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Review

Stand-Level Fuel Reduction Treatments and Fire Behaviour in Canadian Boreal Conifer Forests

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Abstract: Stand-level fuel reduction treatments in the Canadian boreal zone are used predominantly in community protection settings to alter the natural structure of dominant boreal conifer stands such as black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia*). The aim of these fuel treatments is to inhibit the development of fast-spreading, high-intensity crown fires that naturally occur in boreal forest ecosystems. We document fuel treatment design standards used in boreal forests in Canada and review data requirements and methodological approaches for investigating fuel treatment effects on fire behaviour. Through a series of illustrative examples and summaries of empirical observations, we explore the implications of data and modelling assumptions used to estimate fire behaviour in fuel-treated areas and identify insights about fuel treatment effectiveness in boreal conifer stands. Fuel treatments in black spruce, jack pine and lodgepole pine stands were generally effective at reducing modelled and observed fire behaviour and inhibiting crown fire development and spread under low to moderate fire weather conditions. Evidence suggests that fuel treatments in these fuel types will be ineffective when rates of spread and wind speeds are very high or extreme. High surface fuel loads combined with the relatively short stature of boreal conifer trees can further undermine fuel treatment efforts. Priority areas for future study include examining alternatives for managing surface fuel loads in treated stands, exploring the viability of alternative horizontal fuel reduction protocols such as clumped fuel configurations, and integrating suppression and containment strategies within the fuel treatment planning and design process.

Keywords: vegetation management; wildland–urban interface (WUI); FireSmart; fire risk; mitigation; crown fire initiation; crown fire modelling; fuel structure; wildland fire; fire management planning; Canada

1. Introduction

The North American boreal zone traverses the entire Canadian land base (Figure 1, [1]) and is characterized by high-intensity, crown fire ecosystems fueled by conifer species that have coevolved with wildfire [2,3]. Fire behaviour and fuel structure in boreal black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia*) stands vary by tree species [4] and factors such as stand age [5,6]; however, at maturity, these stands commonly present in dense, even-aged structures, with a continuous canopy of fuels that can support high-intensity crown fires [2,3]. In black spruce stands, surface fires burning in abundant feather moss fuel beds and slowly decomposing flammable litter can reach intensities that enable easy vertical transition into tree crowns, which is further facilitated by branches that extend nearly to the ground, high bulk density of canopy fuels and low foliar moisture content [2,7–12]. Mature lodgepole pine and jack pine stands have a comparatively elevated canopy base [13–15] but are also susceptible to crown fire [3,16], particularly when an understory of spruce is present (e.g., [17]), and vertical fire spread is assisted by the flaky bark fuels that are characteristic of these stands [5]. The propensity of boreal conifer stands to support high-intensity crown fires makes them a hazard and a priority for proactive fuel management when they occur in proximity to high-value areas like communities [18].

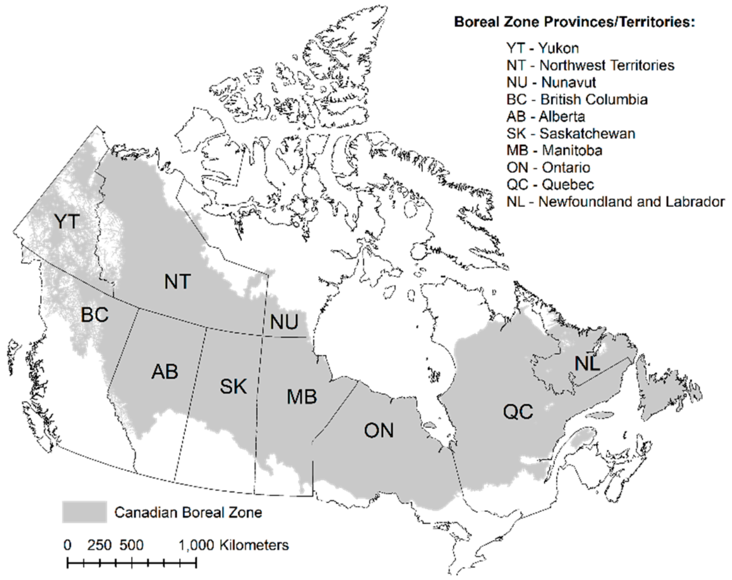

Figure 1. Extent of the North American boreal zone [1] across Canada and in relation to provincial and territorial jurisdictional boundaries.

Fuel management can include reducing the quantity of fuel, converting fuel to less flammable types, or isolating fuels [19]. At a fundamental level, all three of these activities involve a managed process of increasing the spacing between high-flammability fuel elements within a given unit of area. At a property or site level within the built environment, fuel management typically involves localized removal of some vegetation types to separate built structures from trees, shrubs and other flammable vegetation [20,21]. Within the broader landscape mosaic of a region, fuel management involves managed spacing of flammable land cover types and stand age-classes. This is achieved through the removal and replacement of flammable land cover patches with nonfuel in the form of human developments such as roads or conversion of the patch to a lower flammability state or fuel type through activities such as harvesting [22].

The stand-level fuel treatments that are the focus of this review are also known as sheltered fuel breaks [23] or fuel reduction treatments [24] and typically consist of thinning mature trees in the stand to reduce stand density, pruning branches on the lower portion of remaining tree boles and removing understory vegetation and surface biomass to increase the separation between crown fuels and the ground using a range of possible methods alone or in combination, including manual, mechanical, chemical (herbicide) or prescribed fire [25,26]. Management of waste fuel is typically handled through onsite piling and burning, mastication into mulch wood chips using machinery such as a rotary drum and redistribution across the site [27,28], or alternately, transport and disposal offsite. Prescribed surface fire, also termed broadcast burning, is sometimes used to reduce surface fuel loads, alone or in combination with manual and mechanical fuel alterations, but is a limited practice in proximity to populated areas due to public safety priorities and potential undesirable smoke impacts on human health and visual quality concerns [26].

Regardless of the scale of implementation, all fuel management activities increase spacing between physical fuel elements, which serves to disrupt fundamental wildfire combustion processes. In order to spread, wildfires must generate sufficient heat to preheat and ignite adjacent or nearby fuels [2,29,30]. Heat transfer mechanisms such as direct contact with flames, radiation and travelling embers all operate over limited distances [31,32]. As the spacing between fuel elements within a unit of area increases, the amount of fuel available for combustion is reduced and the heat released from combustion is diminished, which slows the rate of heat transfer to adjacent or nearby fuels and reduces ember propagation. In this manner, fuel management addresses both variables in Byram's equation [33] for frontal fire intensity by reducing the amount of fuel available for combustion as well as the rate of fire spread. Reduction in potential fire intensity is a primary target of stand-level fuel treatments in community protection settings because fire intensity is a key determinant of whether or not a fire will develop into a crown fire, which, in turn, will determine the viability of different operational tactics to suppress the fire and the likely success of those efforts. For example, firefighters can effectively contain slow-moving, low-intensity (< 500 kW/m) surface fires with direct suppression action along the fire's edge, but these tactics are considered ineffective once frontal fire intensities increase beyond 2000 kW/m [34–36].

In Canada, stand-level fuel reduction treatments have been used in localized community protection settings for several decades, with well-established programs for protecting townsites in national parks such as Banff, Alberta [37]. Development and expansion of cohesive fuel management programs by provincial-level jurisdictions, primarily in western Canada [38], have been ongoing over the past 20 years in response to a series of destructive fire seasons and individual wildland fire events that resulted in unprecedented structure losses [39–43]. Complex and dispersed administrative and funding frameworks, e.g., [44–47], inhibit the tracking of provincial and national statistics on the extent and costs of treating fuels. Ad hoc reporting provides some insight into the land area being subjected to fuel reduction treatments and indicates that jurisdictions in western Canada, where programs are most developed (i.e., BC, AB; Figure 1), treat relatively small areas, covering approximately 1200 to 5200 hectares annually at a cost of roughly CAN$5000 to CAN$7400 per hectare [44,48,49].

