intensity wildfire activity. The isolated nature of these communities lends to resource constraints, reduced accessibility for initial attack and suppression response further emphasizing the vulnerability of these communities to wildfire disturbance (Christianson 2015). A majority of these communities are represented by Indigenous populations, disproportionately affected by the direct and indirect effects of wildfire disturbances (Christianson 2015; Lake and Christianson 2019; Mottershead et al. 2020; Tithecott 2022). Figure 6 illustrates the intersection of Indigenous communities and areas burned across Canada.

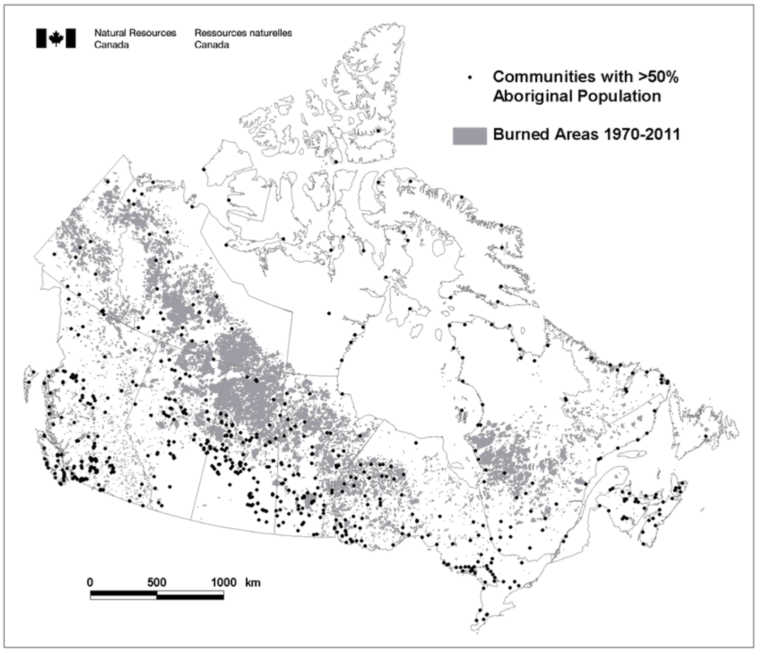

Figure 6. Indigenous community overlap with areas burned between 1970 and 2011 (Natural Resources Canada 2020).

As of 2021, 32.1 percent of all on-reserve Indigenous populations are located within the WUI; a 3 percent annual growth rate (Erni et al. 2021) paired with climate induced wildfire projections suggest these communities can expect greater wildfire disruption in future. Figure 7 illustrates the impact increasing fire return intervals under climate influence are projected to impact First Nation to 'other' communities.

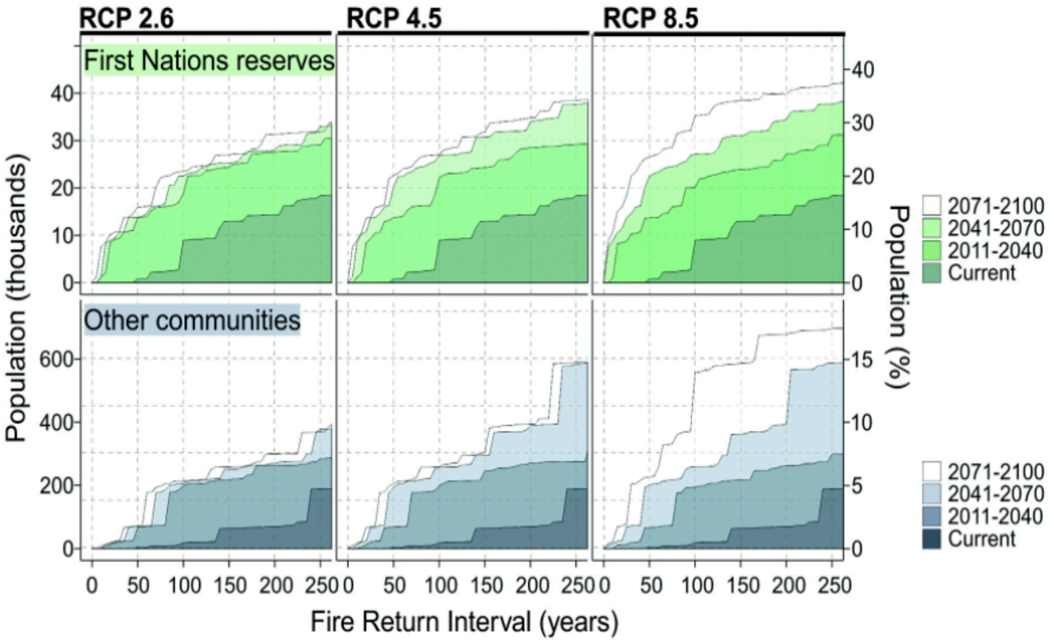

Figure 7. Percent population of interface communities impacted by increased fire return interval under different climate change scenarios from current intervals projected through to 2100. Where a Representative Concentration Pathway (RCP) value of 2.6 represents the best-case climate scenario with significant reduction to CO_2 emissions through to an RCP value of 8.5 representing no change to current emission and climate change trajectories (Erni et al. 2021).

Even under the most optimistic climate scenario, figure 7 highlights the disproportionate effect an increasing fire return interval is expected to have on Indigenous populations. These findings are significant as disruption within these communities reaches further than the direct impacts of wildfire - losses and damages to property - indirect effects such as evacuations often represent disruptive, traumatizing events as community members are separated and displaced to communities far from their homes for indeterminate amounts of time (Christianson and McGee 2019; Mottershead et al. 2020). One third of all evacuees and evacuation events due to wildfire are represented by Indigenous peoples in Canada (Erni et al. 2021). Figure 8a) illustrates the evacuation disparity recorded between Communities with a majority Indigenous population to other communities while figure 8b) highlights the positive trend associated with historical Indigenous evacuee counts as wildfire frequency in Canada increases.

