IMPACTS OF MOUNTAIN PINE BEETLE OUTBREAK AND WILDLAND FUEL REDUCTION TREATMENTS IN JASPER NATIONAL PARK, ALBERTA, CANADA

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DEDICATION

To my loving family, supportive partner, and monster kitten

ABSTRACT

Wildland fuels are deviating from traditional described fuel complexes due to climate-mediated pressures and anthropogenic alteration. However, technological advances have also increased the capacity to obtain fuels information at higher detail across the landscape to capture these changes. Quantifying fuel baselines in disturbed and altered states is paramount to understanding the impact on wildland fire potential. This thesis examines fuels that deviate from traditional fuel types in the montane region of Jasper National Park, Alberta, Canada using field measurements and coincident airborne lidar data. First, the impacts of mountain pine beetle on fuels over a range of severity within the same temporal phase of outbreak are investigated. With increasing severity, overstory and subcanopy fuel loading significantly lowered, forest floor composition became more herbaceous, and organic layer loading increased. Severely impacted stands also exhibited less than half the amount of coniferous seedling recruitment than lightly impacted stands, which could signal a shift in regeneration away from closed-canopy conifer stands in this region. Second, fuel treatment efficacy over two decades was evaluated using field and lidar-derived canopy metrics. Though surface fuels in field-measured stands remained similar over time, stem density, canopy cover, canopy bulk density, and canopy base height varied significantly over time since management. Stand-level fire modelling at dry to extreme weather percentiles (90^{th} – 97^{th}) predicted that stem density and canopy fuels were sufficiently reduced to prevent active crown fire in treated stands, but surface fuels and low canopy base height were conducive to torching of individual trees in most scenarios and treatment years. This research provides critical insight into the variability within both managed and disturbed fuels over time, and the potential impact on fire behaviour as high fire weather indices occur more often in a warming climate.

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LIST OF ABBREVIATIONS & SYMBOLS

AD	Anderson-Darling statistical test
BUI	build up index
C3	mature Jack or Lodgepole pine fuel type in CFFDRS
C7	Ponderosa pine or Douglas-fir fuel type in CFFDRS
CFFDRS	Canadian forest fire danger rating system
CBD	canopy bulk density
CBH	canopy base height
CFIS	crown fire initiation and spread model
CFL	canopy fuel load
CP	conifer pyrometrics modelling framework
CSI	critical surface fire intensity
DBH	tree diameter at breast height (1.3 m)
DEM	digital elevation model
DMC	duff moisture code
FBP	fire behaviour prediction system
FFMC	fine fuel moisture content
FMA	fuels management analyst
FMC	foliar moisture content
FWI	fire weather index
GEDI	global ecosystem dynamics investigation
GIS	geographic information system
GNSS	global navigation satellite systems
IQR	interquartile range
KW	Kruskal-Wallis statistical test
Lidar	light detection and ranging
NG-CFFDRS	next generation Canadian forest fire danger rating system
PCA	principal components analysis
rH	relative humidity
SE	standard error

CHAPTER 1: INTRODUCTION

1.1 Introduction

The montane cordillera, Canada's most diverse and complex ecozone (Natural Resources Canada 2024), encompasses over 31 million forested hectares (~65% of the total region) between central interior British Columbia and the Alberta foothills. In the eastern edge of this ecozone, the Canadian Rocky Mountains to the foothills, the terrain and a host of natural and anthropogenic disturbances bring further complexity and biodiversity (Klenner 2011). As the warming climate primes the historically fire-mediated, fire-deprived (in the past century) forested landscapes of North America for higher intensity and severity wildland fires (Flannigan et al. 2003, Wotton et al. 2017, Kirchmeier-Young et al. 2019), the characteristics of available fuel must be examined within local contexts. Broad descriptive vegetation groupings, or fuel types, have been used operationally for decades in Canada for a quick association of dominating species in an area with potential fire behaviour. These traditional generalized fuel types do not represent the variability within this region well.

Wildland fire in the montane natural subregion of Alberta has been drastically altered by fire exclusion practices beginning in the 1900s (Rogeau et al. 2016). Historically, this subregion was subject to mixed-severity fires with a mean fire return interval of around 30 to 40 years (Rogeau et al. 2016), and now due to suppression, is experiencing a departure from this return interval of over 197%. In Jasper National Park, the majority of fires before suppression had a return interval between five and nine years (Tande 1979). The absence of fire across forested landscapes of western North America has led to an infilling of coniferous trees with closed canopies, numerous subcanopy trees, and vertical fuel continuity (Lydersen et al. 2013, Hessburg et al. 2019). Likewise, the relative absence of fires since 1905 in Jasper has led to a homogenized forested landscape (Chavardés & Daniels 2016), which is susceptible to disturbance from insect infestation (McCullough et al. 1998, Bentz et al. 2010) and elevated fire hazard (Hessburg et al. 2019, Prichard et al. 2021). In recognition of fuel build up near growing communities and spreading human infrastructure, in 1990, FireSmart Canada was established to address wildland fuel proximity to human development (FireSmart Canada 2024). This program was initialized in Alberta and began reducing accumulated fuels found in the wildland-urban interface (Johnston & Flannigan 2017) to minimize fire risk to lives and property.

A warming climate, insect infestation, and fuel accumulation are complementary and compounding disturbances (Bentz et al. 2010). One disturbance or atypical stressor on an ecosystem can create an ideal environment for another. For example, the higher density of a host tree species for mountain pine beetle (*Dendroctonus ponderosae,* Hopkins), allowed for epidemic spread in western Canada since the late 1990's. This was due to the combined effects of fire exclusion and more frequent mild winters occurring, which limited the beetle populations' overwintering mortality (Natural Resources Canada 2024). The distribution of dead and dry fuels from beetle-kill intermixed with live vegetation, which accumulate fine fuels each growing season, is of great concern from a fire hazard perspective. Though there have been many studies focused on fire potential in mountain pine beetle affected stands, the consensus on impacts is limited (Romauldi et al. 2023), and outbreak severity is not often examined at a fine scale.

This thesis aims to examine wildland fuels in stands altered by epidemic level mountain pine beetle outbreak and to assess the impact of regeneration on fuels and potential fire behaviour in managed stands in the wildland-urban interface within Jasper National Park, Alberta, Canada. To understand how fuel distributions impact wildland fire potential, and what can impact these distributions, key concepts are introduced here.

1.2 Key Concepts

1.2.1 Wildland Fuels

Wildland fire fuel is defined as any combustible organic material (biomass) in a particular landscape, living or dead (Albini 1976, CIFFC 2017). Fuels are further broadly classified into ground, surface, ladder, and aerial fuels, and can display infinite variability in arrangement, density, and composition (Keane 2015, Finney et al. 2021, Cruz et al. 2022). The vertical structure and density of fuels can have a large impact on the ability of a fire to ignite, spread, and become a high intensity crown fire (Cruz et al. 2004, Agee & Skinner 2005).

Wildland fire ignition typically begins at the surface level of fuels, which involves all fuels low in stature above the duff layer: litter, moss, herbaceous vegetation, small shrubs, and fine to coarse downed woody debris (Keane 2015). Ignition must take place in fuels dry and fine enough for combustion to occur, and with available fuels nearby also dry and fine enough for the flame to spread (Van Wagner 1983). Once fire has established, the direction of spread is determined by current weather (wind speed and direction, humidity, atmospheric pressure), slope of the environment, and fuel availability (Countryman 1972). The transition from a surface fire to the more hazardous crown fire occurs when the wildfire begins “climbing” from surface fuels into canopy fuels by way of the intermediate “ladder fuels” i.e. tall shrubs, regenerating conifers, or low-extending crowns creating continuity between the surface and canopy (Keane 2015). The ability of a fire to do this depends on the fireline intensity, or heat energy output per length of fire front, generated by the surface fire (Byram 1959). When the fireline intensity reaches a sufficient level, the heat output of the surface fire is enough to dry more elevated canopy fuels in the “preignition phase” and the flame length grows as ladder fuels are involved in combustion (Van Wagner 1977). The fire can then reach the fine fuels of the canopy and spread quickly from crown to crown. Crown fire is the most destructive and hazardous fire type and occurs more readily in dense fuels with vertical continuity (Natural Resources Canada, 2024).

Fuel types, or qualitative descriptions of fuel complexes based on dominant species composition, consist of static stand structure, surface, and canopy fuel loading in the Fire Behaviour Prediction system within the Canadian Forest Fire Danger Rating System (CFFDRS, Forestry Canada Fire Danger Group 1992). The CFFDRS has 16 fuel types meant to broadly characterize all vegetative fuel complexes across a large country with highly variable vegetative characteristics. These are used to model potential rate of spread and headfire intensity of a fire within that fuel type for a given set of weather conditions. It is recognized that the variability in fuels at a fine scale, disturbed fuels due to insect outbreak and disease, and fuel managed stands are not often represented within broad fuel types (Keane et al. 2013). Generalized fuel types were developed when localized forest mensuration data were harder to come by, and necessary for quick operational decision-making, but advancements in remote sensing now allow for more detailed measurements or indicators of some fuel type characteristics across large landscapes and the monitoring of change over time.

In this thesis, forest mensuration data are measured according to the parameters of the Next Generation Canadian Forest Fire Danger Rating System (NG-CFFDRS; Boucher et al. 2023) in combination with airborne lidar data, to quantify ground, surface, understory, and canopy fuels in a detailed manner and over broad, often inaccessible mountain areas.

1.2.2 Impact of Insect Outbreak on Fuels

Mountain pine beetle is a bark-boring insect and a primary disturbance agent in western coniferous forests (Schoennagel et al. 2012). Millions of hectares across Canada now have fuel loading and moisture characteristics that depart from the traditional mature pine fuel type (C3 in

FBP) due to varying levels of insect-induced morality. Trees that are infested by mountain pine beetle typically experience mortality within a year of infestation, after which the foliage changes from green to red, and falls to the forest floor over two to three years (Jolly et al. 2012a). Aerial twigs, branches and bark, and eventually tree stems continue to decompose and fall over time, increasing surface fuel loads (Klutsch et al. 2009, Schoennagel et al. 2012). Increased fire hazard during the stage when the canopy retains foliage is well documented (Page et al. 2012, Schoennagel et al. 2012, Perrakis et al. 2014). In the period following this, or “gray-phase”, when the foliage has fallen but trees retain some twigs and bark, is more ambiguous in terms of fire behaviour potential. Surface fuel accumulation increases intensity (Jenkins et al. 2011, Klutsch et al. 2011), but loss of canopy fuels is thought to reduce crown fire potential (Hicke et al. 2012). However, Agne et al. (2016) found that high severity crown fire often occurred despite lowered canopy fuels, highlighting the influence of varying mortality on crown fire initiation. In Jasper National Park, the majority of the *Pinus contorta* var. *latifolia* Engelm. (lodgepole pine) within the park boundaries has been killed by the recent outbreak. This standing dead fuel is interspersed through a range of vegetative communities including pure pine, mixed conifer and mixedwood including *Picea glauca* Voss x *Picea engelmannii* Parry (hybrid spruce), *Psuedotsuga menziesii* Franco (Douglas-fir), *Abies lasiocarpa* Nuttall (sub-alpine fir), and *Populus tremuloides* Michx. (aspen). Species composition of stands before outbreak, and of stands adjacent to heavily impacted areas will influence fuel continuity and fire potential.

1.2.3 Fuel Reduction Treatments

Fuel reduction treatments are defined as modifications to a fuel complex intended to alter fire behaviour to minimize risks of future wildland fire to human lives, infrastructure, and ecological values (Hoffman et al. 2020). They have been shown to be effective at mitigating fire behaviour by removing fuel accumulation and continuity between heavily forested stands and values at risk such as homes and industry (Agee & Skinner 2005, Loudermilk et al. 2014). The type and timing of fuel management impacts the efficacy of hazard mitigation such as lowered rate of spread and crown fire initiation (Barnett et al. 2016, Beverly et al. 2020, Urza et al. 2023). Mechanical treatment longevity has been found to increase when maintained with prescribed fire to remove regeneration of ladder fuels that connect surface fuels to the forest canopy (Stephens et al. 2012). The interaction of local weather, fire history, and position of the wildland urban interface or values at risk needs to be recognized for effective placement of fuel treatments (Collins et al. 2013). Schoennagel et al. (2004) and Martinson et al. (2003) suggest that fuel treatments are most effective when tied to restoring historical fuel loadings for that forest type. Once established, fuel treatments must also be maintained at a sufficient interval to ensure the protective measures are upheld. Monitoring and maintenance programs are not well implemented in western Canada, however, and information on the longevity of fuel treatments is lacking.

1.3 Knowledge Gaps

In the montane valley subregion of Jasper National Park, there is a unique opportunity to evaluate fuels that depart from traditional fuel types and pre-fire exclusion natural stands. Much of western North America has been heavily impacted by mountain pine beetle, influencing fire behaviour and severity often in unpredictable ways. Knowledge on how varying mortality density in gray-phase mountain pine beetle impacts fuel structure and loading in montane environments is limited as past research often focuses on comparisons between temporal outbreak phases (red to gray to old). For example, it is generally accepted that in red-phase, 2-3 years after initial outbreak, hazard of crown fire is elevated due to low foliar moisture but retained crown foliage. However, this phase is short-lived compared to the gray-phase, which can last over a decade (Schoennagel et al. 2012). Fuels are often considered static within a temporal phase, but lack of consensus on fire hazard (Romauldi et al. 2023) and unpredictable, intense fire behaviour (Moriarty et al. 2019) in gray-phase mountain pine beetle makes understanding the impacts of variability in fuel distribution of heightened interest as fire hazard will impact people and communities. This variability in fuels will persist and influence stand structure as stands move into old-phase (decades post-outbreak), and so baseline fuel distributions across mountain pine beetle impacted landscapes are critical to establish.

When fire hazard is considered elevated to human safety, communities and infrastructure, fuel reduction treatments are a main strategy to mitigate potential loss. These treatments are often designed with the objective of reducing rate of spread and intensity to provide opportunity for firefighting personnel to action the fire safely (Calkin et al. 2014). In areas that have experienced widespread disturbance altering fuels surrounding the community, especially disturbances where the influence on fire potential is context specific, fuels management becomes essential for minimizing risk. Despite this importance, knowledge on the long-term efficacy of fuel treatments is limited in this region. Characterizing fuels across mountain pine beetle impacted stands and over time in the managed wildland-urban interface of this region will provide insights into how disturbance and regeneration impact potential fire hazard in a complex environment within the montane-cordillera.

1.4 Research Objectives

This thesis aims to quantify fuel distributions in disturbed and managed areas of the montane environment within Jasper National Park to better understand the implications of variability in these stands across disturbance severity and over time since management. The overall goals are to characterize fuel composition and loading in each vertical fuel stratum and to evaluate the impacts of deposition and regeneration in these stands using field and lidar data. Further, to show how changes in fuel after fuel management affects fire potential at high fire weather danger, crown fuel involvement and intensity will be assessed using empirical fire modelling systems. To address these goals, the thesis will be divided into two specific objectives:

1) To assess fire fuel distribution along a gradient of gray-phase mountain pine beetle severity (defined as proportion of pine mortality, assumed from mountain pine beetle) by:
    i) Evaluating how severity significantly impacts fuel structure, composition, and loading across vertical fuel strata using field data; and
    ii) Placing these findings within the range of density variability of mountain pine beetle impacted stands using airborne lidar data across the larger landscape.
2) To assess fire fuel distribution and fire hazard potential over time since fuel reduction treatment by:
    i) Quantifying how fuel varies through vertical strata over time since management using field data,
    ii) Comparing field collected data with remotely sensed plots across comparable managed and unmanaged stands using airborne lidar data derived stem density and canopy metrics, and
    iii) Evaluating potential fire behaviour over time since management in field measured stands.