The fundamental scientific basis for utilizing fuel reduction treatments as a community protection measure is well accepted [25,26]; however, the viability and effectiveness of fuel treatments in boreal contexts have yet to be established. Unlike fuel management in other geographic regions, such as the dry forests of the western United States reviewed by Kalies and Yocom Kent [50], boreal stand-level fuel treatments are not designed to restore forests to naturally fire-resistant or fire-resilient states. Stand-level fuel reduction treatments in boreal conifer stands aim to produce decidedly unnatural structural characteristics that complicate fire behaviour predictions. The Canadian Forest Fire Behaviour Prediction (FBP) System [4] is used to estimate potential fire intensity and rate of spread in standard natural boreal fuel types, which include C-2 boreal spruce, C-3 mature jack or lodgepole pine and C-4 immature jack or lodgepole pine. However, these models are based on empirical observations of wildfires and experimental fires, which means they cannot be readily adjusted to account for the unnatural stand structures created by fuel reduction treatments. Empirical data documenting fire behaviour in fuel-treated boreal fuel types could be used to develop new predictive models, but these data are lacking due to the relatively recent introduction of fuel treatment practices in these ecosystems and the proximity of treated areas to the built environment, where aggressive fire detection and response efforts limit potential observations of wildfire activity. As fuel treatments are increasingly embraced as an important component of proactive community protection planning in the boreal zone, there is a need to document current stand-level fuel treatment design standards (Section 2); review data requirements and methodological approaches for studying fuel treatment effects on fire behaviour (Section 3); corroborate modelled fire behaviour with empirical observations of fire behaviour in fuel-treated boreal stands (Section 4); and identify key insights, priority data needs, and research directions for informing stand-level fuel treatment design in the boreal zone (Section 5).

2. Fuel-Treatment Design Standards

General fuel treatment design standards have been promoted nationally in Canada through the FireSmart guidebook, *Protecting Your Community from Wildfire* [20,21], developed and distributed by Partners in Protection, a multidisciplinary nonprofit association of government partners, private businesses and other stakeholders. This guidebook contains fuel reduction standards for forest stands that include the removal of all understory trees, pruning lower branches of large trees to a height of 2 m and thinning the stand to reduce crown cover to < 40%, with a minimum 3 m spacing between crowns. Recommended practices also include the use of a two-stage approach when conducting treatments in dense stands to minimize tree loss from wind damage, with an initial biomass removal of 1/2 to 2/3, followed by the remainder of the treatment 5–10 years later [20,21].

The extent to which individual jurisdictions in Canada (i.e., Figure 1) follow FireSmart design standards in practice can be inferred from agency best practice and reporting documents as well as research studies. While stand-level fuel treatments are not widely used in eastern Canada, guidance in support of fuel reduction treatments in Ontario reference the common FireSmart standard of 40% canopy closure and pruning trees to a minimum of 2 m from the ground [51]. In western Canada, fuel treatments generally follow the FireSmart standards of thinning to increase inter-crown spacing to at least 3 m, along with the removal of all understory vegetation and standing dead trees [52]. Fuel reduction in black spruce stands can also take the form of strip-removal, with 4 m wide spacing of retained strips [53]. Mastication of waste biomass generated by thinning or strip removal into mulch wood chips that are redistributed across the surface fuel bed has been frequently used in Alberta [54]. Fuel treatment prescriptions can also reference a broad range of factors that influence fuel treatment design. These include forest health, riparian and visual concerns; and consideration of forest practices legislation, higher-level plans and land-use objectives.

The use of uniform fuel treatment standards across different forest types can be expected to introduce considerable variability in post-treatment fuel complexes. For example, in Figure 2, a fuel treatment in black spruce in north-central Alberta is pictured. The natural black spruce fuel complex has a relatively low maximum tree height, a small tree bole diameter, and a narrow, columnar crown shape. Thinning and pruning these stands creates a highly unnatural crown shape and stand structure that can result in leaning or windthrow, while the open stand supports conifer regeneration. The fire behaviour implications of these post-treatment fuel conditions can be assessed by measuring pretreatment and post-treatment fuel attributes (Section 3.1) and inputting these values into available fire behaviour modelling frameworks (Section 3.2).

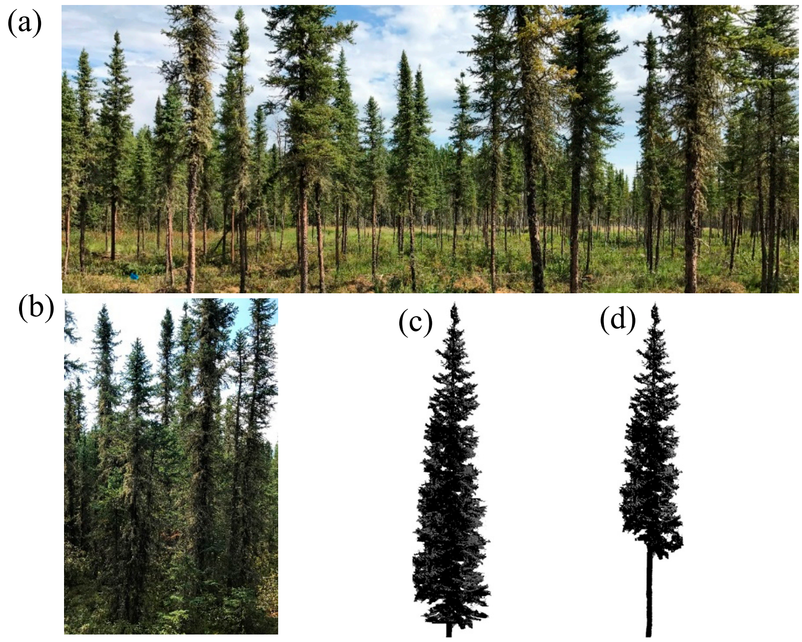

Figure 2. Fuel treatment in black spruce at the Pelican Mountain research site, Alberta. Counterclockwise from top left: (**a**) post-treatment stand structure; (**b**) natural stand structure; (**c**) natural and (**d**) pruned black spruce crown morphological structure. Documented maximum tree heights for black spruce at the Pelican Mountain research site ranged from 11 to 13 m [55].

3. Fuel Characterization and Modeling Frameworks for Fuel Treatment Assessment

3.1. Fuel Characterization

Fuel treatment effects on stand structure are quantified with measurements of four key fuel attributes that are illustrated in Figure 3: surface fuel load, crown base height, crown fuel load and crown bulk density. Figure 3 displays tree-level metrics denoted by the *crown* qualifier. When reported at the stand level, *canopy* is used (e.g., canopy bulk density). These fuel metrics facilitate consistent descriptions of pre- and post-treatment fuel characteristics in a stand and they form critical inputs to modelling frameworks used to assess fuel treatment effects on potential fire behaviour (Section 3.2).

3.1.1. Surface Fuel Load (SFL)

Low amounts of surface fuels limit potential surface fire intensity and inhibit vertical fire spread from surface to crown fuels. Fuel load is defined as the dry weight of combustible biomass per unit area (e.g., kg/m^2) and is typically categorized by status (live/dead), type (woody/nonwoody) and vertical strata (surface/crown) [56]. Fuel strata beneath tree crowns and above the forest floor have been further partitioned into shrub and low-vegetation layers (i.e., [57]), which may or may not be included in estimates of surface fuel loads used in fire behaviour models. Van Wagner [9] notes it would be appropriate to include *bridge* fuels between the ground and crown fuels (i.e., loose bark, dead lower branches, lichen and small understory conifers) in surface fuel load calculations if these fuels are in sufficient quantity to intensify a surface fire and extend the flame height. In the Canadian Forest Fire Behaviour Prediction (FBP) System [4], the surface fuel load consists of the forest floor, woody debris, shrubs and low-vegetation (i.e., herbaceous material).