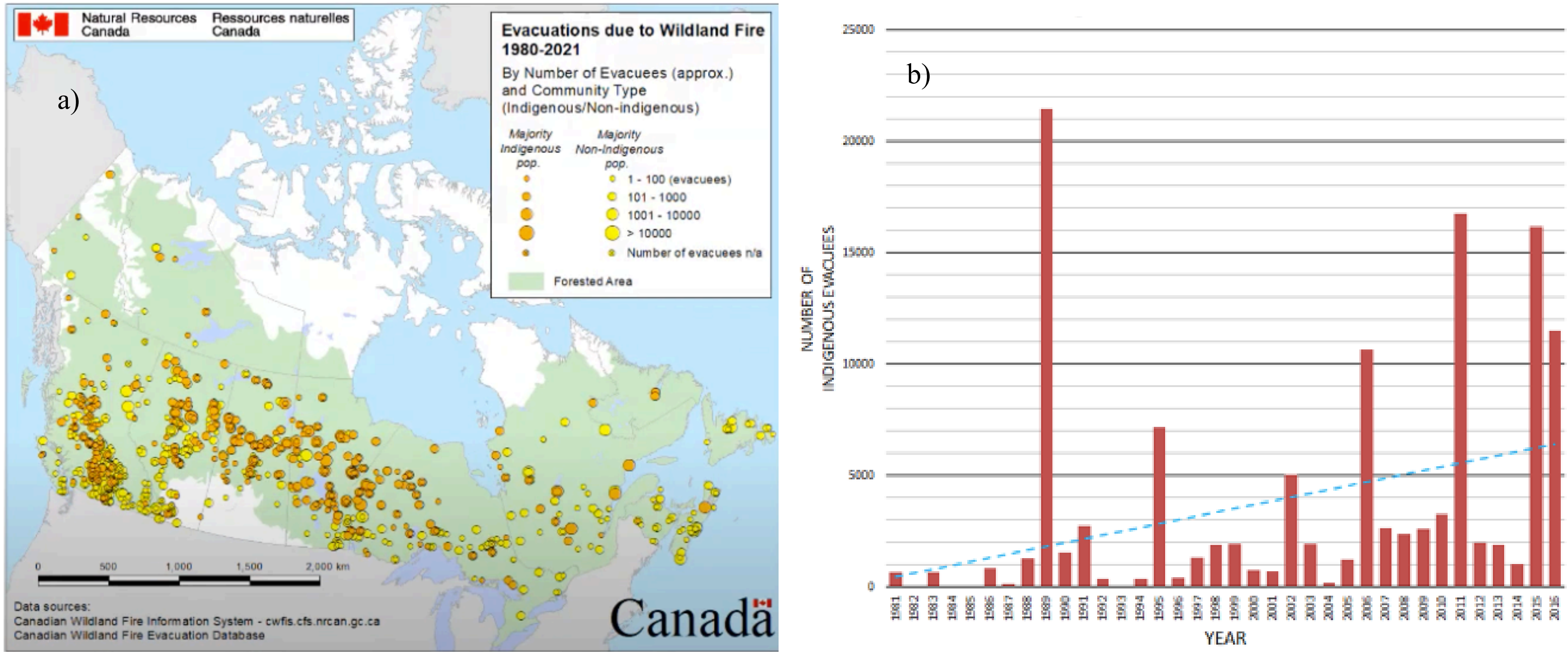

Figure 8. a) Evacuations due to wildland fire by number of evacuees and community type (1980 - 2021) (Christianson 2022).
b) Indigenous evacuees due to wildfire disturbance (1980 - 2016) (Christianson 2017).

Typically, evacuation events in Indigenous communities have been characterized by poor communication and information sharing between emergency response and the affected community (Christianson and McGee 2019 and Mottershead, et al. 2020). Poorly developed evacuation plans result in chaos, confusion and unnecessary delay further increasing stress levels of evacuees (Christianson and McGee 2019). Erni et al. (2021) suggest increased evacuation events within these communities may result in further structural and cultural losses, land alteration and inherent social disruption.

2.4 ECONOMICS OF SUPPRESSION

Increasing wildfire activity, area burned and WUI footprint will result in a larger demand placed on management and monitoring resources, Jahan and Deacon (2018) suggest the increasing demand is expected to become both ecologically and economically unsustainable. The protection and monitoring of public and private property, wood supply and critical infrastructure has resulted in the annual investment of 800 million to 1.4 billion dollars (Hope et al. 2016; Natural Resources Canada (a) 2021; Bénichou et al. 2021). Since 1970 suppression budgets have increased by an average of $150 million with each passing decade as demands continue to expand (Natural Resources Canada (a) 2021). Figure 9 visualizes the variable and fixed costs associated with fire protection in Canada over 40 years.