The outcomes from the first objective will provide contextualization of fuels based on proportion of trees assumed to be killed by mountain pine beetle. The severity thresholds here (Light (< 35%), Moderate (35 – 65%), and Severe (> 65%) beetle-induced pine mortality can be used to inform land managers and researchers on potential stand conditions and fuel loadings in similarly composed and impacted forests. The outcomes from the second objective will highlight the rate at which regenerating fuels may exceed prescription recommendations, and provide predictions of fire type, wind speed required for torching, and fireline intensity based on fuels over time in treated stands.

The organization of this thesis is as follows:

Chapter 2: *Forest Fuel Structure and Loading Along a Gradient of Gray Phase Mountain Pine Beetle Severity*

In this chapter, the first objective is accomplished by examining the impact of variable mortality from mountain pine beetle infestation on fuel loading, composition, and structure across eighteen field plots. Wildland fuels, connectivity, and regenerative establishment are evaluated over a range of mortality, density, and species composition. Stand density and structure were evaluated across the range of mountain pine beetle outbreak across the landscape to place field measured stands within the range of density variability using airborne lidar data. This chapter is presented as a standalone journal manuscript format.

Chapter 3: Fuel Treatment Efficacy and Fire Potential Over Time in Jasper National Park

In this chapter, changes in fire fuel loading and structure over time since fuel reduction treatments in the wildland urban interface of Jasper townsite are evaluated using field data and airborne lidar derived canopy metrics. Fire hazard potential is compared over recent (0 years since treatment), intermediate (13 years since treatment), and old (19 years since treatment) to determine how fire behaviour changes with fuel accumulation and regeneration. This chapter is presented in a standalone journal manuscript format with the study area and methods summarized to reduce repetition within the thesis.

Chapter 4: Conclusions, Scope of Inference, and Future Research

In this chapter, the findings of how fuels are distributed across this region, and the impacts this may have from a wildland fire perspective are reviewed. The variability in fuel loading, vertical structure, surface fuel composition and regeneration across mountain pine beetle mortality levels is discussed with the potential impacts on fire behaviour if a fire should occur, or potential successional trajectories in the absence of fire. The variability in fuels as regeneration occurs over time since mechanical reduction treatment is discussed through the lens of modelled potential fire behaviour. Recommendations for potential monitoring and management are suggested based on the findings of this research. The limitations of this study are reported and potential for future work is suggested to further understanding of disturbed and managed fuel complexes. This thesis contributes to the detailed description of pre-fire fuel conditions as they were prior to the Jasper Wildfire Complex of August 2024 (burning at time of submission), and may assist in understanding fire behaviour and post-fire effects, but it must be noted that the extreme weather and environmental conditions that overtake the influence of the fuel effect and dominated the driving of this fire are not examined here.

CHAPTER 2: FOREST FUEL STRUCTURE AND LOADING ALONG A GRADIENT OF GRAY-PHASE MOUNTAIN PINE BEETLE SEVERITY

Abstract:

The mountain pine beetle (*Dendroctonus ponderosae*, Hopkins) outbreaks across 18 million hectares of fire-mediated western Canadian forests have altered fuel complexes from conventional fuel types. Fuel distribution due to mountain pine beetle has traditionally been described by temporal, time-since-beetle phases, and treated as homogenous within those periods. Around seventy percent of the *Pinus contorta* var. *latifolia* Engelm. (lodgepole pine) forests in Jasper National Park, Alberta were infested before a near absolute mountain pine beetle population die-off in 2018. The objectives of this study were to 1) assess if gray-phase mountain pine beetle severity levels significantly impact fuel community structure, composition, and loading across vertical fuel strata using field data; and 2) To place these findings within the range of density variability of mountain pine beetle impacted stands using airborne lidar data across the larger landscape. To analyze this, detailed fuel measurements were taken in 18 plots across a range of assumed mountain pine beetle-induced pine mortality and categorized based on severity thresholds of Light (< 35%), Moderate (35 – 65%), and Severe (> 65%) beetle-induced pine mortality defined as killed trees out of total number of stems. Stand density and tree heights were derived from lidar data across the larger range of outbreak to compare with field plots.

The strongest relationship between mountain pine beetle severity and wildland fire fuels was found in the sapling or subcanopy cohort of trees. Sapling canopy bulk density was substantially reduced, with 68.5% less than original loading in Severe plots compared to a 9% loss in Light plots. Severe plots also showed a 49% reduction in mature tree canopy bulk density from original foliage loading. Light plots had three times as many seedlings than Severe plots, indicating poor recruitment as severity increases in this region. Herbaceous vegetation and organic forest

floor loading increased with mountain pine beetle severity. These mountain pine beetle severity ratings (Light, Moderate, Severe) can be used to indicate levels of canopy fuel loss, potential shifts to other ecosystem types, as well as identify areas that will present higher hazard as deadfall levels create difficult access scenarios in the case of wildfire in other mountain pine beetle impacted regions.

2.1 Introduction

Since the late 1990s, a mountain pine beetle outbreak in western Canada has affected over 18 million hectares of pine and mixed conifer forests (Natural Resources Canada 2022). This outbreak has led to an abundance of fuel complexes that differ from natural, undisturbed stands, and may result in wildland fire behaviour that is not readily predicted by traditional models (Jolly et al. 2012a, Dhar et al. 2016a). The Canadian Rocky Mountains historically presented a physical barrier to mountain pine beetle's spread beyond British Columbia, but dispersing beetles caught in convective updrafts (Robertson et al. 2009, De la Giroday et al. 2012) managed to establish on the eastern slopes and within the montane region across the Alberta border as early as 2005 (Westfall & Ebata 2006, Cooke & Carrol 2017), with a marked increase in 2011 (Parks Canada, 2016).

Eruptive mountain pine beetle outbreaks are the result of repeating warm, dry summers followed by mild winters, and are only mediated by the exhaustion of host trees or extremely cold winter temperatures (Natural Resources Canada 2022). The mountain pine beetle population rose in an eruptive manner in Alberta until prolonged winter cold periods (-30 to -40°C) in 2018 and 2019 led to a significant reduction from epidemic spread eastward to scattered endemic populations. Now, localized spread within these montane environments is limited (Alberta Forestry, Parks & Tourism 2022), and disturbed forests exhibit a mosaic of canopy mortality depending on species composition and outbreak phase when these die-off events occurred (Alfaro et al. 2015).

Mountain pine beetle outbreak is often classified as "time since beetle", or phases based on year of attack (green, red, gray, old) (Wulder et al. 2006, Klutsch et al. 2009). Spatiotemporal changes in fuel moisture, chemistry, and distribution caused by mountain pine beetle across these phases have been well documented (e.g. Raffa et al. 2008, Jenkins et al. 2014, Woolley et al. 2019). However, within these phases, the level of mountain pine beetle outbreak severity can also have highly variable effects on vegetation structure and the distribution of dry fuels across the landscape. Stand-level outbreak severity here is the proportion of beetle-killed pine trees out of total tree stems. Varying severity levels can create a mosaic of live and dead standing vegetation. This effect is particularly pronounced in montane environments, which exhibit higher variation in terrain, influencing micro-climate, soils, hydrology and therefore, vegetation biodiversity.

Regional factors such as climate, topography, wind patterns, and species composition across the landscape greatly impact how mountain pine beetle spreads and the way in which the fuel structure is altered (Raffa et al. 2008). Mountain pine beetle typically infest larger, older pine trees by boring into the bark and feeding on the thicker phloem, disrupting the flow of nutrients in the tree (Safranyik & Carroll 2007). However, when conditions are favourable (warm and dry), outbreaks of thousands of hectares can occur, and the less preferred, younger pine trees can be infested as well despite having less nutritive stores available in the thinner phloem (Amman 1985).

After initial attack, trees retain their needles for 2-3 years as they turn from green to red and the tree succumbs. This is referred to as the "red-phase" and is thought to result in higher probability of and intensity in crown fire behaviour (Perrakis et al. 2014) due to foliar moisture decreasing by up to ten times (Page et al. 2012) and retention of canopy bulk density. The period after this, when needles have fallen to the surface, lasts about 4-10 years and is termed the "gray-phase". In the earlier years of this phase, fine fuels such as small twigs and bark begin to deteriorate and fall to the surface, but most snags remain standing (Klutsch et al. 2009, Schoennagel et al. 2012). A pulse of fine fuels at ground level can occur after this as regeneration and downed woody debris accrue, thereby increasing surface fuel loading (Jenkins et al. 2008, Hicke et al. 2012). Mountain pine beetle-induced changes such as increased solar radiation to the forest floor or litter increasing over time with defoliation can also influence surface fuel beds as understory regeneration and species coverage shifts (Page et al. 2007). This can increase ignition potential, surface fire intensity and create difficult-to-action scenarios for firefighting professionals (Page et al. 2013).

Mountain pine beetle impacts fuels in spatially heterogenous ways that are difficult to accurately represent within traditional fire behaviour models (Schoennagel et al. 2012, Jenkins et al. 2014). Many models utilize static fuel types with set values for ground, surface, and aerial fuels, as well as height to the base of the crown (eg. C3 fuel type in the Canadian Fire Behaviour Prediction System is set at a canopy base height of eight meters (Forestry Canada Fire Danger Group 1992). A fuel type that captures the increased surface fuel accumulation from the canopy to the forest floor as beetle-killed trees lose foliage and eventually fall, and lowered fuel moisture increasing fuel availability, does not currently exist in the Canadian Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992) or the fuel types used in the United States modelling systems (Deeming et al. 1975, Anderson 1982, Scott & Burgan 2005). Custom fuel models have been developed in some studies to better represent the changes in fuel moisture, distribution, and loading associated with mountain pine beetle mortality (Page et al. 2007, Simard et al. 2011, Schoennagel et al. 2012). For example, a dead balsam fir-mixedwood proxy has been used for fuel typing in Canada (Perrakis et al. 2018), and physics-based modelling approaches have been used (Hoffman et al. 2012), but these have limited field validation. The results of simulated wildland fire behaviour have presented a limited consensus on the impacts of different mountain pine beetle phases (Romualdi et al. 2023). For gray-phase mountain pine beetle, Romualdi et al. (2023) found equal proportions of amplified, neutral, and dampened fire responses reported across 25 studies. This was research method and fire metric (severity or intensity) dependent, with more observational studies evaluating fire severity metrics, and simulation modelling studies measuring intensity.

Crown fire is the most hazardous fire type, often exceeding safe thresholds to fight from the ground (Alexander & Cruz 2013). This has resulted in focused research on crown fire initiation and spread, while other fire behaviour indices such as surface fire rate of spread, surface fire intensity, and fire effects such as severity and area burned that are likely to be impacted in gray-phase stands are less considered (Page et al. 2013, Moriarty et al. 2019). Many studies (e.g. Jenkins et al. 2008, Simard et al. 2011, Hicke et al. 2012, Hoffman et al. 2015) have suggested lower hazard of crown fire potential in gray-phase stands due to the loss of canopy fuels. However, this has been noted to be counteracted by an increase in rate of spread and intensity in surface fire due to increased solar radiation and within stand wind speeds (Perrakis et al. 2014, Hoffman et al. 2015), higher amounts of cured grass or herbaceous material in the spring and fall (Page et al. 2007), and longer burning residence time due to coarse woody debris loading (Klutsch et al. 2011).

Mountain pine beetle impacts each vertical strata of a fuel bed (ground, surface, ladder, and aerial) and the subsequent effects on fire behaviour depends on the context and temporal stage of a fire event. The increased solar radiation and in-stand wind speeds due to mountain pine beetle opening up the canopy can make the surface fuel bed more available for fire starts (Pollet & Omi

2002). Fine fuel loadings as branches break down can accumulate on the surface, raising surface fire intensity and rates of spread (Burgan 1987, Page & Jenkins 2007). If regeneration occurs, conifer seedlings and shrubs can carry the higher intensity surface fire into the remaining aerial fuels (Jenkins et al. 2014). Instances of high severity crown fire, despite low canopy fuel load, have also been found in gray-phase outbreak, highlighting the variation in fire behaviour that can exhibit within these stands (Perrakis et al. 2014, Agne et al. 2016). Talucci et al. (2019) found that branch structure consumption and deep char effects from fire increased with outbreak severity in extreme fire weather instances, indicating higher fuel availability in gray-phase stands. Sloughing bark and compromised structural integrity can also increase spotting and firebrands, and firefighters have witnessed unexpected, sustained crown fire and increased hazards due to the unpredictable nature of falling snags (Moriarty et al. 2019).

Jasper National Park, on the eastern slopes of the Rocky Mountains in central Alberta, is largely in gray-phase mountain pine beetle, with around 229,000 ha (~70% of the lodgepole pine) affected by outbreak after the population peak in 2018 (Landon Shepard, *personal comm*.). A die-off due to cold snaps (prolonged -30°C period) in the winters of 2018 and 2019 led to a population decrease of 98% (Parks Canada 2019, unpublished report), leaving most stands in a gray-phase state. In Jasper, a decrease in fire frequency over the last 100 years or more due to colonial fire suppression has led to a shift from historical mosaic of conifer, *Populus tremuloides* Michx. (aspen), open *Psuedotsuga menziesii* Franco (Douglas-fir), and grassland stands (Tande 1977) to a more homogeneous infilling of lodgepole pine- and spruce- dominated forests (Achuff et al. 2001, Rhemtulla et al. 2002, Chavardes & Daniels 2016). This shift in fire regime dominated by absence of fire in fire-regulated ecosystems aligns with other montane ecoregions of the Canadian Rockies described as early as the 1970s (Hawkes 1979, Rhemtulla et al. 2002, Van

Wagner et al. 2006). The absence of fire has resulted in a simultaneous growth pattern of closed canopy forest stands with shade-tolerant species forming ladder fuels (Chavardes & Daniels 2016). The homogenous build-up of coniferous species density, largely pine, created an ideal scenario for high severity mountain pine beetle spread. Coupled with warming climates, this has led to increased concern over elevated wildfire risk throughout the park (Zabjek 2018).

This study aims to evaluate the impact of mountain pine beetle outbreak severity on fuel complexes using Jasper National Park as a case study. To quantify how the vertical and horizontal distribution of vegetative structure and fuel characteristics vary with mountain pine beetle outbreak severity, plots were divided into a relative mortality threshold (e.g. Wulder et al. 2009), increased in scale to Light (0-35% mortality), Moderate (36 – 65% mortality), and Severe (66 – 100% mortality) based on the number of dead to living trees within each plot. While many studies have considered mountain pine beetle impact on forested landscapes across western North America by comparing temporal phases (green, red, gray, old) or focusing on the early red-phase (Page & Jenkins 2007, Simard et al. 2011, Schoennagel et al. 2012, Hoffman et al. 2012), only a few studies in Canada have categorized mountain pine beetle outbreak severity (Van Sickle et al. 2001, Kurz et al. 2008, Wulder et al. 2009). Also, no severity classes have been updated to reflect the cumulative impact of the substantial outbreak continuation after 2005. The forest mortality that occurred in Jasper presents a unique opportunity to evaluate fuels on a basis of varying severity and stem density, as it is captured in the range of characteristics within plots, at a relatively static point in time to create a baseline for the successional trajectory into old-phase mountain pine beetle (decades post-epidemic). Post-epidemic, old-phase mountain pine beetle is a critically important period for fire impacts as it could be the highest hazard fire scenario: forests include regenerating conifers for crown fire inclusion, retention of high surface fuel loads, and high accumulation of downed woody fuels (Page & Jenkins 2007, Hansen et al. 2014). Combined, these add to fire intensity and can create inaccessible areas for fire operations. With climatic warming increasing wildland fire potential, the compounding effects of mountain pine beetle on fuel heterogeneity and how these complexes differ from traditional fuel types must be examined more closely in as many local contexts as possible.