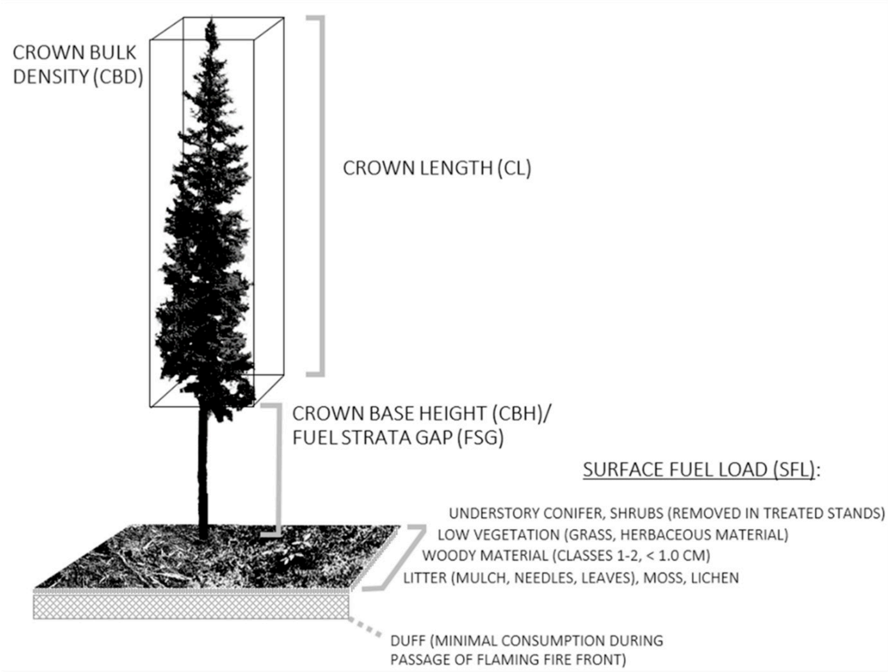

Figure 3. Diagram of fuel metrics required for determining inputs to crown fire modelling frameworks. Tree-level metrics are shown (denoted by the *crown* qualifier). When reported at the stand level, *canopy* is used (e.g., canopy bulk density).

Surface fuel load has also been defined as the weight of forest floor biomass and dead and downed woody fuel available for combustion during the passage of the flaming fire front (i.e., [58]) and is measured directly by field sampling. Forest floor fuel layers and their relationship to flammability have been reviewed by de Groot et al. [59]. Fuel layers are commonly defined using standard depths established for classification and modelling [4]. The litter layer consists of fast-drying small fuels, including dead needles, leaves, herbaceous material, lichen, live mosses and dead woody debris < 1 cm diameter, equivalent to size classes 1 and 2, following McRae et al. [60]. A partially decomposed organic soil layer beneath the litter layer includes dead moss and upper duff to a depth of 7 cm. The deeper organic layer consists of compact organic soil to a depth of 18 cm. Forest floor fuel loads, as summarized by Letang and de Groot [61] and documented for Canadian upland boreal conifer types, are highly variable. Fuel loads estimated at experimental fires for the mature and immature jack pine or lodgepole pine fuel types of the FBP System (i.e., C-3, C-4) were 1.3–4.7 kg/m^2 compared with 1.5 kg/m^2 in the C-1 spruce-lichen woodland fuel type and 1.9 kg/m^2 in the C-2 boreal spruce fuel type.

3.1.2. Canopy Base Height (CBH)

Elevated canopy base height inhibits vertical fire spread from surface to crown fuels. Canopy base height (CBH) is the vertical distance separating surface and canopy fuel layers and can be estimated as the average height from the ground to the live crown base [9]. At the individual tree-level, crown base height is easily defined conceptually, but it is notably challenging to estimate in field-settings due to the inherently subjective process of identifying a horizontal limit within a vertically heterogeneous and discontinuous fuel complex. Cruz et al. [58,62] reviewed various definitions of CBH, including an analogue termed the fuel strata gap (FSG, [63]), in which the lower limit of canopy fuels is deemed the height at which ladder and live canopy fuels are capable of sustaining vertical crown fire propagation. A quantitative reference point for establishing canopy fuel sufficiency for vertical crown fire spread (i.e., 0.011 kg/m^3) has been proposed [64], but may lead to the underprediction of potential crown fire behaviour in conifer forests of western North America [65].

The relatively short stature of natural boreal conifer forests [55,66] means that maximum achievable CBH through pruning is limited in comparison with species such as ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*), which are characterized by substantially higher tree heights [67]. It is also noteworthy that in mature stands represented by the C-2 fuel type, black spruce tree crowns can extend nearly to the ground, such that thinning alone cannot be relied upon to elevate CBH. In the FBP System [4], the C-2 fuel type has an assigned reference CBH of 3.19 m, which was selected to approximate field observations of forest structure, but is inconsistent with the description of the C-2 fuel type in which black spruce crowns extend nearly to the ground. Reference CBH for mature and immature natural jack pine and lodgepole pine stands represented by the C-3 and C-4 fuel types in the FBP System are 8 and 4 m, respectively.

3.1.3. Canopy Fuel Load (CFL) and Canopy Bulk Density (CBD)

Low amounts of fuel distributed within the three-dimensional expanse of a canopy fuel layer will inhibit fire spread from tree crown to tree crown. Canopy fuel load (CFL) is the weight of combustible aerial biomass per unit area (e.g., kg/m^2). Aerial fuels consumed by crown fires consist primarily of fine fuels in the form of live needle foliage [9]. For black spruce trees in Ontario, Stocks [68] estimated 74% of crown fuel weight consisted of live needle foliage. Aerial fine fuels such as branch wood < 1 cm, lichen and bark also contribute to canopy fuel load in boreal conifer fuel types [66,67]. The general process for estimating CFL involves using standard allometric equations to estimate foliage biomass in relation to tree diameter, followed by application of a tree expansion factor to obtain canopy load, as detailed by Cruz et al. [62]. Standard equations for calculating foliage weights are a source of potential error when estimating CFL for stands where crown shape deviates from the sample trees used for allometric model development. Fuel treatments necessitate adjustments to tree-level crown fuel weight estimated from allometric equations due to pruning that results in a shortened crown length (CL; i.e., the average vertical distance between the top of the tree and CBH) that does not conform with standard natural conditions. CFL and CL are used to calculate canopy bulk density (CBD), which is simply the amount of fuel available to burn per unit volume (e.g., kg/m^3). Thinning and pruning conducted during fuel treatments produce a comparatively shallow and porous canopy fuel strata, with lower CFL and lower CBD than a natural stand. In the FBP System [4], a standard CFL is assigned to each fuel type, for example, 0.80 kg/m^2 (C-2 boreal spruce), 1.15 kg/m^2 (C-3 mature jack or lodgepole pine), and 1.20 kg/m^2 (C-4 immature jack or lodgepole pine), but even within natural, untreated stands, CFL and CBD can be expected to vary by stand age, site condition and other factors that influence stand density and basal area.

3.2. Crown Fire Modeling Frameworks for Fuel Treatment Assessment

Measurements of SFL, CBH, CFL and CBD form key inputs to a range of modelling frameworks used to assess fuel treatment effects on potential fire behaviour.

3.2.1. Linked Van Wagner and Byram Models

The Van Wagner crown fire initiation model [9] and the Byram fireline intensity equation [33] provide a structured process for predicting potential fire behaviour given pre- and post-treatment fuel measurements. A primary objective of fuel treatments in boreal conifer stands is to inhibit the development of crown fires that are natural in these ecosystems. Van Wagner [9] defined the critical surface fire intensity (CSI) necessary for the onset of crowning:

$$CSI = 0.001 \times CBH^{1.5} \times (460 + 25.9 \times FMC)^{1.5} \quad (1)$$

where CBH is the height of the base of the live canopy above ground, and FMC is percent foliar moisture content. This model combines both physical theory and empirical observation that is reviewed in detail by Cruz et al. [58] and it has been widely used to explore fuel treatment effects. Van Wagner [9] also defined the conditions required for sustained propagation of a crown fire based on a critical minimum rate of spread ($R_\circ$) that will vary by the density of crown fuels:

$$R_\circ = S_\circ / CBD \tag{2}$$

where CBD is canopy bulk density (kg/m^3), and $S_\circ$ is the mass flow rate of fuel expressed as mass per unit cross-sectional area per minute, typically estimated as 3.0 kg/m^2 per minute following field observations in red pine plantations reported by Van Wagner [9].