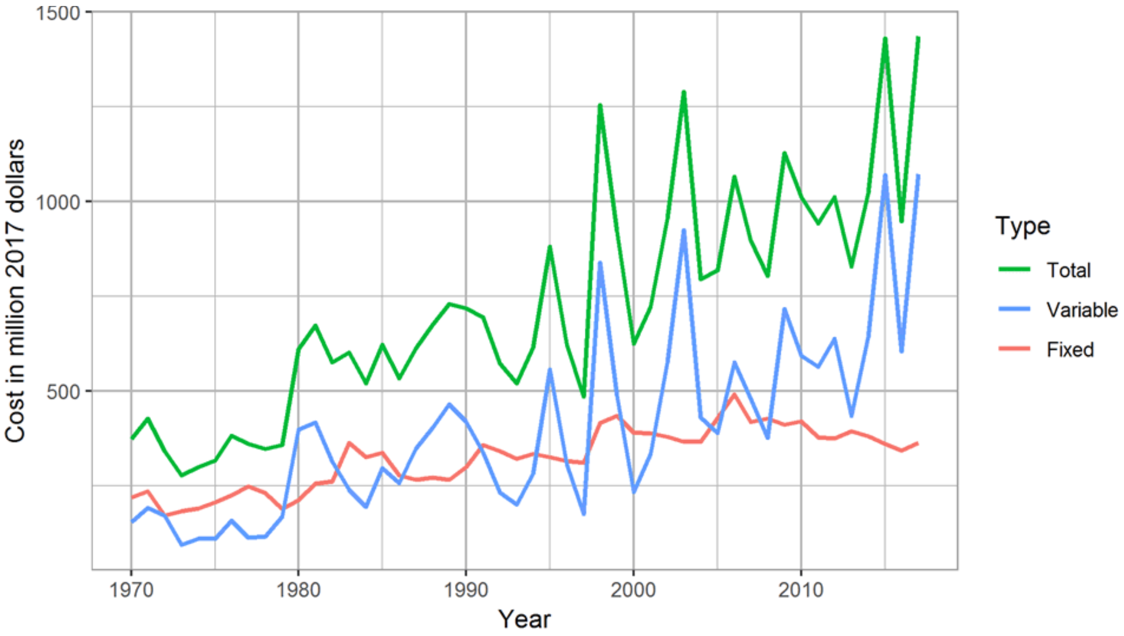

Figure 9. Cost of wildland fire protection in Canada (1970-2017) (Natural Resources Canada (a) 2021).

Measuring the total economic costs associated with wildfire are difficult to quantify; these costs often are reflected as a tally of suppression investment and values lost (Hope et al. 2016). Difficult to measure in dollar amounts are factors such as long-term human health, as well as losses to ecosystem function and services that may impact social and economic resources in future (Zybach et al. 2009). As fire activity and severity under climate projections are expected to increase so too are the expected financial requirements to manage and address these events.

2.4.1 Costs

Suppression costs are variable and challenging to calculate due to the stochasticity associated with wildfire disturbance events. Weather, fuel conditions, total area and location of the burn as well as operational factors represent variable inputs that influence the costs associated with suppression efforts (Hope et al. 2016). Gebert et al. (2006) suggest fire intensity, size and proximity to community are the primary factors that govern suppression expenditures. Table 2 details the direct, indirect and post fire costs associated with wildfire disturbance and suppression efforts.

Table 2. Costs associated with wildfire suppression.

Cost Type	Direct	Indirect	Post Fire
Suppression	Wages, Transportation, Equipment, Services, Supplies, Depreciation, Community losses and disruption	Preparedness and training, Equipment maintenance, Investment into forest management planning	Repairs, Capital loss, Medical costs
Property	Structures, Communication and transportation networks, Timber and agriculture	Insurance, Building/landscape maintenance	Reductions in property values, Repair
Public Health	Injuries, Fatalities, Hospitalizations, Evacuations, Medical equipment	Health insurance	Long term health effects, Cost of care
Vegetation	Timber, Significant forage areas, Agriculture, Habitat	Growing stock	Future harvest, Replanting
Recreation and Aesthetics	Closures, Damaged assets	Pre-fire investment	Restoration, Degraded assets
Energy	Grid closures and shutdowns	Pre-fire investment, Planning costs	Repairs, Sales reductions
Culture and Heritage	Sites supporting businesses	Pre-fire investment	Restoration, Loss of site

*While the author recognizes the significance of ecological function and its subsequent importance on ecosystem productivity, table 2 omits the ecological and biodiversity direct, indirect and post fire costs in efforts to focus on social and economic values.

Zybach et al. 2009 and Prevail 2020.

Zybach et al. (2009) highlight the short and long term direct, indirect and post fire costs can amount to 10 to 50 times the reported suppression costs. As the threat of wildfire frequency, intensity and severity continue to rise, Hope et al. (2016) suggests annual suppression costs currently considered extreme - experienced at a frequency of once every 10 years - are expected to increase to a frequency of once every two years suggesting significant increases to current management expenditures

2.5 SHIFTING MANAGEMENT PARADIGMS

Future wildfire projections have spurred further research and development of wildfire mitigation strategies; strategies designed with greater acceptance and incorporation of fire on the landscape over conventional exclusion practices. The threat of increased wildfire due to fuel accumulation and a warming climate has highlighted that suppression as a primary landscape management tool represents an ecologically and economically unsustainable practice (Jahan and Deacon 2018). Without modification to the current wildfire management practice these disturbances are expected to exceed the available financial, equipment and personnel resources (Johnston and Flannigan 2018). Current projections have provoked change and innovation to management strategies that favour proactive, mitigation strategies designed to curb wildfire behaviour in high value areas prior to ignition events. Successful application and management reform will require continued collaboration between multiple stakeholders, agencies, governments, Indigenous groups and the public to effect lasting change. A new focus has begun to emerge as managers aim to achieve healthy, wildfire resilient forests for future generations (Tithecott 2022).

2.5.1 Fuel Management

Fuel reduction and management strategies are now being explored as a means to reduce the potential for fast spreading, high intensity, crown fires that occur naturally in the fire-prone boreal ecosystem (Beverly et al. 2020). Fuel management practices offer land managers increase suppression success and efficiency in areas of high vulnerability by effectively reducing the potential for highly damaging wildfire behaviour. These strategies are designed to increase community protection and resilience to the risks posed by wildfire. Fuel management strategies are typically applied in conifer dominated stands due to the highly flammable nature of species such as black spruce (P*icea mariana* Mill.), jack pine (*Pinus banksiana* Lamb.) and Western lodgepole pine (*Pinus contorta* Douglas) (Beverly et al. 2020). Fuel availability and continuity represents the only element in the fire behaviour triangle (pictured in figure 10) land managers can modify in efforts to manipulate wildfire behaviour. Uncontrollable drivers of wildfire activity include fire weather, time since last fire as well as the topography and aspect of the land that govern factors such as short- and long-term droughts, fuel hazard levels and fuel drying rates (Tolhurst and McCarthy 2016). The primary objective of fuel reduction treatments are to reduce the available fuel for ignition; designed to effectively reduce flame length, surface fire intensity, rate of spread and potential for crown fire (Prichard et al. 2021). This is achieved through reductions to available surface fuels, increasing the height to live crown ratio, reducing the canopy bulk density while reducing the continuity of available

Figure 10. Fire behaviour triangle (Fitzgerald et al. 2019).

fuels at a site (Graham et al. 2004; Beverly et al. 2020). Wildfire intensity and rate of spread can be reduced through fuel management in efforts to increase the ease and speed at which wildfire can be suppressed, providing opportunity for strategic fire line control and anchor points while also increasing the probability of self-extinguishment (Grant and Wouters 1993; Tolhurst and McCarthy 2016). While fuel management and mitigation strategies offer opportunity for reduced fire behaviour in treatment areas it is important for land managers to understand that under extreme fire weather conditions these treatments may be rendered ineffectual at reducing fire behaviour (Graham et al. 2004; Tolhurst and McCarthy 2016; Blackwell 2019). Outlined below are some of the primary fuel management strategies employed in efforts to reduce wildfire activity in areas of high value or vulnerability.