To address the uncertainties presented by this phase of outbreak, the following question was asked: what are the implications of varying severity, density, and regeneration on fire fuel distribution in gray-phase mountain pine beetle stands? To answer this question, the specific objectives were: 1) To assess how severity significantly impacts fuel structure, composition, and loading across vertical fuel strata using field data; and 2) To place these findings within the range of density variability of mountain pine beetle impacted stands using airborne lidar data across the larger landscape.

2.2 Materials and Methods

2.2.1 Study Area

Jasper National Park (52.8 N, -117.9 W) is located on the eastern slopes of the Canadian Rocky Mountains along the western border of central Alberta, Canada (Figure 2.1). This region is within Treaty 6 and 8 lands, as well as the traditional territory of the Anishinabe, Aseniwuche Winewak, Cree, Nêhiyawak, Stoney Nakoda, Secwépemc, Dene-zaa, Mountain Métis and Métis peoples for thousands of years. Jasper encompasses an area of 11,000 km^2 and includes montane, subalpine, and alpine ecotypes. The montane region is dominated by *Pinus contorta* var. *latifolia* Engelm. (lodgepole pine) with areas of Douglas-fir or *Picea glauca* Voss x *Picea engelmannii* Parry (hybrid spruce) (Chavardès & Daniels 2016), but also includes *Picea glauca* (white spruce) and *Populus tremuloides* Michx. (aspen) interspersed with grassland (Holland & Coen 1982). The subalpine ecoregion forests consist mainly of *Picea engelmannii* Parry (Engelmann spruce) and *Abies lasiocarpa* Nuttall (subalpine fir) (Holland & Coen 1982). The alpine is generally above the treeline and most vegetated areas consist of shrubs and forbs. Jasper is in the Montane-Cordillera ecozone of Canada, with a subarctic climate (Kottek et al. 2006), and is in the rain-shadow of the Canadian Rockies. Climate normals from 1981-2010 show monthly mean temperatures range from -6.9 to 15.3°C with 598.7 mm of mean cumulative annual precipitation (Jasper Warden Station, Environment Canada 2022). The Montane-Cordillera region experiences the highest density per hectare of combined lightning and human-caused wildfires in the country, which increases the risk of wildfire for inhabited residential areas (Coogan et al. 2020).

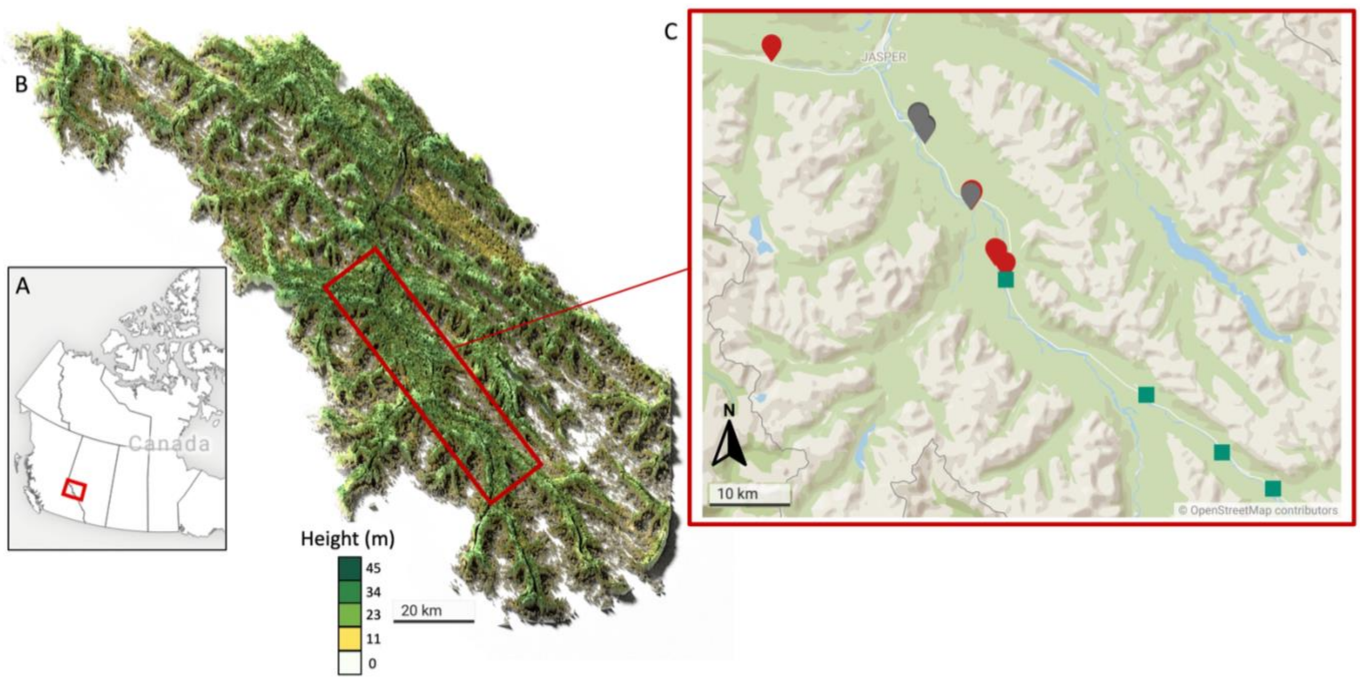


Figure 2.1. Map of study area A) Jasper National Park's location within Alberta, Canada. B) Jasper National Park colourised with canopy height estimated from 10 m resolution tree height distribution from 2020 Sentinel-2 imagery fused with GEDI LiDAR vertical distribution data (Lang et al. 2022). White areas indicate non-vegetated areas. Inset (C) shows locations of 18 Mountain Pine Beetle fuel mensuration plot pairs including Light outbreak (green squares; n = 5), Moderate outbreak (red markers; n = 8), and Severe outbreak (gray markers; n = 5).

2.2.2 Study Design

Potential locations for forest mensuration-based fuel plots were initially identified using high resolution satellite images (Google Earth Pro, 2021) followed by physical reconnaissance to ensure the range of mountain pine beetle severity was captured. Sites measured were lodgepole pine dominated and of little to no topographic relief, located in the montane Athabasca Valley. Plots were categorized into relative mortality threshold bins (e.g. Wulder et al. 2009) scaled to Light (0-35% mortality), Moderate (36 – 65% mortality), and Severe (66 – 100% mortality) based on the proportion of dead trees within each plot (Figure 2.2). All measured plots had some pine mortality, assumed from mountain pine beetle, therefore the 'Light' severity class is assumed as a reference as this is relatively undisturbed compared to the Moderate and Severe classes. The percent mortality thresholds used here were adjusted from those used in Wulder et al. (2009), as they classed severity levels as 11-30% mortality = "moderate", 31-50% = "severe", and > 50% = "very severe". Wulder et al. (2009) predicted that cumulative disturbance over time could require an increase of severity rating threshold values to better reflect the level of mortality after 5 – 10 years of continued infestation, which has since been seen in western Canada. The higher mortality thresholds used in this study can thus be more relevant to any area that has been heavily impacted by mountain pine beetle for a prolonged amount of time than ratings developed early in the epidemic spread.

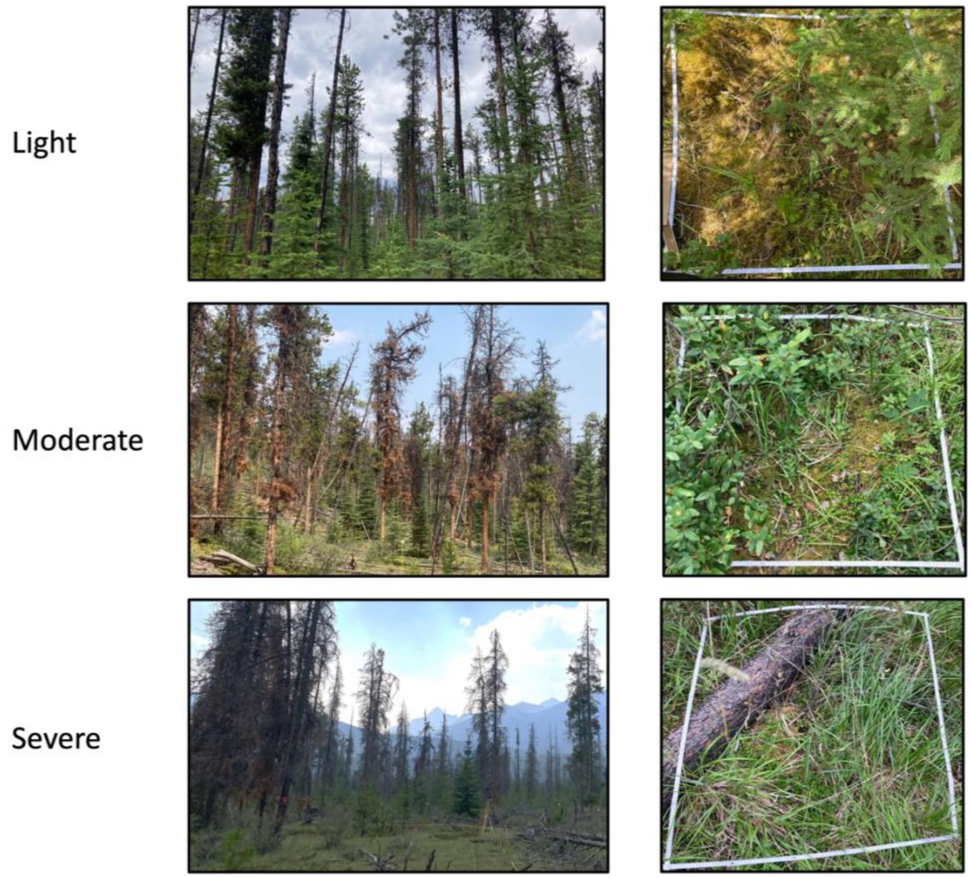


Figure 2.2. Examples of stand structure, canopy conditions, and surface vegetation composition for each severity class showing greater moss coverage and seedling recruitment in Light plots, higher shrub loading in Moderate plots, and greater herbaceous material coverage in Severe plots.

2.2.3 Field Data Collection

To quantify fuel variability across forest stands, detailed measurements were taken for each fuel strata (ground surface, understory, canopy) within forest mensuration plots outlined by Boucher et al. (2023), (Figure 2.3). Twelve plots were measured in 2021, six plots in 2022, and two plots in 2023. Two plots from 2022 were excluded from analysis due to the large proportion of deciduous trees (> 50%), making fuel comparisons inappropriate between largely varying species compositions. A total of 18 valid plots were thus used for analysis. Each plot was centrally located using Global Navigation Satellite System (GNSS, Topcon, Inc. California, USA) receivers with sub-decimeter positional accuracy. Markers at 4 m and 11.28 m were staked out in each cardinal direction as distance from centre to delineate a 50 m^2 circular understory plot and 400 m^2 circular overstory plot, respectively. To measure surface fuel, 8 x 1 m^2 microplots were installed, where fuel bed depth and weight (of litter and fermented/humic layer), forest floor vegetation/detritus coverage by category and conifer seedling density were recorded. Downed woody debris was measured along 40 m transects separated by diameter and characterized by condition (sound or rotten) and position (elevated or on the ground) (Boucher et al. 2023). To measure understory fuel attributes, height of all saplings with a diameter at breast height (DBH) greater than or equal to 3 cm and species were recorded within the 400 m^2 plot. Heights of seedlings (DBH $\leq$ 3cm), dominant shrub and herbaceous species were measured within the 50 m^2 plot. To measure overstory fuel attributes, tree species, tree height, height to live crown, height to dead crown, DBH, and condition (percentage defoliated, live or dead, mountain pine beetle status) were determined for all trees (DBH $\geq$ 9 cm) and saplings (DBH $\geq$ 3 cm) within the 400 m^2 plot.

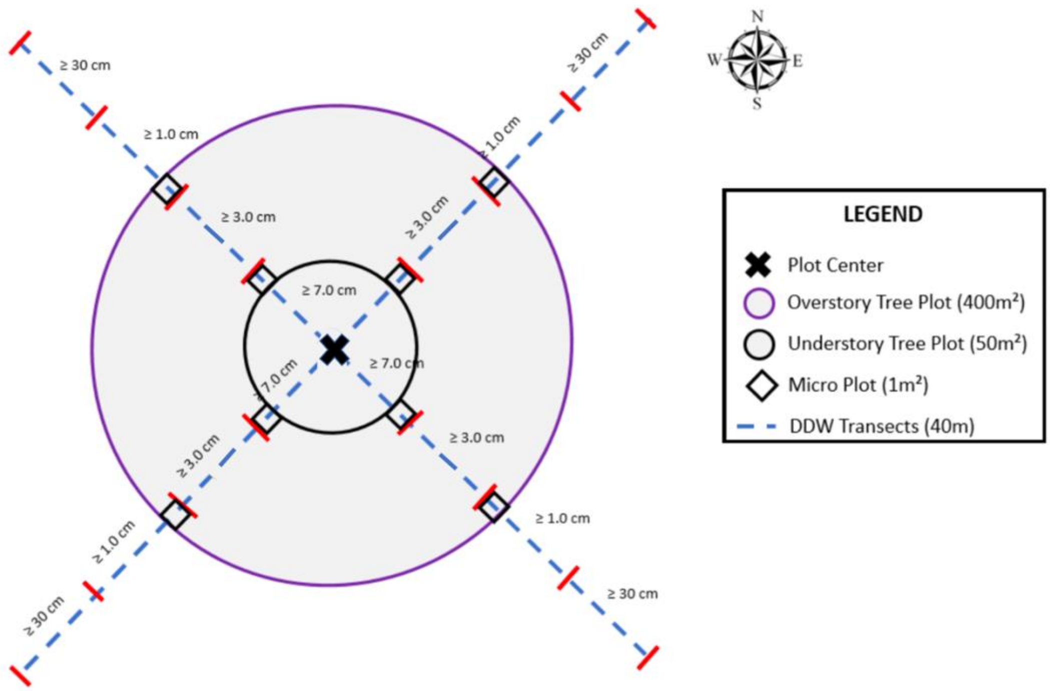


Figure 2.3. Forest mensuration sampling schematic adapted from the Next Generation Canadian Forest Fire Danger Rating System by Boucher et al. (2023) used as sampling methodology for data collection at 18 sites within Jasper National Park. Dashed blue lines indicate downed woody debris transects (40 m each) over plot centre with diameter thresholds over segments. The purple circle indicates the overstory tree plot in which every tree and sapling (DBH ≥ 3 cm) was measured. The black circle indicates understory plot in which seedlings and shrubs were measured. Small black squares indicate surface and ground fuel 1 m^2 microplots for surface coverage and organic layer depth.