To assess whether or not a surface fire in a treated or untreated stand will exceed the threshold CSI required for the onset of crowning, Byram's [33] equation of fireline intensity I (kW/m), hereafter referred to as fire intensity or intensity, provides a mechanism for estimating surface fire intensity from surface fuel load (SFL) measurements of fuels expected to be consumed during the passage of a fire front, given a hypothetical rate of spread:

$$I = Hwr \tag{3}$$

where H is the fuel's low heat of combustion (18,000 kJ/kg), w is the weight of the fuel layer consumed per unit area (kg/m^2), and r is the rate of spread (m/s). The Byram [33] model of fireline intensity was used in the development of the Van Wagner [9] crown fire initiation model, and both of these models form core components of the Canadian Forest Fire Behaviour Prediction (FBP) System [4]. In contrast, Rothermel's [29] surface fire spread model is used in several modelling systems in the United States, as reviewed by Scott [69]. A review of approaches for assessing crown fire potential in the coniferous forests of western North America [65] highlights the incompatibilities between the underlying assumptions of the Van Wagner [9] crown fire initiation model and the Rothermel [29] surface fire model and reports a significant underprediction bias in assessments of crown fire initiation that result from the linkage of these two models.

3.2.2. Canadian Forest Fire Behaviour Prediction (FBP) System

The FBP System [4] uses Van Wagner [9] and Byram models [33] to predict fire behaviour in natural, untreated conifer stands. The FBP System models for boreal conifer fuel types are based on fixed CFL and CBH derived from a dataset of experimental fires used in the development of the system. Set values for CFL and CBH means the FBP System models cannot be readily adjusted to reflect the effects of pruning on CBH and thinning on CFL, which are critical for determining the potential for crown fire initiation and sustained crown fire spread, respectively. The FBP System also relies on surface fire intensity estimated from empirical surface fuel consumption models for natural C-2, C-3, and C-4 fuel types derived from the relationship between postfire observations of forest floor consumption and the Buildup Index (BUI, [70]), a unitless relative rating of fuel moisture in the organic layer that is calculated from the Duff Moisture Code (DMC) and Drought Code (DC). These surface fuel consumption models are specific to the surface fuel complexes represented in the relatively small number of experimental fires (i.e., 13–41) used to estimate the C-2, C-3 and C-4 models and cannot be readily customized to predict surface fuel consumption and surface fire intensity when the surface fuel load varies from these reference conditions.

Despite the general incompatibilities of standard C-2, C-3 and C-4 fuel types with fuel-treated stand structures, the FBP System models for other fuel types permit user-defined fuel attributes that may be considered crude analogues of fuel changes that result following stand-level treatments. For example, the C-6 (conifer plantation) fuel type is unique among the FBP System conifer fuel types in that users can modify CBH to evaluate corresponding effects on predicted fire behaviour. Unfortunately, crown and surface fuel loads in these stands bear little resemblance to boreal conifer stands such as black spruce, even following thinning treatments. The M-1 (boreal mixedwood) fuel type provides a crude mechanism for exploring the responsiveness of fire behaviour metrics to changes in the amount of conifer in a stand. Fire intensity in M-1 stands was not modelled from observations of fires in mixedwood stands, but rather represents a hypothetical value approximated as the average of fire spread rates and surface fuel consumption values estimated for C-2 boreal spruce and D-1 leafless aspen fuel types and weighted proportionately to their relative percent composition in a hypothetical mixedwood stand. In FBP System calculations, crown fire initiation is inhibited in M-1 fuels by higher reference CBH (6 m) compared with C-2 (3 m), which is consistent with a fuel treatment effect. However, the contribution of crown fuels to M-1 fire intensity is based on the C-2 crown fuel load (0.80 kg/m^2), omitting any CFL reduction that would be associated with a thinned conifer stand.

3.2.3. Canadian Fire Effects Model (CanFIRE)

The limitations of FBP System models for exploring fuel structure modifications have motivated the development of tools that deconstruct surface fire spread and crown fire initiation modelling components and give users the ability to vary model inputs. The Canadian Fire Effects Model (CanFIRE), which originated as BORFIRE [71,72], uses Canadian Forest Fire Weather Index (FWI) System [70] parameters and rate of spread from the FBP System [4], in combination with field-measured or estimated surface fuel load values and empirically-derived fuel consumption models [59] to output surface fire intensity following Byram [33]. CanFIRE uses estimates of tree height and crown length (CL) to calculate CBH and estimates the critical surface fire intensity (CSI) necessary for the onset of crowning, following Van Wagner [9]. Tree biomass equations are used to estimate the fuel load of canopy foliage and bark, which is used to calculate canopy fuel consumption when CSI is exceeded.

3.2.4. Crown Fire Initiation Spread (CFIS) System

In confronting the limitations and assumptions of the linked Van Wagner [9] and Byram [33] modelling framework, some researchers have sought insight from alternative statistical modelling methods. Using a database of wildfires and experimental fires, Cruz et al. [58] developed a logistic regression model to estimate the probability of crown fire occurrence as a function of 10-m open wind speed, surface fuel consumption, fine fuel moisture, and fuel strata gap (FSG). Cruz et al. [73] developed a nonlinear regression model for estimating the rate of spread (m/min) of an active crown fire as a function of 10-m open wind speed, CBD and fine fuel moisture. The Crown Fire Initiation Spread (CFIS) System software tool [74] allows users to easily vary stand structure inputs to assess the resulting probability of crown fire occurrence and predicted rate of crown fire spread.

3.2.5. Canadian Conifer Pyrometrics (CCP)

Neither the deterministic nor probabilistic modelling frameworks described above explicitly account for the effects of canopy structure on in-stand wind conditions and fuel moisture regimes, which can be expected to influence fire intensity and rate of spread. During drying weather trends conducive to crown fires, open stand conditions in thinned areas that are exposed to increased solar radiation and wind flow will result in comparatively drier surface fuel moisture conditions in treated stands than untreated areas [75]. That means the surface fire rate of spread and surface fire intensities in treated stands can be higher than immediately adjacent untreated locations with identical surface fuel loads. Furthermore, reductions in surface fuel loads following fuel treatments may not result in the expected corresponding reduction in surface fire intensity. Perrakis et al. [76] addressed this issue by adapting stand-specific fuel moisture models [75] based on the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and stand-closure, among other variables, for compatibility with crown fire occurrence and spread models presented by Cruz et al. [58,73], which use Rothermel's [77] estimated fine fuel moisture (EFFM) parameter. The resulting Canadian Conifer Pyrometrics (CCP) modelling framework accounts for in-stand fuel moisture differences in treated stands in addition to structural fuel differences when estimating probabilities of crown fire occurrence and spread using the Cruz et al. [58,73] modelling framework.

3.2.6. FIRETEC and QUIC-Fire

The emergence of physics-based, stand-level fire behaviour simulation models like FIRETEC [78] have created a fundamentally different approach for studying fire behaviour in boreal conifer fuels [79] and the effects of fuel treatments in those fuel types [80] within a simulated fuel complex. These models are currently limited to research studies due to their computational complexity. However, a recently developed fast-running coupled-atmospheric modelling tool, QUIC-fire [81], simulates the effects of fuel structure on local winds and fire behaviour and offers a new option for exploring fuel treatment effects on crown fire initiation and spread that holds promise for informing operational fuel management activities and decisions in the years ahead.

3.3. Assessing and Interpreting Fuel Treatment Effects

Probability of crown fire initiation and rate of crown fire spread can be estimated and compared between treated and untreated stands using the statistical modelling framework developed by Cruz et al. [58,73] and supporting software tools [74] and model enhancements [76], which rely on inputs that describe fuel attributes (i.e., SFC, FSG, CBD, moisture content) and wind speeds. Likewise, Van Wagner [9] crown fire initiation and spread models, in combination with Byram's [33] fireline intensity, can be used to determine if canopy bulk density (CBD) following a fuel treatment has been reduced to the point where the minimum rate of spread needed to sustain crown fire spread ($R_{\circ}$) exceeds anticipated rates of spread in all but the most extreme conditions, and likewise, if the separation between surface and canopy fuels (i.e., CBH) has been increased to the point where the critical surface fire intensity (CSI) required for crown fire initiation is not achievable, given reasonable assumptions about the potential surface fire rate of spread, surface fuel consumption, and foliar moisture content. Regardless of the modelling framework used to assess fuel treatment effects on potential fire behaviour, subjective or inconsistent model inputs can be expected to influence results.