2.5.1.1 Prescribed Burn

Prescribed burns or fuel reduction burns are designed to remove accumulated organic material, plant debris and understory plants that add to the surface fuel load available for ignition (Grant and Wouters 1993). Surface fuels are typically composed of fine fuels such as needles, twigs and bark, cured grasses and shrubs that represent an aerated, highly combustible layer that governs fire rate of spread (Fernandes and Botelho 2003; OMNRF 2017; Beverly et al. 2020). Prescribed burns alter the fuel bed characteristics by reducing the overall fuel energy stored on the site (Graham et al. 2004). The objective of these burns are to disrupt the vertical and horizontal fuel structure, reducing fuel continuity in efforts to moderate wildfire intensity and slow the rate of spread (Fernandes and Botelho 2003; Graham et al. 2004; Penman et al. 2020). In addition, low severity fire maintains forest structure variability promoting landscape resilience to future wildfire (Koontz et al. 2020). Figure 11 visualises how the horizontal and vertical fuel structures are altered through prescribed burn treatments. Figure 11 illustrates how the surface to live crown and dead fuel ratio is increased after a burn treatment while the shrub and litter layer loads are significantly reduced comparatively to pre-treatment conditions. Increasing the height to live crown and removing ladder fuels such as the shrub layer and larger coarse woody material reduces the likelihood of active crown fire initiation where the reduction of fine, surface fuels typically result in a decreased or slowed rate of spread (Grant and Wouters 1993; Beverly et al. 2020). In treated areas, fire takes longer to reach peak fire behaviour under severe weather conditions effectively lengthening the window of time for initial attack, increasing the efficiency of suppression and safety of personnel (Tolhurst and McCarthy 2016).

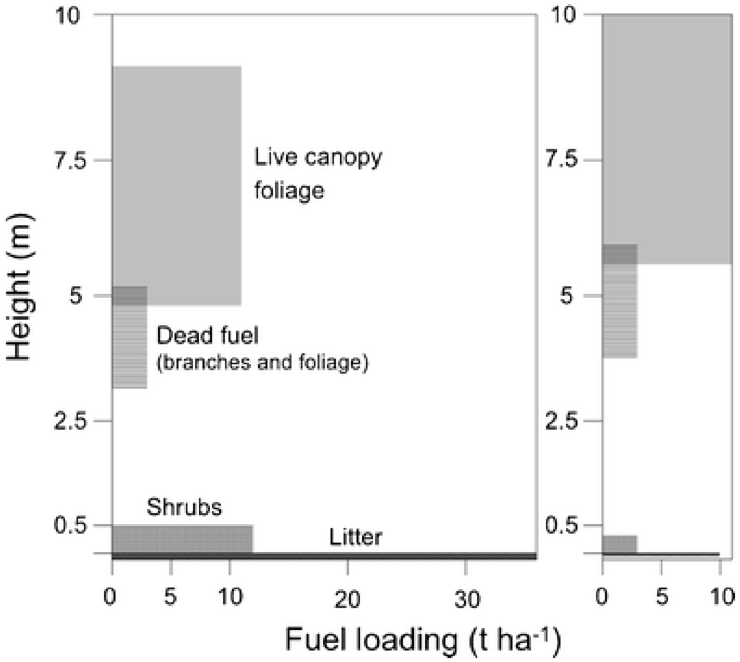

Figure 11. Comparison of stand structure of an untreated (left) to prescribe burn treated (right) pine stand (Fernandes 2015).

The efficacy of the burn treatment - measured by reduced fire behaviour post treatment - diminishes over time as fine fuels, duff layers, coarse woody debris and live surface fuels naturally reaccumulate on the site. Van Wagtendonk and Sydoriak (1987) illustrate the reduction to fuels post treatment and subsequent re-accumulation of surface fuels over time in figure 12.

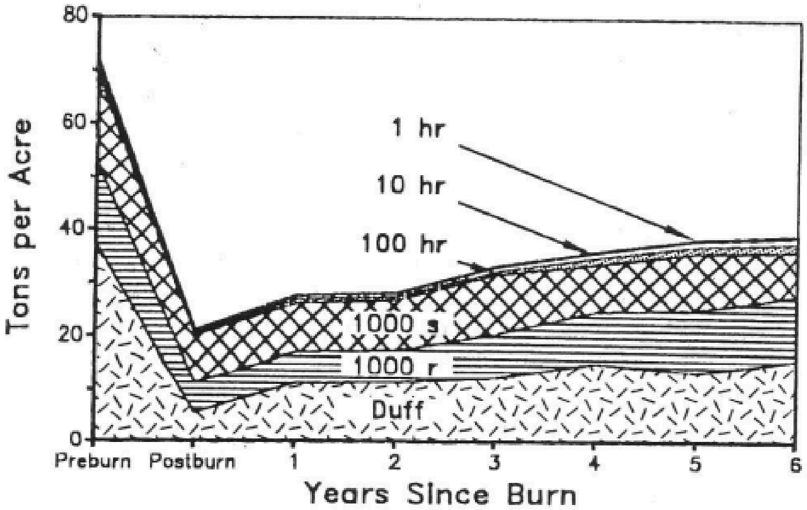

Figure 12 Illustrates fuel accumulation post treatment (Van Wagtendonk and Sydoriak 1987).