2.2.4 Data Processing

Fuel characteristics were processed from measured plot data into forest inventory data per stand type. Stand density, basal area, quadratic mean diameter, tree height, height to the base of crown, species composition and mountain pine beetle mortality proportions (assumed for any dead lodgepole tree within each plot) were averaged by stand type. Crown fuel load and crown bulk density were calculated for all trees and saplings using allometric equations for biomass from Lambert et al. (2005) and Ung et al. (2008) based on DBH and tree height. These regression models provide estimates of biomass for wood (bole), bark, foliage, and branch components of trees for each species present (root-mean-square-error for foliage component 2.6 – 12.9 kg). Crown fuel load is the dry weight of the foliage in the crown available for consumption in a fire, and canopy bulk density divides this weight by the crown length (Phelps et al. 2022). Foliage refers to the needle component of a tree or shrub species and is typically highly available for fire consumption (in conifer species) due to the high surface area to volume ratio and lower moisture content than deciduous species (Doran et al. 2004). The definition of crown fuel load is not consistently applied between researchers and can include twigs, small branch wood up to 1 cm diameter or 3 cm diameter, and aerial lichens and mosses (Alexander & Cruz 2011) or foliage alone (Van Wagner 1977). Biomass equations separating branch wood by diameter were not available in this case, and so only conifer foliage was included in the initial calculation (Phelps et al. 2022). Canopy fuel load per unit area across the plot was calculated by status of the tree; standing trees in gray phase (dead with no needles) were excluded from the canopy fuel load calculation, as complete loss of foliage was noted. To highlight the loss of canopy fuels that has occurred due to mountain pine beetle, foliage load was calculated for trees and saplings as if all were in live condition, and then condition was classified to show foliage reduction that has already taken place (gray trees) and soon to be lost (red trees) from the canopy. To calculate what additional woody fuels may be available for fire consumption due to high mountain pine beetle severity in cases of extreme fire weather (Talucci et al. 2019), a secondary calculation of canopy fuel load with all diameters of branch wood was performed including the foliage component for live trees, the foliage and branch structure components for red-phase trees, and branch structure components for gray-phase trees.

Stand mean of shrub and seedling fuel loading were calculated using Jasper-specific equations from Delisle (1986). Downed woody debris loading was calculated using equations from McRae (1979) with constants from Delisle & Woodard (1988). Mean surface fuel load of moss and herbaceous material was calculated using percent coverage within plots and equations developed using data from the Kananaskis region of Alberta (~500 km south of Jasper) as a regional proxy from Bessie & Johnson (1995). Litter and duff layer samples were dried and weighed for ground fuel loading for all plots.

Fuel strata gap is an adjustment of the canopy base height to include the effect of ladder fuels between the surface and the aerial fuels at a stand level introduced by Cruz et al. (2003). It has been recently updated for inclusion in a revised crown fire initiation modelling framework (Perrakis et al. 2023) and is calculated by subtracting the center of the sapling canopy from the mean stand overstory canopy base height. The fuel strata gap better captures vertical continuity between the forest floor and aerial fuels by using the height information of multiple strata in uneven and regenerating stands, than using the traditional canopy base height value of the mean lower limit height of the mature tree canopy. Stand age was evaluated from a vegetation resource inventory vector GIS layer provided by Jasper National Park.

2.2.5 Airborne lidar plot extraction and stand analysis

To compare stand density and height across the total area impacted by mountain pine beetle with the limited number of field collected plots, point cloud data from airborne lidar surveys were utilized. To span the spatial range of mountain pine beetle across the Park's landscape, 450 400m^2 plots were extracted from three airborne lidar survey flight polygons collected in 2021 and 2022 (Figure 2.4). These polygons include 50 plots for each severity rating. Potential qualifying polygons were limited to areas of limited topographic relief to remain comparable to field data collections within gray-phase mountain pine beetle and exclude more recent infestation (red-phase) on valley sides. One additional lidar polygon (South of townsite) was excluded due to further pre-processing needed to remove noise, which skewed the max height of returns due to the effects of atmospheric smoke. The surveys were flown with a Teledyne Optech Inc. Titan airborne laser terrain mapper equipped with multispectral channels at wavelengths 1550 nm (shortwave infrared), 1064 nm (near infrared), and 532 nm (green). The point clouds were cleaned and classified within TerraScan (Terrasolid, Finland), normalized to ground elevation, and digital elevation models (DEM) and canopy height models were derived within LAStools based on average maximum height at 1 m cell resolution (rapidlasso GmbH, Germany).

To isolate "plots" for tree and canopy data to be extracted within gray phase valley areas, DEMs for each polygon were resampled to a 20 m by 20 m cell resolution, and slope was calculated. A new slope raster was calculated to isolate the areas with less than or equal to 3 degrees slope (~5%, or negligible topographic relief). The Jasper 2020 vegetation resource inventory vector GIS layer was then introduced, clipped to the extent of the polygon, and rasterized with the mountain pine beetle disturbance code attribute value. The vegetation resource inventory layer's mountain pine beetle disturbance codes 1-3 aligned with this study's "Light" severity rating, 4-6 aligned with "Moderate", and 7-9 aligned with the "Severe" rating, as the single digit value translated to the percentage (x10) of pine mortality from mountain pine beetle. To find appropriate areas to sample, the raster calculator was used to isolate areas of each severity rating that also had little to no topographic relief. A stratified random sampling was performed to place 50 plot centres across the geographic extent of the lidar survey for each severity level in each polygon and extrapolated to 400 m^2 circular plots (Figure 2.4).

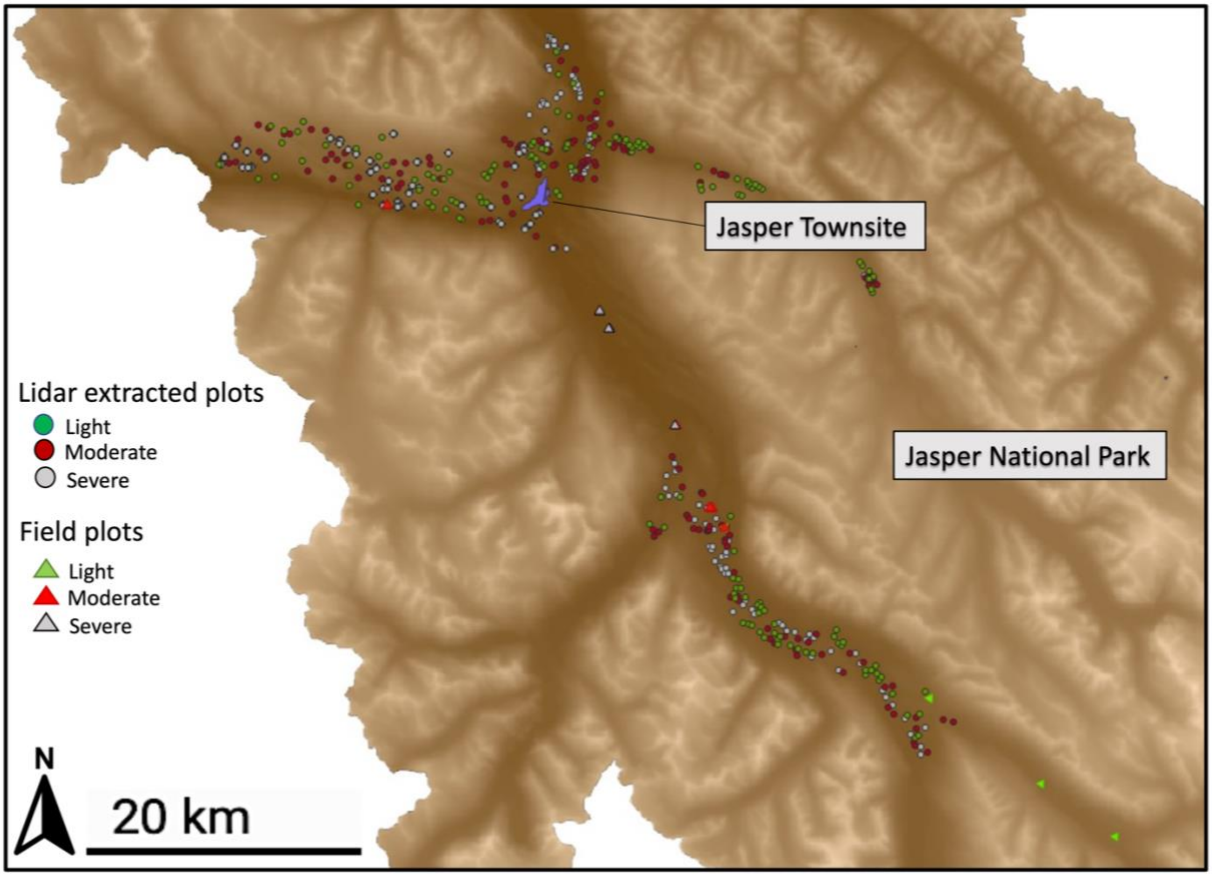


Figure 2.4. Locations of plots with tree density and height data extracted from airborne lidar point clouds overlaid on to a hillshade DEM (DEM provided by Jasper National Park). Mountain pine beetle severity is represented by green circles (Light, n=150), red circles (Moderate, n =150), and gray circles (Severe, n=150). Field measured plots are shown by triangles.

The canopy height model was clipped per lidar 'plot' polygon and further analyzed in R package "lidR" (Roussel et al. 2020) for individual tree detection and segmentation using a variable window filter originally designed for watershed evaluation (Popescu & Wynne 2004) within the ForestTools package (Plowright 2023). The variable window filter isolates local maxima within a window that changes sizes depending on the height of the current cell, accounting for varying crown morphology. The local maxima were computed with a minimum height of two meters to exclude understory. The result was a data frame with heights and coordinates for 13 898 identified trees which allowed for stem density (per ha) calculations. These derived heights and densities were compared to field collected densities and tree heights (744 trees) to determine if the field derived fuels were comparable to those across the mountain pine beetle affected landscape.

2.2.6 Statistical Analysis

To better understand how the vertical distribution of fuels vary between mountain pine beetle-induced severity levels, comparisons were applied across ground, surface, understory, downed wood, and aerial fuels and vegetative structural components between plots. To compare, the Kruskal-Wallis rank test with Dunn's pairwise comparison as well as the Anderson-Darling pairwise distribution test was used. The Kruskal-Wallis (KW; Kruskal & Wallis 1952) is a non-parametric analogue of ANOVA that can be used to compare groups and is an extension of the Mann-Whitney U test applied to more than two groups. The test was used due to the skewed nature of numerous variables, where transformation aligned some within a suitable parametric distribution, yet still displayed unequal variances. Data were tested for normality per variable using the Shapiro-Wilk test and Quantile-Quantile plots to visualize the distribution of each structural and fuel loading characteristic within mountain pine beetle plots. As most attributes were not normally distributed, even after attempts at log, square-root and power transformation, non-parametric tests were necessary for statistical comparisons. When a KW test was significant (i.e. the mean ranks between two mortality ratings were significantly different), a Dunn's test (Dunn 1964) for pairwise comparison was performed. For each pair of severity ratings (Light vs. Moderate, Light vs. Severe, and Moderate vs. Severe), the difference in mean rank scores divided by the rank pooled variance estimate (from the KW test) is calculated with the Holm correction for multiple comparisons (Holm 1979). The Dunn's test allows for evaluation of which severity ratings were statistically different from one another for each fuel characteristic. The Holm step-wise correction test is necessary to reduce type one statistical error by reducing the significance level for the number of pairs being compared (Dinno 2015). It is important when comparing multiple groups such as the three severity ratings to standardize the original alpha (0.05) for each pairwise test, to not produce falsely significant results between the fuel loadings and structural characteristics of the different groups.

To understand if the distributions of fuel variables differ between severity ratings, an Anderson-Darling (AD; Anderson & Darling 1952) pairwise test was also performed on all fuel and structural characteristics. With highly variable forest inventory data, the distribution of values and acknowledgement of high and low data endmembers may be more informative than the comparison of central tendencies between groups. The AD test is a modified Kolmogrov-Smirnov that applies more weight to the tails of the distribution and is used to determine if samples come from significantly different distributions. All KW, Dunn's, and AD tests were performed in R (R Core Team 2023) using the "rstatix" (Kassambara 2023) and "PMCMRplus" packages (Pohlert 2023).

Fuel characteristics are often highly correlated and their associated variables or indicators may index similarities or differences as groups. Principal components analysis (PCA), as a data reduction, or dimension-seeking approach, can be used to reduce the complexity of multiple indicators (Daultrey 1976). To explore how the fuel structural and loading variables in this study co-vary, and can potentially be reduced to a set of unique underlying dimensions of variation, a PCA was carried out on a set of key indicator variables measured for each of the study plots. Due to the high number of characteristics measured, a suite of ten variables thought to be important indicators of stand classification or influential to fire behaviour (Van Wagner et al. 1977, Forestry Canada Fire Danger Group 1992, Loudermilk et al. 2012) were included, hypothesized to be within four distinct groupings or "domains" of fuel strata. These variables were as follows:

Domain 1: Overstory canopy structure – variables canopy base height and basal area of trees

Domain 2: Subcanopy structure & fuels – variables sapling canopy bulk density, basal area of saplings, and tree canopy bulk density

Domain 3: Ground & surface fuels – variables litter and duff layer, sapling height, shrub, herbaceous & seedling fuel load

Domain 4: Downed woody debris – variables coarse woody debris and fine woody debris

PCA is generally performed on a matrix of Pearson Product Moment Correlation Coefficients (Pearson's r), which assumes normality. However, although not common, PCA has also been applied to downscaled (weaker) non-parametric correlation matrices using the Spearmans's Rank Correlation Coefficent. Computing the PCA (with Pearson's r) on ranks of the input variables essentially replaces the Pearson's input correlation matrix with a Spearman's rs matrix. Due to non-normality of some of the input variables, we carried out the PCA using the latter approach, with an input matrix of 18 cases by 10 variables. To maintain complete distinctiveness (uncorrelated dimensions) of the resulting components, a Varimax orthogonal rotation with Kaiser normalisation was selected to aid interpretability, rather than an oblique rotation which allows the axes to become partially correlated. Although an eigenvalue of 1.0 is generally the default criteria for stopping extraction, it is considered beneficial to examine the scree slope of eigenvalues and consider extraction criteria slightly above or below eigenvalue 1.0 if warranted and if the axes are interpretable (Cattel, 1966). Visual inspection of the inflection points of the scree plot and eigenvalues indicated that retention of four components was suitable. This solution had an eigenvalue of 0.971 for the 4^{th} component and accounted for 78.2% of the variability in the ten input variables. Furthermore, all the communalities were above 0.65, so the majority (>65%) of the variance of each input variable is captured by the four-dimension solution. The characteristic of, or relative position of, each study site on each of the four components was measured by component scores. A biplot was created to show separation of plots within severity ratings along the first two components.

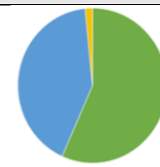
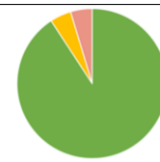
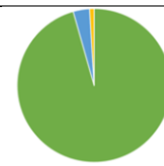
One of the aims of this study is to compare structural differences by mountain pine beetle severity. To determine if significant differences are evident in the average dimensional characteristics (i.e. mean component scores) of the study sites based on their mountain pine beetle status classification of Light, Moderate, or Severe, a one-way ANOVA (Girda, 1992) with Tukey's post hoc pairwise comparison tests was carried out. The PCA and ANOVA were performed in IBM SPSS Statistics (Version 29).

2.3 Results

2.3.1 Stand characteristics across mountain pine beetle severity gradient

The majority of mountain pine beetle-impacted stands were located along the Athabasca valley south of Jasper townsite. Severity was not limited to a specific geographic area and was classed as proportion of dead standing infested pine trees (Light < 35%, Moderate 36-65%, Severe > 65% gray phase mortality), but generally decreased in severity from north to south along the valley. This is due to general direction of spread prior to the mountain pine beetle mortality event, and host tree concentration. Light plots had a higher mean age of 156 years (standard error, SE = 25 years) than Moderate and Severe plots which had a mean age of 105 (10), and 94 (14) years, respectively (Jasper Vegetation Resource Inventory). Light plots had a greater proportion of spruce intermixed with pine, and Moderate plots contained more subalpine fir and aspen than the other severity classes (Table 2.1). Quadratic mean diameter was comparable in both Light and Moderate classes but slightly larger in the Severe class (Table 2.1).