3.3.1. Subjective or Inconsistent Model Inputs

Van Wagner's [9] model of crown fire initiation requires an estimate of foliar moisture content (FMC), which affects the heat of ignition. In boreal conifer forests, FMC varies over the fire season with an average range of 87–119% and a strong seasonal trend that includes a *spring dip*, marking the annual minimum [4]. In the FBP System, FMC is determined using an empirically-based seasonal curve adjusted for latitude and elevation. There is no standard FMC considered appropriate for evaluating fuel treatment effectiveness. If fuel treatments are designed to be effective throughout the fire season, a minimum possible FMC could be used, or alternately, a seasonal average or mid-range value such as 100%.

Wind speed and rate of spread values used for assessing fuel treatment effectiveness are also subjective assumptions in the estimation process. It is generally accepted that fuel treatments are not designed to be effective during fire weather and fire behaviour conditions conducive to extremely high rates of spread (e.g., [18]). The sensitivity of modelled crown fire initiation and crown fire spread to assumptions about the rate of spread and wind speed can be explored by varying these parameters during the modelling process. For example, the rate of spread can be increased in increments from 5 to 15 m/min and wind speeds from 5 to 20 km/h.

Assumptions about the surface fuel consumption (SFC) should also be approached using a sensitivity analysis, given the difficulty of obtaining accurate and precise measurements. SCF will depend on the amount of surface fuel that is present (i.e., surface fuel load, SFL) and the proportion of SFL that is actually available for consumption, given anticipated fuel moisture conditions. Options for estimating SFL include field measurements or, alternately, the use of equivalencies from representative forest types and site conditions summarized in reference studies or compiled in classification systems such as the Fuel Characteristic Classification System (FCCS) [82,83]. Regardless of the data source used to estimate SFL, the amount of SFC used to estimate surface fire intensity and assess the potential for crown fire initiation will depend on two critical factors: (1) assumptions about the mix of surface fuel components that will be consumed by the flaming fire front, and (2) assumptions about the proportion of those surface fuel components that will be consumed.

For example, 100% of surface fine fuel load consisting of litter, moss, lichen and fine woody debris < 1.0 cm can be expected to be consumed by the passage of the flaming fire front. Some or all of the fuel load within the low vegetation layer (i.e., grass, herbaceous material) may also contribute to fire intensity, depending on the season and the associated fuel moisture conditions. In comparison, duff fuel load consumed during flaming combustion will be minimal to nil but is routinely inflated in surface fire intensity calculations due to the difficulty of isolating flaming and smouldering components of combustion in post-fire measurements of forest floor consumption. This issue is acknowledged in the FBP System ([4], p.38) with respect to fire intensity calculations where "no attempt is made in the computational process to exclude fuel that may have been consumed by smouldering combustion after the passage of the fire front".

In the FBP System [4], surface fuel consumption is estimated by the modelled relationship between post-fire field-measured fuel consumption of the forest floor and the Buildup Index (BUI). As BUI increases from 20 to 80, surface fuel consumption increases from 1.03 to 3.01 kg/m^2 in C-2 boreal spruce and from 0.29 to 2.48 kg/m^2 in C-3 and C-4 fuel types (mature and immature jack or lodgepole pine). Surface fuel consumption observations in four studies summarized by de Groot et al. [59] for the C-3 and C-4 fuel types were highly variable: 0.6–0.9, 1.7, and 2.5 kg/m^2. Recognizing the challenges of obtaining accurate and precise SFC measurements and estimates, Cruz et al. [58] modelled crown fire occurrence with a categorical SFC variable with three general classes: < 1.0, 1.0–2.0, and > 2.0 kg/m2.

Assumptions about surface fuel consumption are further complicated by fuel beds that are modified or completely engineered during the fuel treatment process, such as mulch woody debris generated by the mastication of waste biomass. Average mulch fuel load measured at field sites in Alberta using destructive sampling methods, were estimated at approximately 8-11 kg/m^2 with test fires indicating a depth of burn of 0.8–3.7 cm when BUI was 61–69 [54,84]. A study of moisture and thermal regimes in masticated fuel beds [85] reported a total mulch fuel load (all size classes) of 14 kg/m^2 and indicated rapid wetting and drying of surface fuels in response to ambient conditions and comparatively extended, stable moisture retention in deeper horizons than natural fuel beds. Further study will be required to determine the portion of mulch fuel load that can be expected to contribute to surface fire intensity in treated stands where mastication has been used for biomass waste.

3.3.2. Model Sensitivity to Assumptions—Illustrative Examples

The sensitivity of crown fire initiation predictions to assumptions about surface fuel load and surface fuel consumption is illustrated in Figure 4 for fuel-treated black spruce stands at the Pelican Mountain research site in Alberta. Given the field-measured mean CBH of 3.45 m documented by Cameron [55] and assuming 100% foliar moisture content, Van Wagner and Byram models indicate that surface fuel consumption ≤ 0.72 kg/m^2 would be required to inhibit crown fire development under relatively low surface fire spread rates of ≤ 5 m/min, which would drop to fuel consumption thresholds of ≤ 0.36 kg/m^2 and ≤ 0.24 kg/m^2 for inhibiting crown fires at rates of spread of 10 and 15 m/min, respectively.

Probability of crown fire occurrence from Cruz et al. [58] indicates that with a 3.45m gap between surface and canopy fuel strata (FSG), crown fire occurrence is unlikely, even at a relatively low fine fuel moisture content (~9%), provided surface fuel consumption is < 1.0 kg/m^2 and wind speed is ≤ 10 km/h. While these estimates seem promising, an expectation of surface fuel consumption < 1.0 kg/m^2 is inconsistent with observations of postfire fuel consumption of the forest floor in the C-2 fuel type, which ranged from 2.04 to 4.59 kg/m^2 [59].

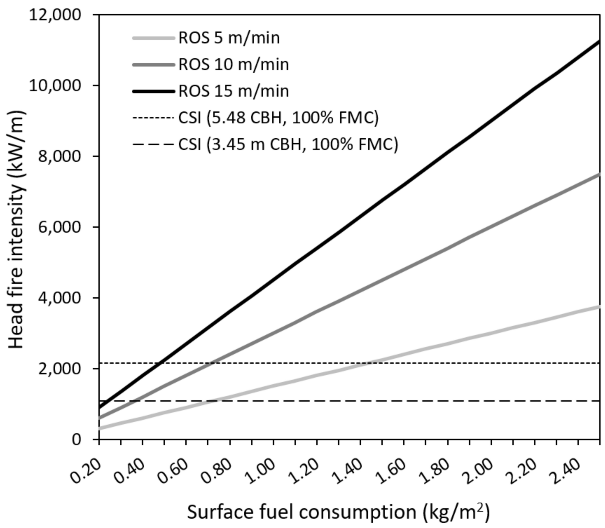

Figure 4. Relationship between Byram's equation for surface head fire intensity and surface fuel consumption shown for three rates of spread (5, 10, and 15 m/min) in relation to Van Wagner's critical surface fire intensity (CSI) for the onset of crowning, given mean (3.45 m) and maximum (5.48 m) canopy base heights (CBHs) measured at fuel-treated boreal spruce stands at the Pelican Mountain research site [55] and assuming 100% foliar moisture content (FMC).

If we assume a surface fuel consumption of 2.0 kg/m^2, then a CBH of at least 11 m would be required to inhibit crown fire initiation in this example stand based on Van Wagner and Byram models, in the event that the rate of fire spread reaches 10 m/min and foliar moisture content is 100%. In contrast, a FSG of at least 7 m is required to inhibit crown fire occurrence using the Cruz et al. [58] model if surface fuel consumption exceeds 2.0 kg/m^2, assuming 10 km/h wind speed and 9% fine fuel moisture. While both modelling frameworks can accommodate high CBH/FSG values, these are decidedly incompatible with black spruce stands that, in this case, have a maximum tree height of just 13.1 m.

Reductions in CBD from thinning is intended to limit sustained crown fire spread in situations when high wind speed, fast rate of spread, and high surface fuel consumption (SFC) lead to a surface fire intensity that exceeds the critical fire intensity needed for vertical spread into crown fuels [25]. Field-measured CBD for fuel-treated black spruce stands in Alberta had mean and maximum values of 0.19 and 0.34 kg/m^3 [55], respectively. Following Van Wagner [9], the critical minimum rate of crown fire spread that would be required to sustain a crown fire in these stands would be 15.8 and 8.8 m/min, given mean and maximum CBDs, respectively. In comparison, untreated stands had mean and maximum CBDs of 0.57 and 1.06 kg/m^3, respectively, which correspond to a critical minimum rate of crown fire spread of 5.3 and 2.8 m/min. These estimates are based on CFL estimated with both live foliage and branch wood < 1.0 cm, which inflates CBD in comparison with foliage-only canopy fuels used in Van Wagner's model.