These findings suggest 55 percent of the total pre-treatment fuel weight is achieved six years post treatment while the one-hour fine fuel accumulation has reached nearly 100 percent of its pre-treatment weight (Van Wagtendonk and Sydoriak 1987). Evidence suggests prescribed burn treatments show a measurable reduction in wildfire behaviour for up to 10 years post treatment (Van Wagtendonk and Sydoriak 1987; Grant and Wouters 1993; Fernandes and Botelho 2003; Martinson and Omi 2013; Tolhurst and McCarthy 2016). It is important however to note that treatment efficacy is largely affected by additional factors such as seasonal dryness or drought, topography, fire weather and fire size that play a significant role in treatment longevity (Martinson and Omi 2013 and Tolhurst and McCarthy 2016).

2.5.1.2 Thinning

Thinning represents a fuel management strategy that offers managers increased control over stand structure, species composition while also maintaining stand aesthetics which may be of consequence to public interest (Graham et al. 2004; Parker et al. 2006). Reducing the density or crown closure of a stand can be used as a measure to slow or stall crown fire in sensitive areas. Increasing intercrown spacing between mature individuals may result in the transition of dangerous crown fires to more manageable surface fires while ignition within treatment areas are less likely to develop into active crown fire (Schroeder 2010; Beverly et al. 2020). The primary objectives of stand thinning are to reduce stand density and available canopy fuel load as a means to decrease fire behaviour within the treatment area (Schroeder 2010). In order to achieve the desired effect of reduced fire behaviour within the treatment area, thinned material must be removed from the site so as to reduce available fuel loads (Kalabokidis 1998; Graham et al. 2004; Schroeder 2010; Martinson and Omi 2013). Thinning without effective fuel management results in ineffective fuel management as the fuel load on the site remains the same, only altered is the form at which it occurs. Figure 13 illustrates the importance of removing thinning slash from the treatment site.

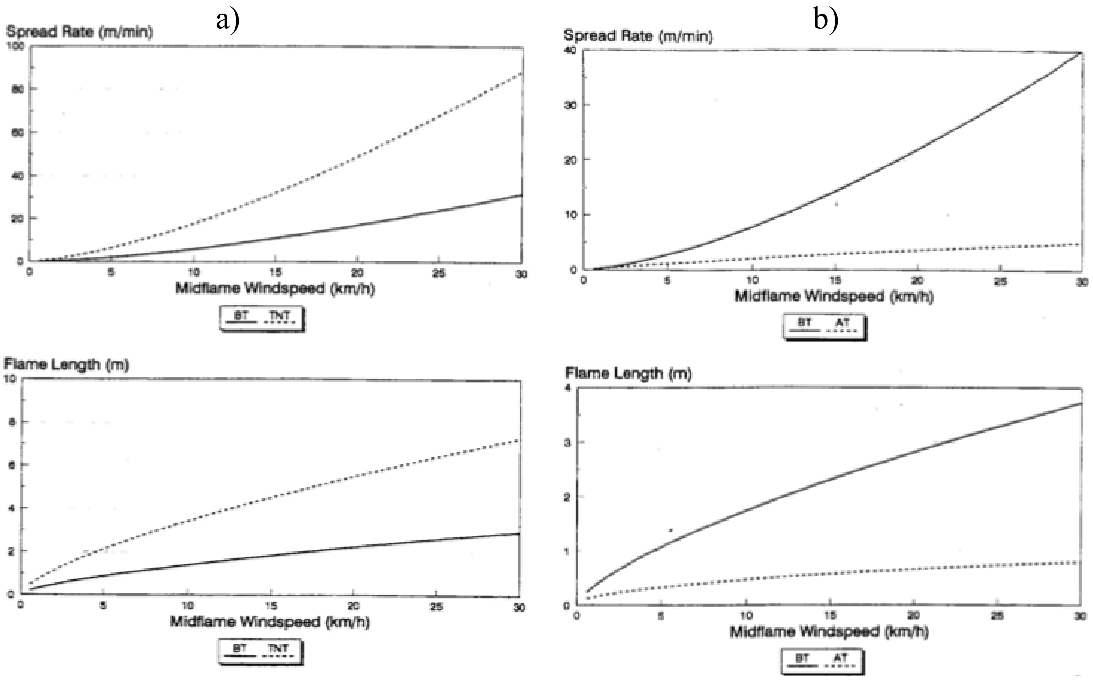

Figure 13. Where the solid line (BT) represents fire behaviour pre-fuel treatment while the dashed line (TNT/AT) represents post treatment surface fire response. A) Depicted is the fire behaviour to stand thinning without any slash removal. B) Depicted is the fire behaviour response to both thinning and slash removal (Kalabokidis 1998).

Note the significant reduction to both rate of spread and flame length achieved in the thin and slash removal treatment comparatively to a thinning treatment with no slash management. The OMNRF (2017) suggest common spacing standards suggest 40 percent canopy closure and an inter-tree spacing of 1.5 times the crown width or 3 meters between individuals. Schroeder's (2010) findings (supported by Beverly et al. 2020 and Banerjee et al. 2020) found that thinned plots showed increased resilience to crown fire initiation at greater wind speeds comparatively to natural, untreated stands. Results indicate that reductions to stand density may increase the length of time required to achieve peak fire behaviour, resulting in the increased success of fire containment and control by initial attack efforts (Schroeder 2010). Figure 14 compares the wind speed required to initiate passive crown fire in treated to untreated stands.