Table 2.1 Mean (± standard error (SE)) of stand characteristics determined from plot measurements and scaled per ha within forest stands with varying severity thresholds of mountain pine beetle infestation in Jasper National Park, AB

Outbreak Severity	Total Trees (stems ha^{-1})	Live Trees (stems ha^{-1})	Saplings (stems ha^{-1})	Live Basal Area (m^2 ha^{-1})	Dead Basal Area (m^2 ha^{-1})	Quadratic Mean Diameter (cm)	Mountain Pine Beetle Mortality (%)	Species Proportions
Light	**1420** (424)	**1100** (323)	**705** (114)	**23.1** (5.9)	**4.1** (2.2)	**16.7** (0.7)	**18.0** (6.3)	
Moderate	**1028** (127)	**609** (63)	**334** (114)	**13.8** (1.9)	**8.6** (2.1)	**16.8** (0.6)	**54.6** (2.6)	
Severe	**660** (177)	**310** (84)	**25** (14)	**7.9** (1.8)	**8.8** (3.2)	**18.5** (1.5)	**76.0** (4.0)	
Lodgepole Pine, Spruce, Aspen, Subalpine Fir								

2.3.2 Comparison of stand density and height distribution across mountain pine beetle severity gradient

Severe plots showed a significant reduction in live overstory tree (DBH > 9 cm) and sapling (3 – 9 cm DBH) density compared to lightly disturbed plots (KW H = 7.68, AD A^2 = 2.93, $p < 0.05$). Severe mountain pine beetle stands had 72% fewer live tree stems per hectare while Moderate mountain pine beetle had 45% fewer live stems per hectare than Light severity plots (Table 2.1). Severe mountain pine beetle stands had 96% fewer live sapling stems per hectare than Light mortality plots, which corresponds to what one expects during a prolonged outbreak where preferred host trees (> 20 cm DBH) are killed and beetles start to attack smaller trees (Amman 1985). Moderate and Severe plots both had significantly reduced live basal area relative to Light plots (KW H = 6.61, Dunn's z = -2.55, $p <0.05$), and twice the dead basal area as Light plots (Table 2.1).

Tree height distribution was not significantly different between severity ratings, indicating that this is not a critical influence on mountain pine beetle infestation and subsequent mortality or vice versa (Figure 2.5). Canopy base height distribution was significantly different between Severe and Light mountain pine beetle impacted plots (AD, $A^2 = 2.0$, $p <0.05$), with the highest canopy base height above ground found in lightly disturbed plots (mean = 6.4 m; SE = 1.2 m). The base height above ground was reduced in Moderate plots (mean = 5.98 m; SE = 0.6 m), while Severe mountain pine beetle affected plots had the lowest canopy base height (mean 3.45 m; SE = 0.62 m) (Figure 2.4). While Severe plots had canopies that extended nearest to the ground, live saplings in these plots were sparse and thus contain less burn available fine fuel.

The vertical distance between canopy base height and the midpoint of ladder fuels, the fuel strata gap, was significantly smaller in higher mountain pine beetle severity classes than Light, but only when dead fuels were considered as readily available carriers of fire into the aerial strata (central tendency: KW H = 8.46, Dunn's z = -2.68, $p < 0.01$; distribution: AD $A^2 = 3.45$, $p < 0.05$). Fuel strata gap often defines canopy base height as height to the live crown, where fine fuels (foliage) are dense enough to facilitate fire spread. In cases of prolific mortality due to infestation, however, the dry bark and small twigs of beetle-killed trees can fill this role. Fuel strata gap is an important consideration for potential wildland crown fire initiation, and notable difference was observed in the vertical gaps from understory to overstory between severity classes when dead fuels were included. The lowest fuel strata gap was in Severe plots (mean = 1.4 m; SE = 0.31 m), Moderate had a slightly larger gap (mean = 3.75 m; SE = 0.56 m) and Light had the largest (mean = 4.0 m; SE = 0.90 m) (Figure 2.5). However, the density and distribution of saplings between severity ratings and the enhancement of ladder fuels can be observed comparing the frequency (n =171 in Light plots vs n = 30 in Severe plots) of measured sapling heights, which have much greater fuel continuity and potential impact on fire intensity despite a larger fuel strata gap in Light mountain pine beetle plots (Figure 2.5).

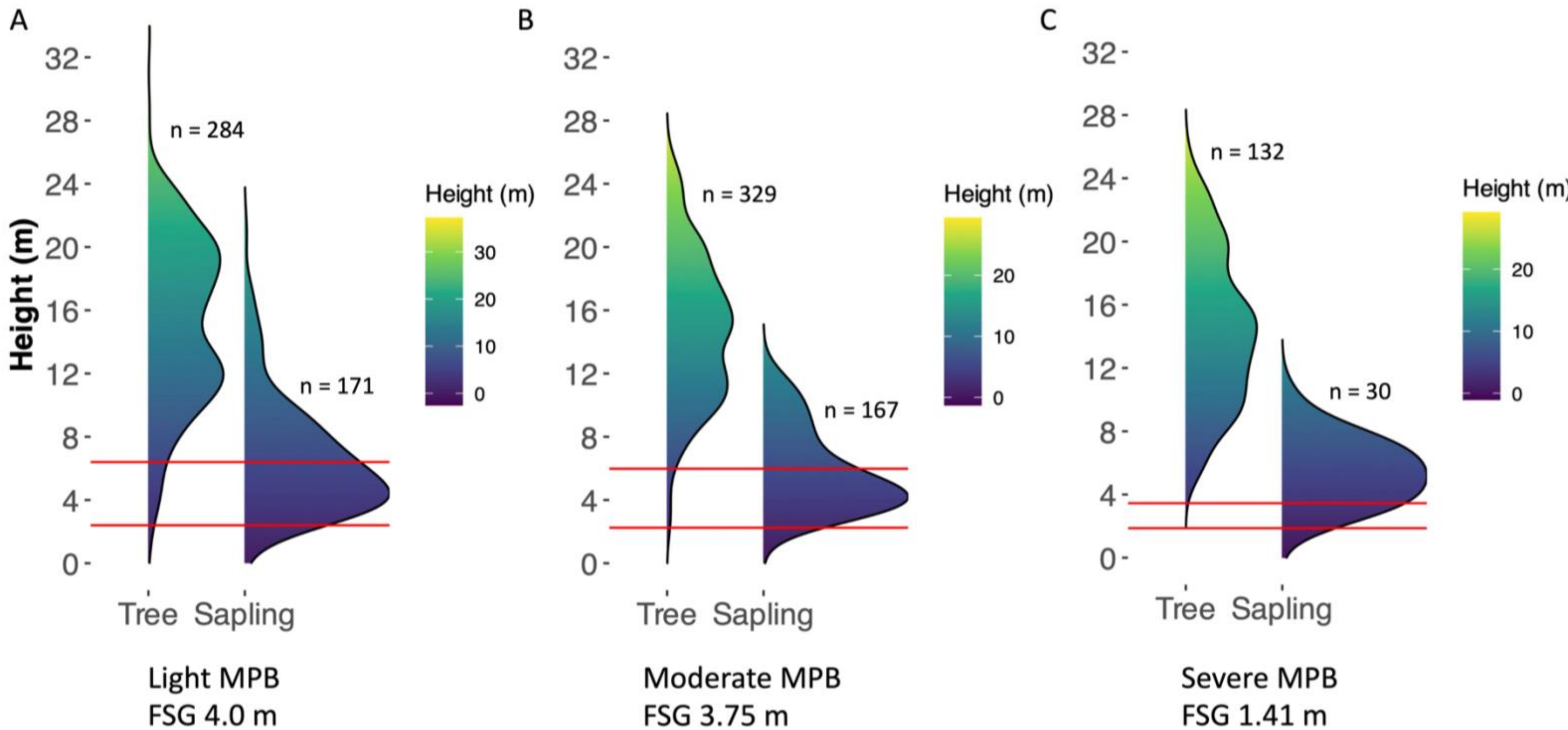


Figure 2.5. Height histogram frequency distribution of all trees (DBH > 9 cm) and saplings (3 cm < DBH < 9 cm) along a gradient of mountain pine beetle severity in A) Light mountain pine beetle outbreak (< 35% pine mortality), B) Moderate mountain pine beetle outbreak (36 – 65% pine mortality) and C) Severe mountain pine beetle outbreak (> 65% pine mortality). Fuel strata gap (FSG) is denoted by distance between mean canopy base height (top red line) and midpoint of the sapling cohort canopy (lower red line).

2.3.3 Comparison of understory community composition and structure across mountain pine beetle severity gradient

Severe mountain pine beetle plots had greater percent coverage of herbaceous and grass vegetation, and less coverage of shrubs, moss, litter, and number of seedlings than Light and Moderate stands (Table 2.2). Light mountain pine beetle plots had the most conifer seedlings per hectare and litter coverage (Table 2.2). An increase in seedling regeneration may be expected in some cases where a severe beetle outbreak causes the canopy to open and solar radiation increases (Stuart et al. 1989), but this is not shown in these stands. As severity increased to Moderate, the mean depth layer of organic material (litter and duff) was almost three times thinner, but this did not change across the two higher severity classes (Table 2.2), and may be a function of plot location.

Table 2.2 Mean (± SE) understory characteristics of stands with varying severity of mountain pine beetle infestation in Jasper National Park, AB. Values with the same black (KW with Dunn's post-hoc test) or red letter (AD test) are significantly different for that surface fuel component.

Mountain pine beetle Severity	Seedlings (stems ha^{-1})	Shrub Cover (%)	Herbaceous Cover (%)	Moss Cover (%)	Litter Cover (%)	Organic Layer Depth (cm)
Light	**3345** (1663)	**40.6** (17.2)	**22.8** ^{a} ^{a} (3.4)	**70.5** (16.8)	**35.8** (14.1)	**17.8** ^{ab} ^{ab} (5.8)
Moderate	**1500** (795)	**57.5** (4)	**37.8** ^{b} ^{a} (5.7)	**75.4** (6.3)	**12.2** (3)	**6.4** ^{a} ^{a} (1.1)
Severe	**1080** (294)	**31** (9.8)	**61** ^{ab} ^{a} (4.7)	**39.9** (13)	**8.8** (2.5)	**6.4** ^{b} ^{b} (1.3)

2.3.4 Comparison of canopy fuels across mountain pine beetle severity gradient

Canopy fuel load

Figure 2.6 shows the estimated foliage reduction by severity rating. From total modelled canopy fuel load amounts for each severity rating (both trees and saplings), Severe plots have lost the highest proportion of original canopy foliage to the surface fuel as needle litter (mean = 52.0%; SE = 4.9%), while Moderate plots have lost slightly less (mean = 38.6%; SE = 5.2%), and Light plots have only lost some to the forest floor from mountain pine beetle mortality (mean = 11.8%; SE = 4.4%). The proportion of foliage load in red phase at the time of measurement can also indicate how fuels will move from aerial strata to the surface. Severe plots will lose another third of canopy fuels (mean = 28.4%; SE = 3.1%) when the red needles fall, Moderate plots another 16% (SE = 3.3%), and Light only a small proportion (mean = 3.3%; SE = 1.7%). The cumulative loss that will occur is mainly due to higher instance of infested mature trees that were still retaining foliage, as sapling canopy fuel load in the red phase was negligible, and so will not significantly contribute to the fuel moving from the canopy to the surface fuel bed.

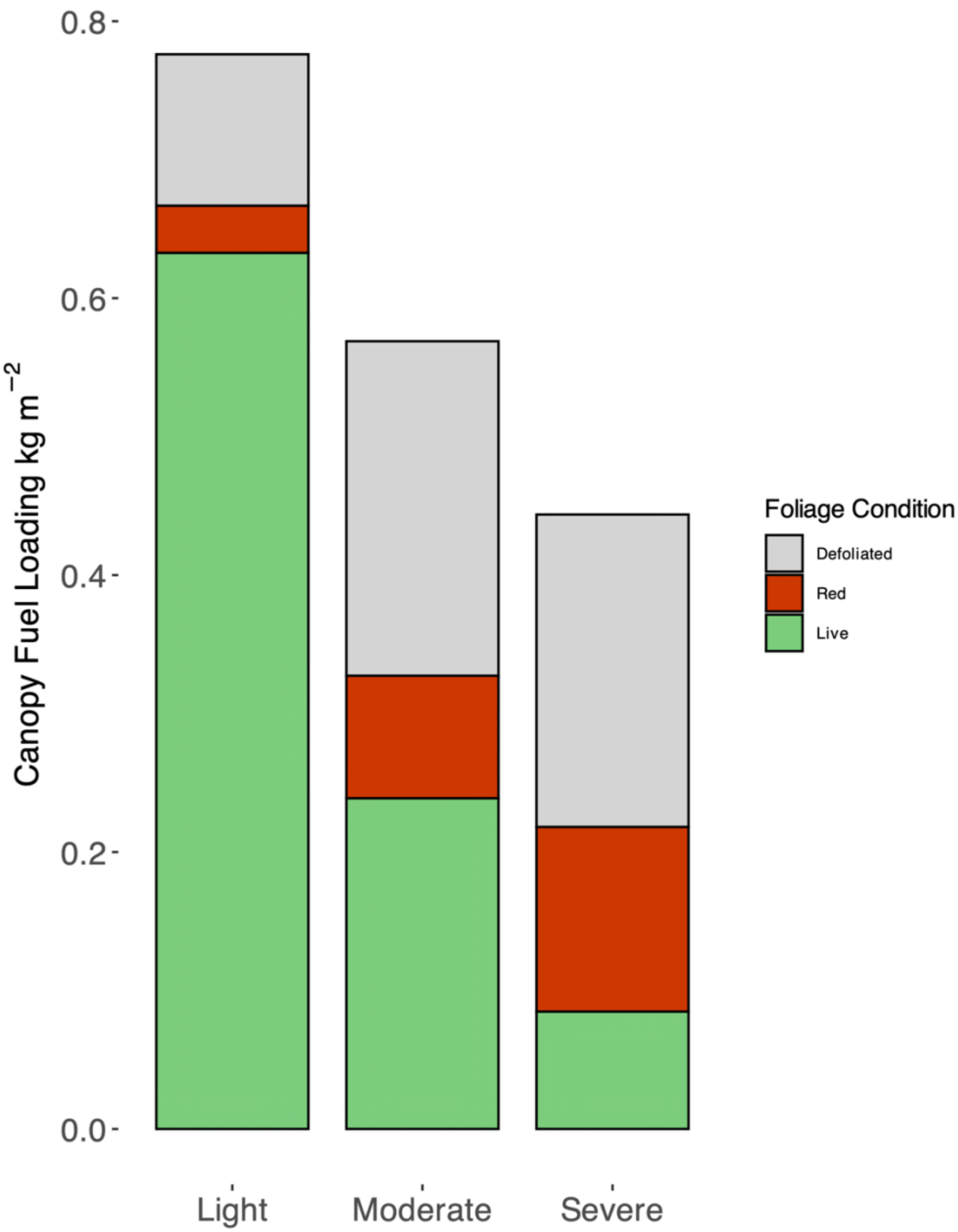


Figure 2.6. Modelled mean stand canopy fuel biomass for each mountain pine beetle severity rating based on allometric equations and tree condition (live, infested but foliage retained, and defoliated) to outline historical aerial crown fuels before mountain pine beetle induced mortality. Defoliated portion shows the foliage biomass the beetle-killed trees had before defoliation occurred.