Fuel-treated lodgepole pine stands documented in Banff National Park [37] had a 77% reduction in post-treatment stand density (from 2825 to 650) and a 73% reduction in canopy bulk density (from 0.26 to 0.07 kg/m^3), which produced a 52% reduction in modelled surface fire intensity from 2550 to 1230 kW/m, following Byram [33]. Calculations assumed a 10 m/min rate of spread and a reduction in surface fuel consumption from 0.85 to 0.41 kg/m^2 in thinned stands following fuel treatments. In this study, surface fuel consumption was assumed to consist exclusively of understory conifer, herbaceous material, and dead and downed woody fuel < 3.0 cm in diameter. Following Van Wagner [9], a canopy base height of > 3.5 m would be required to inhibit crown fire initiation in the treated stands, assuming a foliar moisture content of 100%. The minimum fire spread rate required to sustain crown fire spread was 11.5 m/min in untreated stands compared with 43 m/min in treated stands.

Field-measured fuel characteristics in thinned and untreated jack pine stands in the Northwest Territories [52] were associated with < 10% likelihood of crown fire occurrence in treated areas based on the CFIS modelling framework [58] given wind speeds up to 12 km/h, 9.8 m FSG, 8% fuel moisture and 1–2 kg/m^2 surface fuel consumption. The model predicted an active crown fire under the same conditions in untreated stands with a FSG of 0.8 m. These estimates can be compared with predictions following the Van Wagner and Byram models, which indicate that a crown fire would not develop in the treated stand provided the rate of surface fire spread remained below 12 m/min, assuming 100% FMC and surface fuel consumption of < 1.44 kg/m^2. Even if a crown fire did develop in the treated stand, model results indicate the low CBD (0.07 kg/m^3) following stand thinning would necessitate a rate of spread of 43 m/min to sustain a crown fire.

Based on the Canadian Conifer Pyrometrics (CCP) modelling framework [76], raising the FSG from 4.7 to 7 m in a dense pine stand and decreasing CBD from 0.22 to 0.07 kg/m resulted in the initiation of passive and active crown fires in fuel-treated areas at wind speeds of 13 and 33 km/h, respectively, compared with a 9 km/h wind speed threshold for active crowning in untreated fuels. Modelling assumptions included surface fuel consumption of 1.5 kg/m^2 and low fuel moisture conditions given by 92 FFMC and 80 DMC.

FBP System models for boreal conifers are not well-suited for exploring fuel treatment effects. However, the M-1 boreal mixedwood fuel type can be used to estimate the fire behaviour effects of varying conifer density in a stand, which could be viewed as a crude analogue to thinning treatments. Figure 5 illustrates the effect on head fire intensity of varying conifer composition in the M-1 fuel type, assuming 100% foliar moisture content, fine fuel moisture of 9% (FFMC = 92) and surface fuel consumption that varies from 1.0 to 2.5 kg/m^2 (BUI = 60). Under a relatively high wind speed (20 km/h), reducing percent conifer composition from 100% to 30% produces a corresponding 70% reduction in head fire intensity to 5078 kW/m. However, the resulting predicted fire behaviour would still involve intermittent crowning and remains above the threshold for direct suppression along the fire's edge by firefighting crews. Under a moderate wind speed (10 km/h), a reduction in conifer composition from 100% to 30% has a corresponding reduction in head fire intensity from 12,390 kW/m, with intermittent crowning to 2380 kW/m, resulting in an intense surface fire near the upper limit of direct suppression tactics along the fire's edge. While presented for illustrative purposes only, the M-1 model results suggest that substantive reductions in black spruce stand density of ≥ 70% would likely be required to reduce potential fire intensity within thinned stands below the threshold for direct suppression by ground crews.

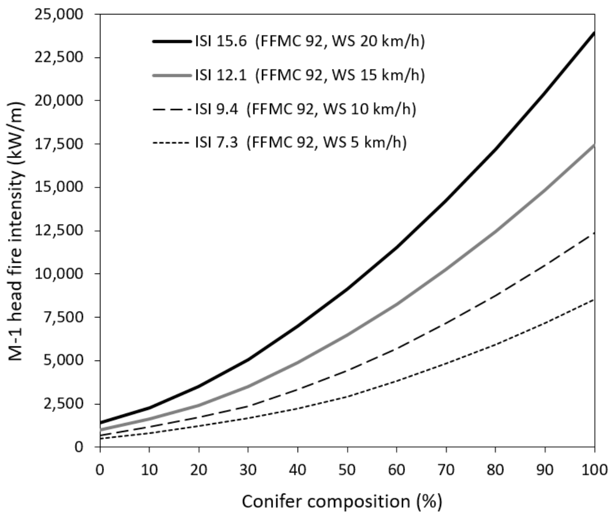

Figure 5. Relationship between conifer fuel composition (%) and head fire intensity (kW/m) in the Canadian Forest Fire Behaviour Prediction (FBP) System M-1 fuel type for four wind speeds (WSs) ranging from 5 to 20 km/h, assuming fine fuel moisture of 9%—Fine Fuel Moisture Code (FFMC) of 92, surface fuel consumption of 1.0–2.5 kg/m^2 given a Buildup Index (BUI) of 60, and 100% foliar moisture content (FMC).

4. Observations of Fuel Treatment Effects—Experimental Fires and Wildfires

In Section 3, we demonstrated the process of inputting pre- and post-treatment fuel metrics into various modelling frameworks to explore the effects of fuel treatments on predicted fire behaviour. Observations from experimental fires or wildfires can also provide important insights into fuel treatment effectiveness in boreal conifer stands. Unfortunately, these types of anecdotal observations are not conducive to simple cross-comparisons due to the wide range of information collected by observers and the highly variable fire environment and fire weather conditions during the observation period. Evidence from empirical observations should, therefore, be considered individually.

4.1. Wildfire—Northern Saskatchewan (Black Spruce)

Observations of fire behaviour in fuel-treated stands were documented during the Lagoon Fire, which encroached on the community of Stanley Mission in northern Saskatchewan in May 2014 [86]. Black spruce stands on the outskirts of the community were hand-thinned and pruned in 2008 and 2009, with dead and downed wood piled and burned. Fuel treatments reduced stems per hectare from 8100 to 1000 and crown closure from 90% to 25%. The separation between stems was increased in treated stands to 2–3 m from 0–0.5 m pretreatment. CBH of 2 m did not differ between treated and untreated areas. A high-intensity crown fire (4000–10,000 kW/m) that developed in the black spruce forest near the community was observed to spread as a surface fire in the thinned stand and it encroached only 120 m into the treatment area, leaving scorch heights on tree boles of ≤ 1.25 m. Given fire weather conditions on the day the fuel treatment burned, observed fire behaviour in treated stands was inconsistent with fire intensity predicted with the FBP System for the natural C-2 fuel type, where a high-intensity crown fire (14,700 kW/m), with 98% crown fraction burned, was predicted.

4.2. Experimental Fire—Alaska (Black Spruce and White Spruce)

Fuel treatment effects on crown fire intensity in Alaskan boreal forests were assessed from observations of fuel consumption, burn severity, and fire behaviour during a prescribed fire in 2009 [24]. Fuel reduction treatments involved pruning trees to a height of 1.2 m and reducing stand density from 3849 to 7531 stems per hectare in control areas to 1290 to 2359 stems per hectare in thinned stands. Waste biomass was removed from thinned stands and hauled offsite. A high-intensity crown fire (38,990 kW/m) that developed in natural, untreated black spruce and white spruce (*Picea glauca* (Moench) Voss) was observed to transition to a surface fire within 30 m of spreading into thinned fuel-treated areas.