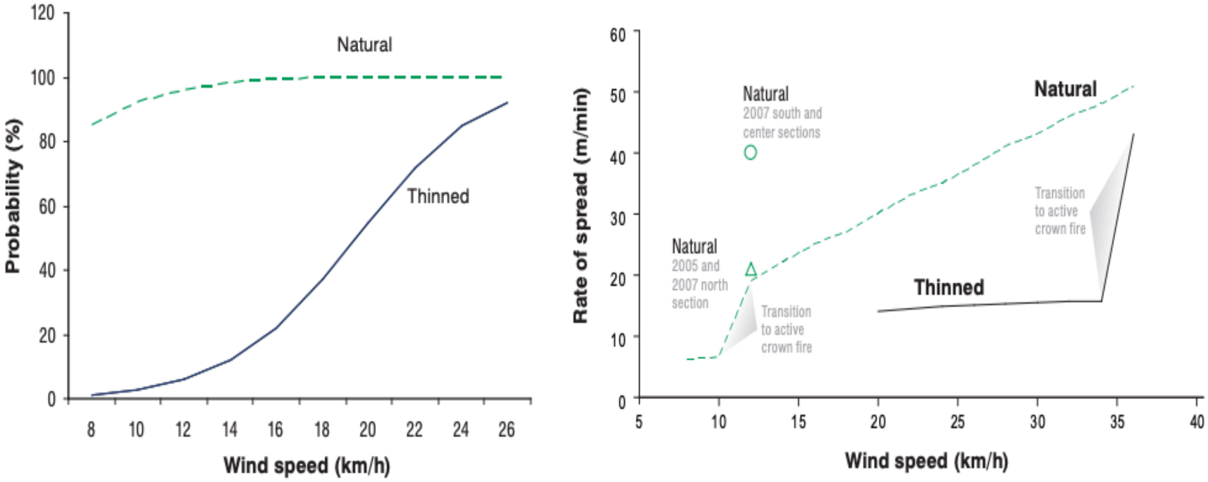

Figure 14. Fire behaviour modeling within a natural to thinned jack pine (*Pinus banksiana* Lamb.) stand – Findings show increased wind activity is required to initiate active crown fire (Schroeder 2010).

Notice that wind speeds must reach moderate to high level before the probability of surface to crown fire transition is likely to occur in treated stands. Schroeder's (2010) study suggests thinned stands are resistant to passive crown fire initiation up to three times the wind speed of untreated stands. In addition to reducing fire activity, initial attack crews reported accessibility, visibility and safety were improved as stand density declined and potential danger trees were removed in treated areas (LM Forest Resource Solutions Ltd. 2020). Improved also were response times and efficacy of ground and aerial suppression efforts.

Thinning from below or midstory thinning removes ladder fuels, increases the surface to live crown ratio, increasing intercrown spacing while also removing the shade tolerant understory component (Graham et al. 1999; Fitzgerald and Bennett 2013). Banerjee et al. (2020) suggests thinning treatments applied at the midstory in contrast to thinning mature, overstory individuals may produce the most effective wildfire mitigation results. Decreasing crown closure may impact fine fuel moisture content due to increased solar and wind exposure while effectively reducing understory relative humidity levels (Graham et al. 2004; Varner and Keyes 2009; Butler et al. 2012; Beverley et al. 2020; Banerjee et al. 2020). Increased wind activity within a stand may also result in increased rate of spread and erratic fire behaviour increasing the difficulty to control and suppress wildfire activity (Varner and Keyes 2009). Figure 15 illustrates Banerjee et al.'s (2021) findings when modelling midstory thinning treatment intensities on wildfire activity for both dry and moist site types.

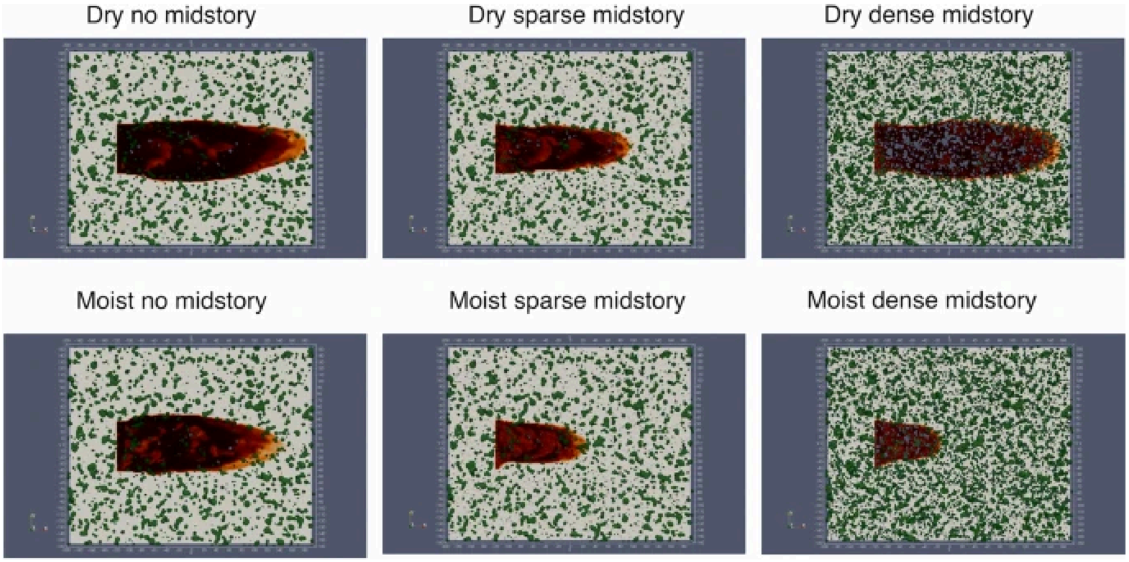

Figure 15. Midstory thinning intensity on dry to moist sites with modelled fire response in each treatment. Where the modelled treatment intensities decrease from left to right (Banerjee et al. 2020).

Banerjee et al.'s (2020) model (supported by OMNRF 2017 and Beverly et al. 2020) suggests moderate level thinning treatment within the midstory provides the greatest reductions in wildfire intensity while also reducing the probability of surface to crown fire transmission in both dry and moist sites. Midstory thinning strikes a balance between altering and reducing the vertical fuel structure while maintaining surface fuel moisture levels through maintenance of shading and increasing wind drag within the stand.

Thinning treatments have been recorded successful at reducing active crown fire behaviour for an approximated 8 to 10 years (Vaillant et al. 2013). Analogous to prescribed burn treatments, treated areas will reaccumulate the removed fuel component over time that subsequently impact both flame length and rate of spread (Vaillant et al. 2013).