Differences in canopy fuel load as a result of the level of mountain pine beetle-induced mortality can be especially noticeable within the sapling cohort as increased severity means the supply of available larger host trees was exhausted and beetles moved on to the less preferred smaller pines (Amman 1985). Plot mean canopy fuel load, based on live and red infested trees (with dead needles), was highest in Light severity plots (mean = 0.67 kg m^{-2}; SE = 0.1 kg m^{-2}) and lowest in Severe plots (mean = 0.22 kg m^{-2}; SE = 0.02 kg m^{-2}) (Figure 2.6). The sapling cohort in the Light severity plots were dominated by spruce and subalpine fir and did not have any pine trees affected by mountain pine beetle. Both Moderate and Severe plots also exhibited some spruce and subalpine fir in the understory, but also had sapling pines in both the red phase and in the needleless gray phase. Sapling canopy fuel load was greatest in Light plots (mean = 0.12 kg m^{-2}; SE = 0.02 kg m^{-2}), decreasing to less than half that in Moderate plots (mean = 0.05 kg m^{-2}; SE = 0.02 kg m^{-2}) to substantially lower amounts in Severe plots (mean = 0.004 kg m^{-2}; SE = 0.002 kg m^{-2}), which may also be a function of plot sampling location.

To show the potential change in biomass in the canopy available for consumption in high severity fire weather scenarios in the Moderate and Severe sites with over 50% mountain pine beetle mortality, a comparison was made between modelled foliage only and foliage (from trees still retaining foliage) and all branches (from mountain pine beetle killed trees) included based on allometry. The greatest change in available fuel was seen in Severe sites, increasing from 0.22 kg m^{-2} to 0.83 kg m^{-2} (SE = 0.17 kg m^{-2}), a 3.8x increase. Moderate sites' available fuel increased just over two times from 0.4 to 0.87 kg m^{-2} (SE = 0.94 kg m^{-2}) (Figure 2.7). This substantial increase in potential available fuel has important implications for head fire intensity potential as well as burning residence time in high fire weather scenarios.

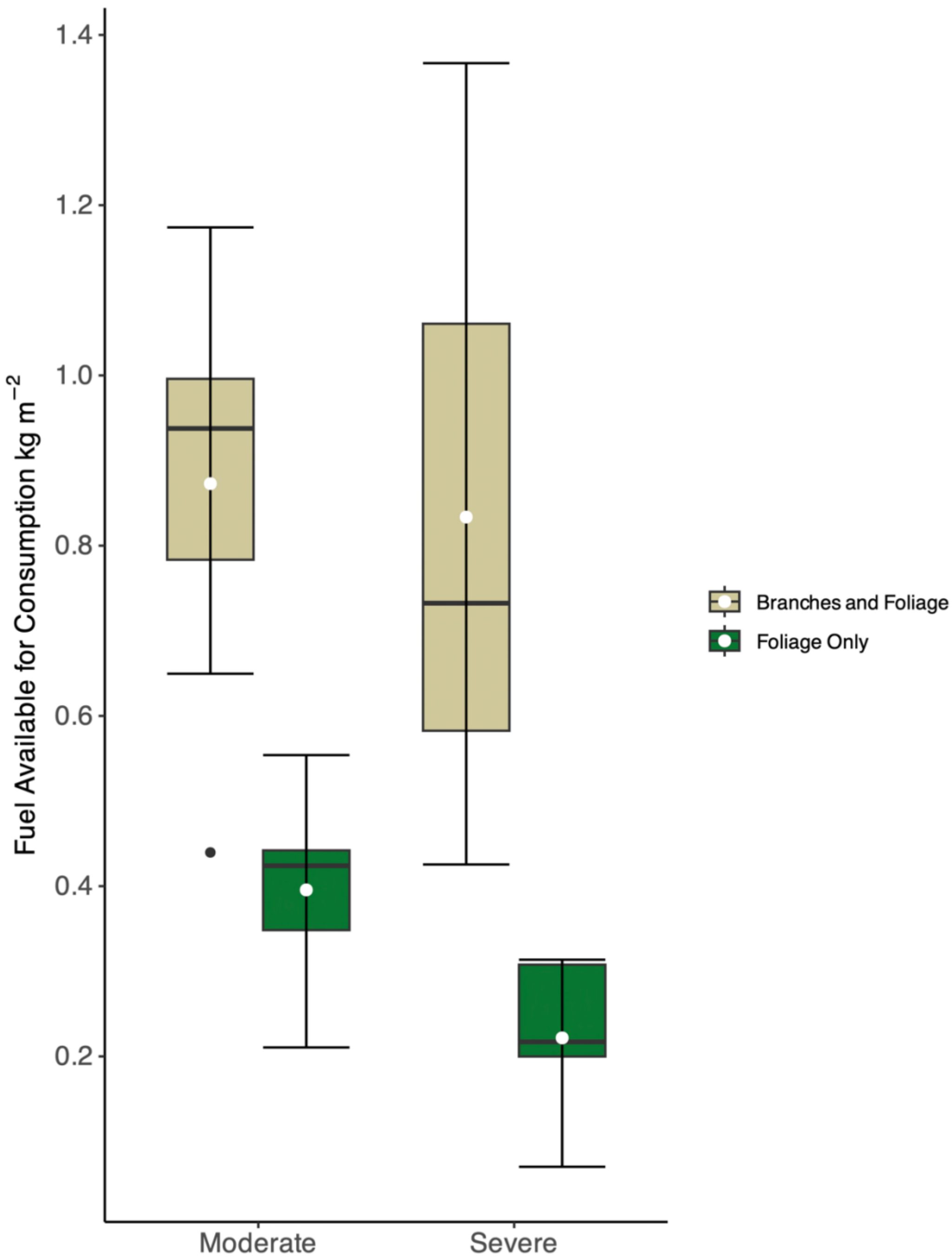


Figure 2.7. Modelled mean stand canopy fuel biomass of foliage component only (green) and branch wood included (tan) available to burn in extreme fire weather scenarios for Moderate and Severe mountain pine beetle outbreak based on allometric equations and tree condition (live, infested but foliage retained, and defoliated) per plot. Mountain pine beetle-killed trees' (infested but foliage retained or defoliated) branches may become available to fire consumption given high fire weather indices (Talucci et al. 2019).

Canopy Bulk Density

Severe mountain pine beetle mortality plots had the lowest canopy bulk density when foliage loss was accounted for (mean = 0.02 kg m^{-3}; SE = 0.01 kg m^{-3}), which is a 76% reduction compared to Light mountain pine beetle mortality plots (mean = 0.10 kg m^{-3}; SE = 0.02 kg m^{-3}, Figure 2.8). Moderate mortality plot mean canopy bulk density was about 50% of Light mortality plots (Figure 2.8). To reduce the effect of stand density variation on canopy bulk density values, the proportion of canopy fuels that has been defoliated from each severity ratings' pre-infestation mean was compared to see the relative loss. For trees, Light stands lost a mean of 17.4%, Moderate stands lost a mean of 34.9%, and Severe stands lost 49% of original canopy bulk density. For saplings, lightly impacted stands lost 9%, moderate stands lost 19.7%, and severe stands lost 68.5% of original canopy bulk density. Saplings in the Light mountain pine beetle mortality plots were the tallest and most dense (Figure 2.5), and therefore had the greatest canopy bulk density of the understory strata (mean = 0.03 kg m^{-3}; SE = 0.01 kg m^{-3}). As severity increased, the number of saplings that remained live and retaining foliage significantly declined, resulting in negligible canopy bulk density values for Severe plots (mean = 0.001 kg m^{-3}; SE = 0.0009 kg m^{-3}, Figure 2.8).

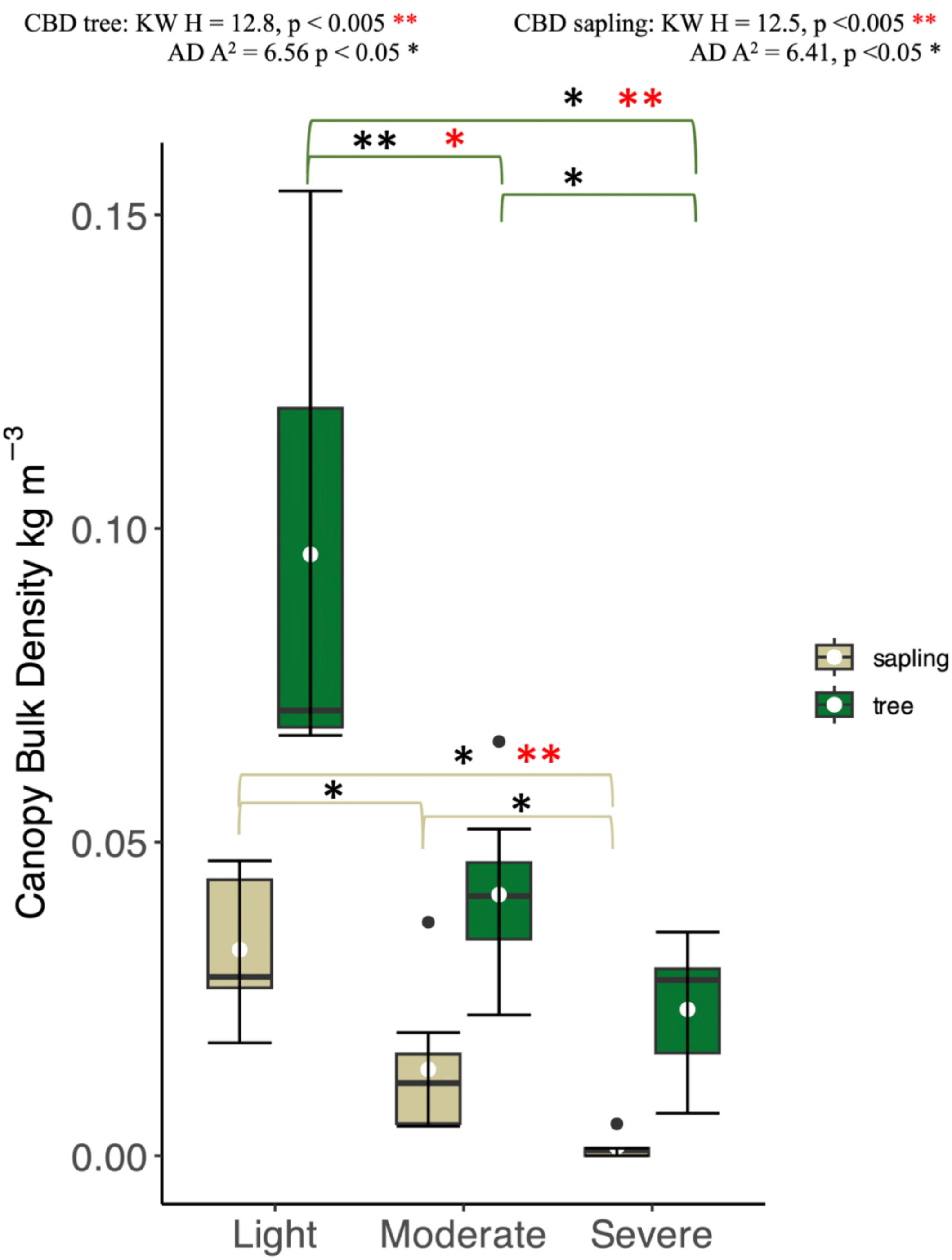


Figure 2.8. Canopy bulk density (CBD; kg m^{-3}) of trees and saplings retaining foliage across a gradient of mountain pine beetle-induced severity. Pairwise significance is denoted by red asterisks for central tendencies (Kruskal-Wallis with Dunn's post hoc test) and black asterisks for distributions (Anderson-Darling).

2.3.5 Comparison of ground, surface, and downed woody fuels across mountain pine beetle severity gradient

Light severity plots had the highest seedling fuel load (mean = 0.08 kg m^{-2}; SE = 0.03 kg m^{-2}), over two and three times greater than Moderate and Severe mountain pine beetle plots respectively (Figure 2.9). Differences in shrub loading and coverage were not significant (KW H = 1.91, p = 0.38). Grass and herbaceous fuel material were greater in Severe than Light mountain pine beetle impacted plots (KW H = 11.0, Dunn's z = 3.32, $p < 0.005$; AD $A^2 = 4.96$, $p < 0.05$) (mean = 0.06 kg m^{-2} and 0.02 kg m^{-2}, respectively) indicating early post-recovery shift to herbaceous and grassland species in plots decimated by mountain pine beetle.

Mountain pine beetle mortality levels also impacted the distribution of coarse and fine downed woody debris. Coarse woody debris here is any large downed log (> 7 cm diameter), while fine woody debris encompasses both medium woody debris (3 – 7 cm diameter), and fine woody debris (< 3 cm diameter). At this temporal stage, Moderate sites had the highest loading of coarse woody debris (mean = 3.21 kg m^{-2}; SE = 0.49 kg m^{-2}) approximately 1 kg m^{-2} more than both Light and Severe sites (Figure 2.9). This is likely associated with the combination of higher average stem density than Severe and more mortality than Light severity plots. As Moderate and Severe sites have comparable dead standing basal area (Table 2.1), this ratio will likely remain constant as dead pines fall to the forest floor. The relative loading of fine woody debris was an unexpected result to emerge from the data, as both Light and Moderate mountain pine beetle plots had around double the fine woody debris (mean = 0.92 kg m^{-2} and 0. 86 kg m^{-2}) than Severe plots (mean = 0.35 kg m^{-2}). It is important to recognize that these plots are within the same range of time-since-beetle and increased severity does not always equal increased decay rates of dead standing trees, but severity may influence potential litter fall. However, the weight of litter in this case did not significantly vary between mountain pine beetle severity classes. The dry weight of the duff layer in Severe plots was approximately twice (mean = 5.1 kg m^{-2}; SE = 0.54 kg m^{-2}) as much loading as Moderate and Light mountain pine beetle plots (Figure 2.9). The organic layer was significantly lower in Light than Severe plots (KW H = 8.04, Dunn's z = 2.78, $p < 0.01$; AD $A^2 = 3.84$, $p < 0.05$).