4.3. Experimental Fire—Northwest Territories (Black Spruce)

A case study of a test fire conducted in a treated black spruce stand at an experimental burning site in the Northwest Territories [87] also suggested that thinning reduces fire intensity and involvement of crown fuels. In 2011, the stand was hand-thinned, cleaned of standing and downed woody material and pruned to a height of 2 m, with waste biomass hauled offsite, resulting in minimal disturbance of the surface fuel bed. Thinning involved only a limited reduction in overstory stems per hectare from 734 to 575. Understory stems per hectare were reduced from 550 to 183. Resulting reductions in CFL (0.94 to 0.81 kg/m^2) and CBD (0.15 to 0.13 kg/m^3) were modest compared with reduction in surface fuel load from 1.21 to 0.50 kg/m^2. A test fire was ignited 1-year post-treatment in natural black spruce adjacent to the treatment area under relatively high fire behaviour conditions (FFMC 92, ISI 12, BUI 72) and variable winds of 6–10 km/h, gusting to 10–20 km/h. During wind gusts, when the most extreme fire behaviour occurred, a high-intensity intermittent crown fire was observed in untreated areas, with fireline intensity estimated above 2700 kW/m. As the fire transitioned to the treated area, it became a moderate-intensity vigorous surface fire with high intensities and individual consumption of tree crowns (i.e., *candling*) during wind gusts that progressed to a low-intensity surface fire of < 300 kW/m within the core treatment area, where no crown involvement was observed.

4.4. Experimental Fire—Red Earth Creek, Alberta (Black Spruce)

Fuel treatment effects in black spruce were assessed at the Red Earth Creek experimental burning site in northcentral Alberta in 2015. Fuel treatment prescriptions (i.e., thinning and strip removal) were conducted at the site in 2013 and 2014 [53]. Stand density was reduced from 1260 to 400 and 650 stems per hectare in thinned and strip-removed treatments, respectively. Waste biomass generated by the treatments was masticated into mulch chips and redistribution onsite, with an average mulch fuel loading of 2.67 kg/m^2 estimated from destructive sampling. A high-intensity crown fire (13,440–27,840 kW/m) was ignited in adjacent untreated black spruce under low fuel moisture conditions and relatively high winds (14–29 m/min) that facilitated fire spread into the treatment plots. Sustained crown fire spread was inhibited in the thinned stand, which had a reduction in canopy fuel load from 1.2 to 0.3 kg/m^2 and a reduction of canopy bulk density from 0.20 to 0.05 kg/m^3. Observed fire behaviour was consistent with the Van Wagner [9] model of sustained crown fire spread, which indicates that winds of 60 km/h would be needed to sustain a crown fire in the thinned stand. In contrast, the area treated with strip-removal sustained crown fire spread, including continuous crowning, likely due to CBD remaining unchanged in the retained strips. Despite the apparent effectiveness of thinning at inhibiting crown fire spread, the majority of the trees in the thinned plot experienced crown consumption due to candling and would have been a source of aerial embers. Black spruce can host abundant arboreal lichens and are very susceptible to ignition from embers, such that pruning was not effective at inhibiting crown involvement. Feathermoss, aerial lichen, and mulch fuels at the site were all observed to be highly receptive to ignition from embers transported during the fire.

4.5. Experimental Fire—Pelican Mountain, Alberta (Black Spruce)

A similar test fire was conducted at the Pelican Mountain experimental burning site. A high-intensity crown fire was ignited in natural black spruce stands in May 2019 under extremely low fuel moisture conditions and high wind speeds (i.e., 12 km/h, gusting to 27 km/h) and spread into a stand that had been thinned and pruned during the prior winter [88]. Thinning reduced stems per hectare from 12,000 to 2300. However, ground cover remained uniform across treated and control locations. Surface fuels dominated by feathermoss were observed to sustain very high rates of spread (35–60 m/min) and fireline intensity (> 23,000 kW/m). Fireline intensity in fuel-treated areas decreased, but the rate of spread did not. Two key factors are thought to have contributed to the apparent ineffectiveness of the fuel treatment: hand-thinning conducted during the winter season left surface fuel intact and undisturbed following the treatment, and surface fuel moisture in the thinned stand was significantly drier compared with the upwind control stand.

4.6. Experimental Fire—Northwest Territories (Jack Pine)

Test fires were conducted in 2005 and 2007 in a fuel-treated jack pine stand at an experimental burning site in the Northwest Territories (described in Section 3.3 [52]). The fires were ignited in adjacent, untreated mixed jack pine-black spruce stands and occurred during comparable fire weather conditions in 2005 (FFMC 91, ISI 10-11, BUI 90 and wind speed 11–13 km/h) and 2007 (FFMC 93, ISI 11-14, BUI 132 and windspeeds 10–15 km/h). Observed fireline intensity in the fuel-treated area burned in 2005 was < 500 kW/m, with rates of spread < 1 m/min, compared with crown fire development and a 20 m/min observed rate of spread in the untreated areas where the fire was ignited. Similar results were observed during the 2007 test fire when a crown fire, ignited in natural, untreated fuels, changed to a surface fire as it moved into the fuel-treated area and exhibited rates of spread < 1 m/min compared with 21–40 m/min observed in untreated areas. Both test fires were ignited in untreated areas with fuel complexes that differed from pretreatment conditions in the fuel-treated area, including abundant reindeer lichen that was thought to have contributed to extremely high observed rates of spread in the natural stands.

5. Fuel Treatment Assessment and Design—Challenges and Needs

5.1. Acknowledging the Limitations of Modelled and Observed Fire Behaviour

The most common and accessible method for evaluating fuel treatment effectiveness combines fuel measurements with modelling frameworks, as described in Section 3. Empirical data compiled during observations of wildfire and experimental fires in fuel-treated areas (Section 4), while sparse, represent a potentially invaluable source of corroborating data. Unfortunately, these empirical data suffer from significant limitations. Prefire fuel measurements in treatments burned by wildfires and experimental fires are documented with varying levels of detail, and postfire documentation may omit key measurements such as SFC and assessments of onsite fuel moisture. Underlying differences in fuel complexes between natural and fuel-treated areas can confound fire behaviour comparisons. Natural ecological variability means that regardless of their proximity to treated stands, untreated fuels serving as fire behaviour *control* observations may not necessarily represent the pretreatment state of the treated stand. It is also difficult to disentangle dynamic fire environment variables such as wind speed and direction that can change over a time-scale of minutes as a fire moves from a natural stand into a fuel treatment (e.g. [87]). This is potentially avoided if natural and fuel-treated areas are burned simultaneously rather than sequentially along a linear path. However, experimental plots burning parallel to one another will also confound results through their inevitable interaction (e.g., [53]).

The use of fuel measurements and modelling frameworks to investigate fuel treatment effects on fire behaviour (Section 3) also suffers from significant limitations. Accurate estimates of surface fuel load (SFL), surface fuel consumption (SFC), crown base height (CBH), crown fuel load (CFL) and crown bulk density (CBD) are all essential for assessing fuel treatment effectiveness using available modelling frameworks. Variations in model inputs used in different studies and nuances in definitions of fuel measurements can complicate the comparison of modelled fire behaviour across studies and will limit the extent to which modelling results can be generalized to predict fire behaviour in similar fuel complexes where fuel treatments are contemplated. Notably, fuel components used in SFL estimates are sometimes inconsistent and may or may not be representative of the understory and forest floor fuel complex observed in a stand where a fuel treatment is being planned. Likewise, post-treatment surface fuel conditions can be expected to vary with time since treatment as a result of vegetation response [26]. The common practice of using postfire forest floor measurements to estimate SFC inflates these measurements by capturing fuels consumed through smouldering combustion after the passage of the fire front, which does not actually contribute to crown fire development. The use of SFC estimates from past field studies in fuel treatment design can, therefore, lead to overestimates of anticipated surface fire intensity in a treated stand.

Coupled with SFC, CBH is critical for assessing the potential for crown fire initiation following pruning, but it is difficult to measure reliably in the field, and multiple definitions have been proposed and used in various modelling studies. The relatively short stature of black spruce, jack pine and lodgepole pine stands in northern boreal regions, where mature stands with mean tree heights of <11 m are commonplace, e.g., [53,55,66], also creates a natural upper limit on the extent of CBH changes that can be introduced by fuel treatments. We estimated that an upper limit of surface fuel consumption of approximately 0.70 kg/m^2 would be required to inhibit crown fire development under relatively low wind speeds and rates of spread in a treated black spruce stand in Alberta due to the limited overall tree height and correspondingly low post-treatment CBH, even following pruning. This threshold is substantially lower than the range of SFC measurements reported in many postfire assessments and likely to be exceeded in the event that a high-intensity crown fire encroaches into a fuel-treated area, given the abundant surface fuel load characteristic of most black spruce stands.