2.5.1.3 Thin and Burn

Thin and burn combination treatments have been reported as the most effective treatment at successfully reducing fire behaviour (Martinson and Omi 2013). Both vertical and horizontal fuel components are significantly altered and reduced, altering fire intensity, and increasing site resilience to future fire activity (Graham et al. 1999). Findings suggest sites treated with thin and burn application yielded reduced mortality rates within residuals as the percent crown scorch and the burn severity index were significantly reduced in comparison to sites where thinning only treatments were applied (Prichard et al. 2010; Fernandes 2015). Thinning prior to the burn application also has the added benefit of keeping fire closer to the ground, reducing crown damage to residuals while further reducing the risks associated with escape or accidental release of prescribed fire into the crown (Parker et al. 2006).

2.5.1.4 Fuel Conversion

Forest management planning and harvest can be utilized as a tool to adjust the spatial arrangement of vegetation and fuel continuity, subsequently influencing fire size, rate of spread, intensity, and fire severity at a landscape scale (Koontz et al. 2020;

Beverly 2022). Fuel conversion is the transition of highly flammable fuels toward less flammable or fire resilient stands (Le Goff et al. 2005; Matute 2021); heightened stand resilience can be achieved through increased retention of fire-resistant species, altering the stand structure or age class distribution through harvest and renewal operations (Graham et al. 2004; Long et al. 2021). Stand heterogeneity and variable structure may result in decreased rates of spread, reduced probability of crown fire initiation or spread while also discouraging eruptive fire behaviour due to reduced fuel continuity (Koontz et al. 2020). Prichard et al. (2021) suggest the use of the Individuals, Clumps and Openings (ICO) method can be applied to achieve structural heterogeneity within the stand; effectively reducing edge to interior ratio while encouraging drought resistance in retained individuals while also reducing the potential for development and/or sustained crown fire activity. ICO was designed to emulate the structural patterns achieved and maintained by frequent burn events (Prichard et al. 2021).

Increasing the hardwood component of a stand may result in reduced fire activity in treatment areas due to increased moisture content and lower concentrations of volatile oils that are typically associated with conifer foliage (Fitzgerald and Bennett 2013). Late successional, conifer dominated stands are characterized by increased volumes of small diameter, fine fuels that are highly combustible - these high density, late successional conifer stands are typically associated with increased rates of spread and increased head fire intensity (Hely et al. 2000). Strategic planning and harvest within these stands can be used to reduce the overall flammability of a stand; Erni et al. (2018) suggest younger forested stands have an increased resistance to ignition and fire spread that may result in mitigation effects that extend past the area of treatment termed a ‘fire shadow’. Treatments designed to alter fuel arrangement and age class distribution across the landscape can modify fire behaviour as fire is repeatedly forced to navigate around or through treated areas effectively reducing fire intensity and rates of spread (Conrad and Hillbruner 2003). Large, landscape level applications may indirectly reduce risk to communities as crown fire potential, ember production and smoke impacts are reduced by increasing the surrounding forest's resilience to wildfire (Prichard et al. 2021).

2.5.2 Barriers to Practice

The largest barrier to effective wildfire mitigation efforts remains adequate and consistent funding (Copes-Gerbitz et al. 2022; Christianson 2022). Where current wildfire management strategies represent a reaction-based approach to wildfire stimuli, mitigation strategies are carried out in a pre-emptive fashion, without guarantee the treated area will burn before losing mitigation efficacy. Beverly (2022) terms hazardous fuels the 'grey goose', where the outcome (should wildfire ignite) is known but when ignition will occur is unknown. It is the stochastic nature of wildfire disturbance paired with the cyclic nature and associated financial requirement that results in resistance to and inconsistent funding for effective mitigation application (Donovan and Brown 2007). Treatment type and the size of the area treated are the two primary factors dictating fuel treatment costs (Hesseln and Berry 2004). Where costs can be highly variable due to a variety of external factors, fuel treatments in WUI areas have been reported as significantly higher due to increased complexity and risk associated with proximity to values and developed areas (Hesseln and Berry 2004; Beverly et al. 2020; Prichard et al. 2021). First Nation and smaller (<5000 population) rural and remote communities face a lack of financial resources that serves as a barrier to effective engagement in proactive wildfire mitigation practices (Copes-Gerbitz et al. 2022).

Indigenous communities face additional jurisdictional issues that affect awareness and accessibility to provincial funding due to federal jurisdiction over Reserve lands (Copes-Gerbitz et al. 2022).

Provincial policy and legislation surrounding wildfire management serves as the second largest barrier to effective fuel management practice (Christianson 2022). While land managers begin to recognize the significance of wildfire on the landscape, reintroduction of Indigenous cultural burning and other burn treatment practices are frequently met with policy obstacles and slowdowns by way of liability and air quality concerns (Long et al. 2021; Copes-Gerbitz et al. 2022). Currently, culturally led burn practices are not supported by government led initiatives for proactive wildfire management (Copes-Gerbitz et al. 2022). Cultural and traditional burning are met with similar resistance as is experienced with funding - where wildfire mitigation and management policy and legislation is dictated at the provincial government level while First Nation Reserve affairs are managed beneath the federal level resulting in disconnect and increased jurisdictional complexity (Christianson 2022).

Social factors also impact engagement, support, and acceptance of wildfire mitigation practices. Typically, treatments that are easiest to implement and least likely to affect community values are most widely accepted (Copes-Gerbitz et al. 2022). Mitigation treatment efficacy and familiarity greatly influences community support for these applications highlighting the importance for informed community leaders and officials within this space.