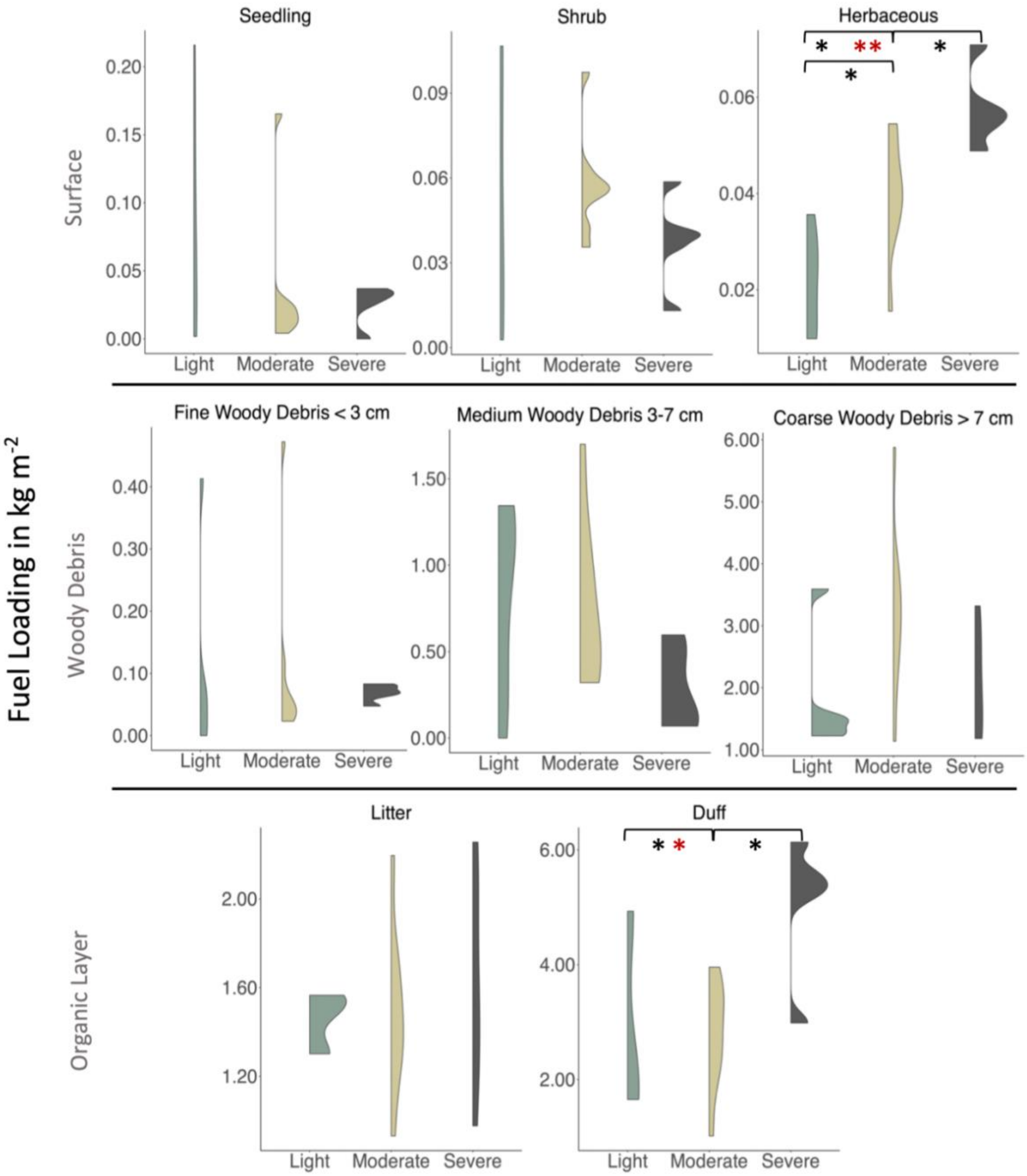


Figure 2.9. Fuel loading (kg m^{-2}) histogram distribution of understory fuels, downed woody debris (fine > 3 cm, medium 3-7 cm, and coarse > 7 cm diameter) and organic layer (litter and duff - fermentation and humic layers) by mountain pine beetle severity rating. Significance levels (* = p <0.05, ** = p <0.01) are denoted by statistical test in black (Anderson-Darling) and red (Kruskal-Wallis).

2.3.6 Mountain pine beetle severity and associated fuel profiles in multivariate space

The rotated, four component solution for principal components analysis accounted for 78.2% of the variance of the ten variable data set (Table 2.3, Figure 2.10). The interpretation of the data aligned the components with prior hypothesized drivers – vertical strata of fuel components (overstory, understory, surface, and downed woody debris).

The biggest driver of variation in gray-phase mountain pine beetle-affected stands can be described as an "overstory tree structure" axis. The first component, accounting for 38.6% of the variance, is defined by (loadings) of variables measuring tree canopy base height and tree basal area. As mountain pine beetle severity increases within plots, it is expected that negative values in the component scores along this first component would be observed.

The second component accounting for 16.0% of the variation, can be summarized as "subcanopy structure and fuels" is dependent on the sapling cohort. This dimension is defined by high loading variables that index sapling canopy bulk density, sapling basal area, as well as tree canopy bulk density, although the latter also shares secondary loading with PC1. There has been a large decrease in sapling density and high mortality as mountain pine beetle severity increases (Table 2.1), and so it is expected that plots with positive component scores on this component would have experienced less mountain pine beetle mortality.

The third component, accounting for 13.9% of the variation, can be summarized as a "ground and surface fuels" axis. It is defined by variables litter and duff loading, surface fuels (shrub, herbaceous, and seedling fuel load), and sapling height. This axis aligns with both fuel loading variables as well as structural indicators (sapling height). Despite interest in the impact mountain pine beetle outbreak has on surface fuel loading and vertical connectivity due to deposition and regeneration, it is only the third most important driver of variation in these stands, aligning with the general lack of significant differences in these values between mountain pine beetle severity ratings.

The fourth component, accounting for 9.7% of the variation, can be summarized as a “downed woody debris” axis. This bipolar axis is defined by a negative loading associated with coarse woody debris (> 7 cm diameter), and positive loading associated with fine woody debris (< 7 cm diameter). High positive component scores on this component therefore index high fine woody debris traits and low coarse debris traits, while high negative component scores index high coarse debris traits and low fine debris traits. This being the last ranked component again suggests less predictability between mountain pine beetle severity and amounts of downed woody debris in mountain pine beetle-impacted areas of Jasper.

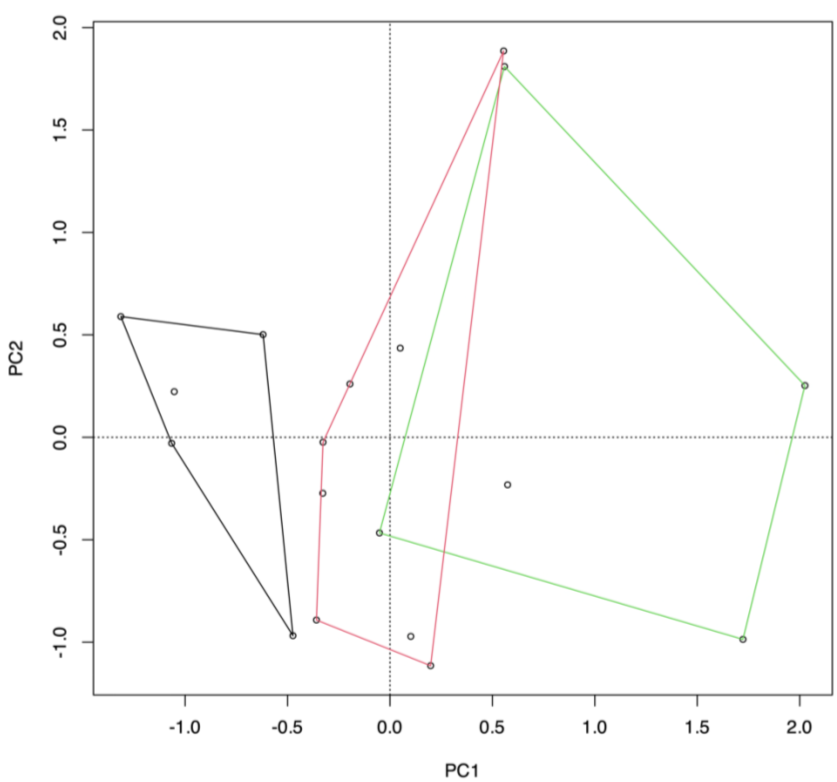


Figure 2.10 Principal components analysis biplot showing clustering of Light (green), Moderate (red), and Severe (black) mountain pine beetle severity ratings along the first two components accounting for 38.6% (PC1) and 16.0% (PC2) of variation.

Table 2.3. Principal Components Analysis component descriptors, variance explained, and loading values for reduced forest structure variables along four fuel strata dimensionalities

Component Title	Variance (%)	Variables	1st rank component loading *	2nd rank loading (>0.4)
Overstory Tree Structure & Fuels *(PC1)*	38.63	**- Canopy base height *(m)***	**0.929**	
		- Tree basal area *($m^2 ha^{-1}$)*	**0.852**	
Sapling Fuels *(PC2)*	15.96	**- Sapling canopy bulk density *(kg m^{-3})***	**0.908**	
		- Sapling basal area *($m^2 ha^{-1}$)*	**0.778**	
		- Tree canopy bulk density *(kg m^{-3})*	**0.567**	PC1 (0.545)
Ground & Surface Fuels *(PC3)*	13.90	**- Litter & duff layer (*kg m^{-2}*)**	**0.763**	
		- Sapling height (*m*)	**0.724**	
		- Shrub, herbaceous & seedling fuel load (*kg m^{-2}*)	**0.635**	PC2 (0.584)
Downed Woody Debris *(PC4)*	9.71	**- Coarse woody debris (*kg m^{-2}*)**	**-0.862**	
		- Fine woody debris (*kg m^{-2}*)	**0.605**	PC1 (0.466)
Total:	78.2			

* Rotation method: Varimax with Kaiser normalization

Component scores for all study sites combined represent z-scores, defined by a mean of zero and standard deviation of 1.0. Mean component scores for sites within each level of mountain pine beetle outbreak were also computed and are shown in Table 2.4. Differences in mountain pine beetle group means of the component scores were tested using four separate one-way ANOVA tests. Three of these four tests showed no significant differences ($p>0.05$) in mean component scores between mountain pine beetle groups. Results therefore indicate that no significant differences in "structural characteristics" (as defined by the components) are observed between Light, Moderate, and Severe mountain pine beetle levels for "overstory tree structure and fuels" (PC1), for "ground and surface fuels" (PC3), and for "downed woody debris" (PC4). The ANOVA tests did point to significant differences ($F = 9.89$, $p = 0.002$) in group means observed for PC2, the "sapling fuels" dimension. It can be seen (Table 2.4) that the Light mountain pine beetle group has significantly higher (and positive) scores on this axis (mean is 1.0 standard deviations above average), meaning that they have greater measures of sapling CBD, sapling basal area, and tree CBD. Both the Moderate and the Severe mountain pine beetle sites have negative or below average scores on these variables. This finding agrees with previous outcomes in this work (Figure 2.8) that mountain pine beetle has had a large impact on this fuel strata in Jasper.

Table 2.4. Mean component scores by mountain pine beetle outbreak severity for each of the four identified dimensionalities from principal component analysis. Mean component score, in bold, shows relative impact of severity on structural fuel characteristics. Asterisks show significance level for one-way ANOVA (p <0.005).

Component Title	Mountain pine beetle Severity	**Mean Component Score**	Std. Dev
Overstory Tree Structure & Fuels *(PC1)*	- Light	**0.202**	1.17
	- Moderate	**0.344**	0.79
	- Severe	**-0.753**	0.90
Sapling Fuels ** *(PC2)*	- Light	**1.009**	0.586
	- Moderate	**-0.033**	0.825
	- Severe	**-0.956**	0.545
Ground & Surface Fuels *(PC3)*	- Light	**-0.617**	1.324
	- Moderate	**0.084**	0.914
	- Severe	**0.482**	0.504
Downed Woody Debris *(PC4)*	- Light	**0.344**	0.650
	- Moderate	**-0.329**	1.157
	- Severe	**0.182**	1.039

2.3.7 Cross landscape variability in stand density and tree height

Stem density for field measured plots (n = 18) ranged from 200 stems ha^{-1} to 1800 stems ha^{-1}. Lidar derived plots (n = 150) ranged from 25 stems ha^{-1} to 1375 stems ha^{-1} (Figure 2.11). The field plots also had a greater interquartile (IQR) range of 537.5 compared to the field density IQR of 275. Field measured tree heights (n = 744) ranged from 2.1 m to 33.4 m, and lidar tree heights (n = 13 898) ranged from 2.0 m to 36.75 m (Figure 2.11). The IQR for tree height was very similar with field having a slightly larger range (7.5 m) than lidar measured trees (6.15 m). Overall, the field data exceeded the maximum stand density estimated with lidar data by 19% and accounted for 90% of the range in tree heights. This indicates that the variability of canopy conditions based on mountain pine beetle severity and stand density across the valley bottom where gray-phase mountain pine beetle stands are most prevalent have been suitably captured by the field measured data.

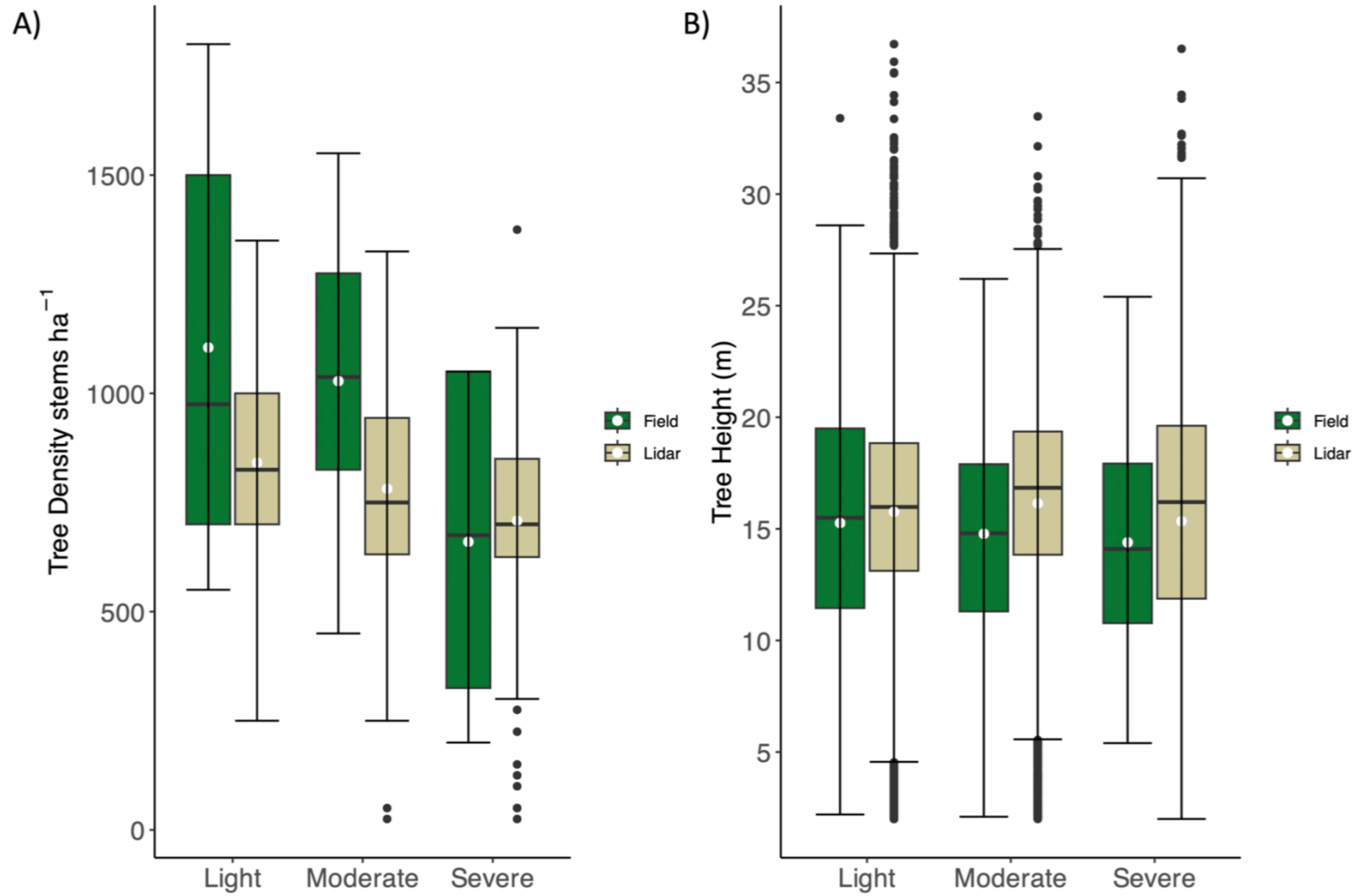


Figure 2.11. Comparison of A) tree density (stems per hectare) in field measured plots (green) vs derived from lidar canopy height model plots (tan) and B) tree height (m). Means are denoted by white dots.