Accurate measurement of CFL and CBD is essential for predicting whether or not a stand can sustain a crown fire following thinning treatment. However, there are inconsistencies in how crown fuel load is measured and the inclusion of branch wood will result in inflated values compared with foliage-only estimates used to calculate CSI from Van Wanger [9]. Furthermore, allometric equations used to estimate crown foliage weight are simply approximations derived from models that may be inconsistent with the tree crown morphology in a stand where a fuel treatment is planned. Minimum CBD values of 0.05 and 0.10 kg/m^3 have been proposed as thresholds for the onset of crowning and sustained crown fire spread [25,67]. Post-treatment CBD of 0.07 kg/m^3 was reported in field assessments of treated jack pine and lodgepole pine stands [37,52]. In comparison, documented CBD in treated black spruce in Alberta was 0.19 kg/m^3 [55], but this value was calculated using fine branch wood in addition to live needle foliage weight, which complicates comparisons.

Fuel characteristics in most planned fuel treatment areas are unlikely to be subjected to time and resource-intensive field sampling regimes to characterize baseline conditions and derive precise fuel-treatment prescriptions and post-treatment fire behaviour predictions. Rather, equivalencies are needed for enabling rapid estimates from visual assessments or limited field measurements (e.g., [67]). To guide fuel treatment prescriptions and fire behaviour estimates, development of reference fuel attribute values for natural and fuel-treated black spruce, jack pine and lodgepole pine stands in boreal regions are needed, similar to those found in classification systems such as the Fuel Characteristic Classification System (FCCS) [82,83]. Data from the Alberta Wildland Fuels Inventory Program is currently under analysis to summarize reference fuel attributes in a range of natural and fuel-treated boreal conifer stand types. Development of rapid photographic fuel load assessment methods and guides are also in progress to aid in pre- and post-treatment fuel assessments and long-term monitoring of post-treatment fuel changes. Rapidly advancing remote sensing technology such as airborne and in-stand laser scanning offers exciting new mechanisms for quantifying detailed fuel attributes across a stand, and more research is needed to develop models for relating these new data forms to field-measured fuel attributes (e.g., [55]).

5.2. Interpreting Evidence and Confronting Uncertainties

Fuel treatments in boreal black spruce, jack pine and lodgepole pine stands that conformed with the general design standards summarized in Section 2 were consistently effective at reducing modelled and observed fire behaviour and inhibiting crown fire development and spread under low to moderate fire weather conditions. Our review of modelled and observed fire behaviour suggests that fuel treatments in these fuel types will be ineffective when rates of spread and wind speeds become very high or extreme. Fuel treatments in boreal conifer fuels may also be ineffective when surface fuel load is high and fuel moisture low, such that surface fire intensity can be expected to easily overwhelm the potentially limited span between surface and crown fuels created by pruning and surface fuel reduction within the relatively short-stature fuel complexes that are characteristic of northern boreal forests.

There are also obvious physical limitations to the intensity of thinning that can be conducted in boreal conifers before stand health is irreparably compromised. Pruned trees in these stands are notably top-heavy, and with the small diameter boles characteristic of boreal conifers, they will be prone to leaning and windthrow. Given constraints on vertical fuel modification during boreal fuel treatments, more research is needed to explore the viability of alternative horizontal fuel reduction protocols, such as the clumped fuel configurations simulated by Marshall et al. [80]. When modifications to canopy fuel attributes such as CFL, CBD and CBH reach their physical limits, modification of surface fuels may offer additional opportunities to dampen potential fire behaviour (e.g., [89]).

Mastication of waste biomass in fuel-treated stands and distribution of the resulting mulch and woody fuels across the site will dramatically transform the surface fuel bed in boreal conifer stands and may reduce surface fuel consumption and surface fire intensity compared with natural fuel beds [e.g., 84]. Results of test fire burns in mulch fuels [54] suggest the intensity of mastication will influence results with finer, more highly processed and compacted mulch material associated with lower surface fuel consumption. Surface fuel loads assessed in jack pine 8 years following fuel treatment that included understory burning at an experimental burning site in the Northwest Territories [90] indicated a 60–75% reduction in surface fuel loads following treatment, from 0.61–0.97 kg/m^2 to approximately 0.25 kg/m^2. In this case, the fuel reduction treatment consisted of removal of standing and downed woody material and manual scraping of flaky bark on tree boles to a height of 2 m, followed by a low-intensity prescribed surface fire.

Unfortunately, prescribed burning is limited in fuel-treated areas by the proximity of the built environment, which introduces public safety and health concerns. Burning operations are also logistically challenging due to the narrow range of fire weather conditions that will be conducive to continuous surface fire spread through a stand to ensure fine fuels are fully consumed while also limiting the contribution of duff to surface fuel consumption to inhibit fire intensity, which restricts burning to periods when fuel moisture is high in the deeper organic forest floor layers. These issues were evident in the results of a series of surface test fires conducted in jack pine [91]. Boreal conifer stands, such as black spruce, are also generally incompatible with prescribed burning due to a characteristically thin bark that offers limited insulation capacity and minimal-to-no fire resistance [92]. More research is needed to explore options for surface fuel management in fuel-treated boreal conifer stands to develop guidelines and best practices for enhancing fuel treatment effectiveness with techniques such as mulch chip fuel beds, manual or mechanical surface fuel disturbance or compaction, and prescribed understory burning.

Modelled and observed fire behaviour in fuel treated boreal conifer stands suggest the value of these treatments could be enhanced by integrating suppression and containment strategies within the fuel treatment planning and design process. Under high to extreme fire weather conditions, fuel treatments in boreal conifer stands cannot be relied upon to slow or arrest fire spread or crown fire development. In these situations, fuel-treated areas could potentially serve as safe, prepositioned locations for igniting fires in advance of an encroaching wildfire to remove the fuel ahead of the fire in what is commonly termed *back burning* or *burn-out operations*. Further study is needed to explore the strategic positioning of fuel treatments as part of broader fire containment planning efforts, which would presumably incorporate assessments of fuel configurations well-beyond the limited stand-level examined herein.

6. Conclusions

In the Canadian boreal zone, stand-level fuel reduction treatments are used predominantly in community protection settings to alter the natural structure of dominant boreal conifer stands such as black spruce, jack pine and lodgepole pine. The aim of these fuel treatments is to inhibit the development of fast-spreading, high-intensity crown fires that naturally occur in boreal forest ecosystems. Crown fire initiation and spread modelling frameworks provide an intuitive and structured process for exploring the effects of fuel treatment effects on potential fire behaviour but are encumbered by many modelling and data assumptions and subjective decisions about model inputs. Real-world observations of experimental fires and wildfires burning in fuel-treated areas can offer insights into fuel treatment effectiveness but are anecdotal in nature and suffer from significant limitations due to inconsistent documentation and highly variable fire environment conditions at observation sites. While documentation of modelled and observed fire behaviour should be approached with caution and may not be readily comparable across studies and locations due to the many assumptions and data inconsistencies involved, collective evidence from these sources suggests that stand-level fuel treatments in black spruce, jack pine and lodgepole pine stands can be expected to diminish fire behaviour and inhibit crown fire development and spread under low to moderate fire weather conditions. Modelled and observed fire behaviour suggest that fuel treatments in dominant boreal conifer fuel types will be ineffective when rates of spread and wind speeds are very high or extreme (e.g., 25 km/h wind speed and 40 m/min rate of spread). High surface fuel loads combined with the relatively short stature of boreal conifer trees can further undermine fuel treatment effectiveness. Priority areas for future study include examining alternatives for managing surface fuel loads in treated stands; exploring the viability of alternative horizontal fuel reduction protocols, such as clumped fuel configurations; investigating the impacts of fuel treatments on in-stand fuel moisture regimes, understory vegetation response, and tree health; and integrating suppression and containment strategies within the fuel treatment planning and design process. The viability of alternatives to stand-level fuel reduction treatments, such as complete stand removal, alone or in combination with conversion to less flammable fuel types, should also be investigated, as should the use of enhanced fuel data sources and novel modelling frameworks.

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