2.5.3 Bridging the Gap and Application

Today, a majority of the wildfire mitigation projects are carried out across Western Canada. British Columbia (B.C.) and Alberta employ and encourage the use of FireSmart principles as a means for increased community protection against wildfire events. B.C. hosts a variety of programs designed to subsidize the costs of wildfire mitigation practices; programs such as the Community Resilience Investment (CRI) program (previously Strategic Wildfire Prevention Initiative (SWPI)) designed to support wildfire mitigation within the WUI (B.C. Community Forest Association 2018). Hazardous fuel evaluation and identification programs such as the Community Wildfire Protection Plans (CWPP) are used to assist local governments identify risks to the community while highlighting mitigation and preventative measures designed to increase community protection and resilience to wildfire (RDCK 2021). The government of B.C. has just released the 2022 budget allocating an additional $145 million dollars toward strengthening emergency management and wildfire services over the next three years. Additionally, the B.C. government will now cover 100 percent of the costs associated with creating community wildfire plans and expand the scope of these plans to provide increased coverage on Indigenous Reserves and private lands (Copes-Gerbitz et al. 2022). The province's wildfire service will transition to a year-round firefighting and risk mitigation workforce where proactive services will be focused on prevention, preparedness, response, and recovery (Potestio 2022). Transitioning from seasonal, contract-based work will increase job security resulting in greater workforce and experience retention (The Canadian Wildfire Network 2022).

Active fuel management application is highlighted in FPInnovations ‘The Forest Will Burn’ documentary released in 2020. The community of Kluskus of the Lhoosk’uz

Dene Nation, the Esketemc community at Alkali Lake and the Kwadach Nation at Fort Ware are showcased as they utilize forest operations in direct proximity to communities in an efforts to abate wildfire risks and protect communities while simultaneously contributing to local economies. Merchantable timber is removed and used for firewood and sawlogs for small community sawmill operations while the residual, unmerchantable biomass is utilized in bioplants. These plants provide communities with electricity and/or heat, effectively reducing these communities' reliance on expensive, unsustainable fuels such as diesel and propane fuel. These types of wildfire mitigation and protection practices create employment and participation opportunities for community members further strengthening the health and economy within these communities.

2.5.3.1 Ontario

2021 represented one of Canada’s busiest fire seasons in recent years; a total of 4.18 million hectares burned across the country nearly doubling the 10-year average (Natural Resources Canada (b) 2021). Figure 16 illustrates the area burned by province contrasted against the 10-year recorded average. B.C., Saskatchewan, Manitoba, and Ontario had areas burned in the 2021 season that far

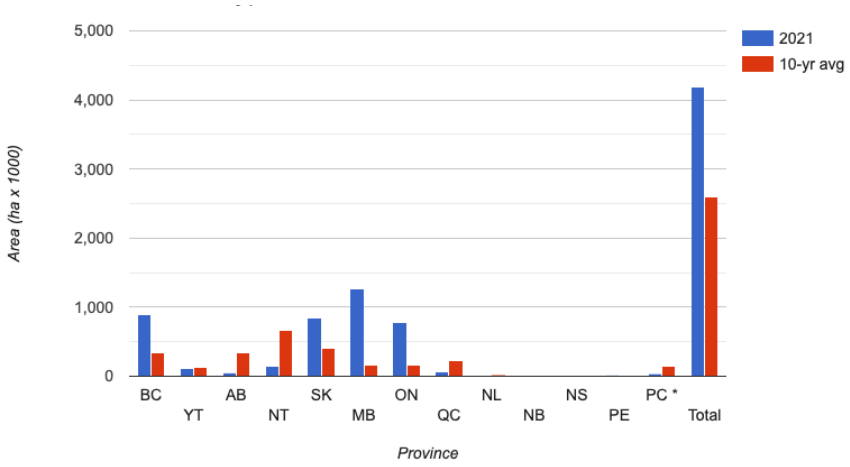

Figure 16. Area burned across Canada (recorded in thousands of hectares) in 2021 (Natural Resources Canada (b) 2021).

exceeded their 10-year average. Ontario experienced a 487 percent increase in area burned over its 10-year average with a total of 773, 404 hectares burned - a majority concentrated across the Northwestern quadrant of the province (Natural Resources Canada (b) 2021). These fires resulted in eight, large evacuation events in Poplar hill, Deer Lake, Pikangikum, Keewaywin, Cat Lake, North Spirit Lake, Koocheching and Wabaseemong First Nations. 3400 community members were displaced from their homes to a variety of host communities across Ontario and into Manitoba (Mclarty 2022). The Nishnawbe Aski Nation (2021) (NAN) released the 'Emergency Management for First Nations' report in May of 2021 calling for increased government support, funding, and collaboration with First Nations in efforts to address gaps within the emergency management system. The report called for increased funding allocation toward emergency preparedness, mitigation efforts as well as greater recognition of the differences between normalized Ontario municipalities and First Nation communities (Nishnawbe Aski Nation 2021). Increased collaboration and communication between all levels of government and Indigenous Peoples are hoped to breathe system reform into Ontario's current wildfire and emergency management agencies.

4.0 CONCLUSION

Current field observations suggest future wildfire activity will meet or exceed current projections with current warming trends and fuel mosaics across the boreal forest (Tithecott 2022). Increased interface events are expected as the WUI expands and wildfire frequency, intensity and area burned increase across the landscape. Research suggests historic wildfire management - based heavily on fire exclusion - has resulted in unnatural forest densification, fuel buildup and age class distributions prone to the development of high intensity, uncontrolled wildfire. Future projections and recent wildfire events have encouraged amendments to current management strategies, employing instead more proactive approaches designed to increase community resilience and protection against highly damaging wildfire. Evidence suggests mitigation efforts such as fuel reduction treatments offer land managers increased control over wildfire behaviour. Reducing fire intensity, rates of spread and crown fire potential increases opportunity for increased suppression efficacy and wildfire control in areas of social and economic significance. Treatment application in these areas may improve landscape resilience to wildfire effectively reducing loss, damage and disruption risks associated with high intensity wildfire. Proactive mitigation efforts are imperative in remote and Indigenous communities, disproportionately affected by wildfire disturbance events that result in frequent, damaging community disruption. Addressing fuel continuity and structure at the landscape level may prove most effective as successfully reducing wildfire behaviour, indirectly reducing risks to WUI communities. While wildfire mitigation practices have gained momentum across the Western provinces of Canada, successful treatment application and routine maintenance are currently challenged with inconsistent government funding, general awareness, and social acceptance. Current events and projected outcomes continue to spur exploration, research and development slowly affecting change within the boreal wildfire management spheres.

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APPENDIX