2.4 Discussion

This study examined the diversity in fuel structures in gray post-attack phase (4 – 10 years since infestation). Overall, the major contributors to variation in stand and fuel characteristics as severity increased were in the affected sapling (advanced regeneration) cohort, dead standing basal area, canopy fuels, and herbaceous material coverage (Table 2.1; Table 2.4). The Severe plots within this study had a notable lack of recruitment in conifer seedlings, lower shrub and moss amounts, and higher herbaceous vegetation fuel loadings (Table 2.2; Figure 2.9). Moderate severity plots had the greatest amount of coarse woody debris (Figure 2.9), but exhibited the same amount of dead standing basal area as Severe plots (Table 2.1). Moderate plots therefore will present high levels of potential fire hazard in terms of impaired firefighter maneuverability, surface fire intensity potential when transitory dead standing fuel falls, and vertical fuel continuity when regenerating strata connect with remaining aerial fuels. Severe plots may exhibit higher potential for fire ignitions due to lack of canopy fuels increasing solar radiation and in stand winds to the forest floor. Despite potentially lowered crown fire hazard in high severity stands due to lack of available ladder fuels cohort and loss of canopy fuels, the extent of dead standing snags and projected increase in large downed woody debris showcases high safety hazard potential in these stands for the public (park visitors) and operational difficulties if a fire should occur. These scaled threshold values for mountain pine beetle severity rating can be used to estimate fuels over the larger landscape in similarly composed montane ecosystems.

2.4.1 Proportion of mortality influences the vertical distribution of vegetation structures

Canopy bulk density is one of the most important factors in crown fire spread (Cruz et al. 2003, Agee & Skinner 2005). Dense aerial fuels are needed to sustain high intensity crown fire.

However, low canopy bulk density increases incident solar radiation to the understory and forest floor (Whitehead et al. 2006, Brown et al. 2012, Reed et al. 2014) and increased spacing between trees can alter the roughness length, thereby increasing atmospheric turbulence and stomatal conductance and evaporative losses from lower canopy and understory (Chasmer et al. 2008, Emmel et al. 2014). Combined, these drying influences can increase ignition potential, surface fire behaviour and spread (Page & Jenkins 2007, Hoffman et al. 2015). Here, a three-fold decrease was identified in overstory canopy fuel loading, and a 40-fold decrease in sapling canopy fuel loading from Light to Severe stands. Relative to initial stand conditions, overstory canopy foliage loading decreased 50% in Severe stands, compared to 35% in Moderate and 17.4% in Light mortality stands (Figure 2.6). A 50% decrease in canopy bulk density was also found in other bark beetle outbreak literature (Schoennagel et al. 2012, Donato et al. 2013).

The impact of mountain pine beetle outbreak severity is highly apparent in the sapling cohort with the relative loss of sapling canopy fuels. Severe stands lost an average of 68.5% of canopy bulk density compared to initial loading, as opposed to only a 9% relative loss in Light stands. The PCA results (Figure 2.10; Table 2.4) align with this finding as the sapling component was the only axis with significant differences in structure and loading. The other components having non-significant results indicates that more variation in other component loadings (overstory structure, surface fuels, downed woody debris) may exist between temporal time-since-outbreak phases (Schoennagel et al. 2012, Jenkins et al. 2014) but within gray-phase, severity has the largest impact on sapling fuels and advanced regeneration. This finding aligns with the notion that there will be a surviving secondary structure after Light and Moderate mountain pine beetle outbreak which alters even-aged pine stands into multi-level cohort stands (Hansen 2014), but the ecosystem may look different in Severe areas. The loss of the sapling cohort may contribute to a significant time lag before regeneration will become sufficient to contribute to ladder fuels and increase crown fire potential in Severe stands, as seedling densities were also low in these plots.

Despite loss of canopy fuels, high fire weather scenarios can make standing mountain pine beetle-killed branchwood available for burning and fuel consumption in high severity mountain pine beetle stands (Talucci et al. 2019). If this fuel is consumed in a passive or active crown fire, the amount of available fuel surpasses the amount of foliage fuels lost from the canopy (Figure 2.7). Fuel consumption of these branch structures may be due to smouldering residence time, thus not contributing to intensity and spread in the flaming front, but this will still impact fire hazard from a containment or mop-up perspective, and will change the structural legacies left post-fire. Talucci et al. (2022) also found that in Interior British Columbia, fire severity was highest in a thorough mix of live and dead vegetation, suggesting the fuel profile found in Moderate stands here may represent higher fire severity risk.

2.4.2 Increasing canopy openness associated with severe mortality may shift montane vegetation communities

The higher level of herbaceous coverage and loading found in Severe plots aligns with an increase in canopy openness and subsequent changes in moisture and solar radiation (Banerjee et al. 2020). The canopy opening could also explain the decrease in moisture- and shade-dependant moss species coverage. Conifer seedling regeneration amounts are impacted by severity of mountain pine beetle and are of interest as very high fire hazard potential may occur when there is a pulse of fine fuels from regenerating conifers connecting the surface fuels, accrued fallen snags, with the remaining overstory trees in “Old”, post-epidemic mountain pine beetle phase (Schoennagel et al. 2012). Pine regeneration post-epidemic in warm climates and drier sites has been noted to increase with severity levels (Pelz et al. 2018). Despite this, there is limited seedling recruitment as severity increases (Table 2.2). Closer to this study area, however, poor regeneration of pine seedlings has been noted 1 – 3 years (McIntosh & Macdonald, 2013) in Robb, Alberta (76 km East of Jasper) as well as 6 – 9 years post infestation in the boreal region near Grande Prairie (~ 400 km North of Jasper) (Lieffers et al. 2023). This previous work as well as Astrup et al. (2008) examining post-disturbance seed beds in British Columbia, Canada attributes the lack of recruitment to mosses being an unsuitable substrate for germination. If the seedbank is below a layer of thick feathermoss, the seedlings struggle to establish. Here, high severity plots exhibiting low recruitment even with low moss coverage may result in an ecological shift to other coniferous (Kayes & Tinker 2012), broadleaf, or more substantially to herbaceous and grass species dominated ecosystems (Whitman et al. 2019, Lieffers et al. 2023). This change is increasingly noted after a wide-spread, disturbance-mediated mortality such as insect infestation or fire in addition to warming climates changing community establishment conditions (Halofsky et al. 2020, Coop et al. 2020, Seidl & Turner 2022, Aspinall 2023). In Jasper, this shift could lead to a restoration of the historical mosaic of conifer, aspen and grassland stands (Tande 1979), promoting heterogeneity across the landscape.

2.4.3 Surface and canopy fuel implications for potential fire behaviour and hazard levels from plot to valley scale

Though many surface fuel variables were not found to differ statistically among stands, the varying ranges may have implications for fire fuel considerations. Lightly impacted stands have less herbaceous material, but a large variability in the seedling and shrub fuel loads (Table 2.2; Figure 2.9). Herbaceous foliage can often retain more moisture than woody stemmed species (Burgan 1979, Pickering et al. 2021) but exhibit more extremes through seasonal curing and less moisture storage in root systems (Loudermilk et al. 2022). Moderate severity stands displayed the greatest range of medium and coarse woody debris, which will contribute to surface fire intensity (Byram 1959) and length of smoulder if a fire should occur (Brown et al. 2003). Light stands exhibited less litter load than higher severity ratings, despite higher spatial coverage (Table 2.2). Litter often serves as the ignitable fine fuel on the forest floor that can start a fire if dry enough (Varner et al. 2015). The largest loading of duff was found in Severe stands (Figure 2.9), which can contribute to longer fire smouldering and residence time (Rein et al. 2008, Cowan et al. 2020).

Both Moderate and Severe stands exhibited larger mean coarse woody debris loading than Light stands, though Light stands exhibited a large amount of variability (Figure 2.9). This study establishes an important baseline of downed woody debris and slash *potential*; if a fire should occur, heavy slash materials increase potential for high-risk and inaccessible scenarios for fire-fighting operations (Stephens & Moghaddas 2005). Standing snags also behave unpredictably while burning, as dry, weakened wood can fall in unexpected ways and create large fire brands from fissured branches (Moriarty et al. 2019). As time since outbreak increases, a large contributor to fuel profile change is falling snags. Page & Jenkins (2007) found that post epidemic stands tend to be dominated by live surface fuels and an 8× increase in coarse woody debris (> 7.62 cm diameter), and similarly, Donato et al. (2013) found the amount to double from pre-outbreak levels. This magnitude of change in coarse woody debris in these stands was not yet apparent (Figure 2.9), but as these standing snags are subject to snowfall, windthrow, and wildlife activity, the transition of many snags to the forest floor will be an important consideration for fire-fighting operations as well as the public at large (Audley et al. 2021). The timing of fall and decomposition can vary depending on regional climactic variables such as wind fields, temperature, and precipitation patterns. In Colorado, only 17% of snags were found to have fallen within 4 – 15 years post infestation (Rhoades et al. 2019). Another study in the western U.S. predicted 75% of snags to fall by 22 years post-outbreak (Audley et al. 2021). In Montana, areas with little topographical relief and low stem densities were found to have shorter snag persistence and found 40% of beetle-killed trees had fallen seven years after the peak of infestation (Latif et al. 2023). With most of this studies' stands approximately four years post-peak infestation, and 40.7% and 53% of all standing stems as snags in moderate and severely impacted stands respectively (Table 2.1), the coarse woody loading can be expected to increase substantially in the next 5 – 10 years.

Overall, significant changes in canopy fuels were observed as severity of mountain pine beetle increases, with the largest differences in loss of the sapling cohort in higher severity classes (Figure 2.8). This is important to note for wildland fire fuels that, though the Light stands experienced a small amount of overstory mortality, they did not experience nearly as much relative midstory mortality (Table 2.1). Based on these plots, the loss of sapling canopy and limited recruitment suggest that severely impacted stands will not have sufficient ladder fuels for torching or enough canopy bulk density to sustain crown fire. The CBD threshold for active crown fire spread is often regarded to be 0.10 kg m^{-3} (Agee 1996, Scott 2003), which Severe stands will not reach until and if a new pulse of regeneration occurs. Though surface fire intensity can increase in severely disturbed stands as downed woody debris and larger surface fuel loads can overcome the connectivity usually provided by a midstory cohort, crown fire spread is not likely able to be sustained in these stands. Fire behavior in gray phase mountain pine beetle has been described as "mixed fire-behaviour" (Perrakis et al. 2014), where some torching occurs where fine aerial fuels still exist, but decreases back to surface fire when aerial connectivity is not sufficient. However, it is important to note that extreme weather or wind-dominated scenarios, coupled with the aridity found in dead standing fuels, can create fire behaviour and spread that is difficult to predict based on past research that utilized modelling systems built on results from more moderate conditions.

2.4.4 Limitations & Future Research

In this study, two forest plots in the Severe rating class exhibited lower stand density than all other plots, and therefore may influence the perceived reduction of canopy fuels. To combat this, relative loss from the initial stand condition was calculated and presented alongside the between-rating comparisons. Another potential limitation was number of plots measured. A total of eighteen may not be ideal, however data collection was constrained to this valley to highlight the impact of severity while limiting the inherent variability found within forest complexes, which still proved to be difficult. While the comparative loss in canopy fuels may be affected by stand density, the inclusion of the lidar derived plots suggest that the field data are representative of the infested stands in the valley (Figure 2.11). In fact, Light and Moderate plots were on the higher end of the densities from the lidar extracted plots, while Severe field plots more completely spanned the range of variability. The field measured plots having a higher maximum and a greater range overall aligns with the lidar occlusion that can occur in higher density areas where stems may have the same local maxima and be counted as one, or have a stem obstructed by a taller trees' foliage. The fuels data presented here for Severe plots can thus be assumed to be representative despite the limited sampling points measured in the field. Using lidar-derived stand density and height is a starting point for deriving more detailed stand characteristics and fuels from airborne lidar surveys and can be used to obtain canopy fuels and structure across the larger landscape. Future research can use these outbreak severity thresholds to scale disturbance severity to potential fuel loadings in comparable pine forest complexes.

2.5 Conclusions

Though much research has been done to examine the differences in forest structure and fuels as time since mountain pine beetle attack increases, this study highlights the variability that can be observed within the same temporal stage (i.e., “gray-phase”) separated into three different outbreak severity classes based on percentage mortality within a stand. The cumulative mountain pine beetle outbreak in western Canada has led to the need for updated classification systems for severity and more regional documentation of gray-phase mountain pine beetle impact on fuels. The mortality thresholds reported here (Light < 35%, Moderate 36-65%, and Severe > 65%) showed partitioning of fuel profile composition and loading along vertical strata, especially in the sapling or subcanopy cohort. The differences found in canopy fuels, sapling cohort loss, surface composition, and organic layer loading drive these differences in severity class fuels. A lack of conifer seedling recruitment suggests a potential reversion to open stands, mixed conifer, or grassland may occur where mountain pine beetle mortality has been most severe. Analysis of lidar-derived overstory characteristics (Coops et al. 2021) across the broader range of outbreak timing and severity in the park suggest that these field plots are representative of conditions across the valley, especially in the Severe rating category. Beyond the potential for increased wildfire hazard, care is needed in moderate and severely rated stands going forward as the prevalence of dead fuel presents increased hazard both standing and as fallen slash for the public using these forests for recreation as well as firefighting and management personnel in operational activities.

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CHAPTER 3: FUEL TREATMENT EFFICACY AND FIRE POTENTIAL OVER TIME IN JASPER NATIONAL PARK

Abstract:

Mechanical fuel reduction treatments have been used in forested areas surrounding the townsite and other values at risk in Jasper National Park, Alberta, Canada for approximately 20 years. A widespread mountain pine beetle outbreak in the past decade has led to extensive fuel reduction work to mitigate potential fire hazard. The objectives in this study were to analyze how wildland fuels accumulate after treatment and assess potential fire behaviour as time goes on using field and airborne lidar data. It is essential to evaluate how fire potential changes with fuel structure in these stands to establish specific maintenance needs for these treatments in localized contexts.

Field measurements showed little differences in surface fuel loading, but exhibited a 55% decrease in stem and 50% decrease in canopy bulk density in recently treated stands compared to older treatments. Assessment of past treatments with current management prescriptions suggested a departure from treatment recommendations in the subcanopy cohort and fuel strata gap between surface and canopy fuels. In recently treated stands, canopy cover was three times lower, canopy base height was approximately 1 m higher, and seedling density was reduced to 1100 stems per hectare compared to intermediate (2700 stems ha^{-1}) and older treatments (2100 stems ha^{-1}). In terms of canopy metrics, stands of intermediate treatment age were very similar to the oldest treatment age stands. Lidar-modelled canopy metrics showed significant decreases in stem density, canopy cover, canopy bulk density, and canopy base height compared to unmanaged stands.

Fire spread modelling was conducted at a range of wind speeds for the 90^{th}, 95^{th} and 97^{th} weather percentiles, which is important for understanding fire potential under the most hazardous fire conditions. Torching or passive crown fire behaviour was predicted in most scenarios in these stands, likely due to high surface fuel availability during these weather conditions, and low canopy

base height values. Surface fire behaviour was maintained for the most recently treated stands for the 90th and 95th low wind scenario only. The Van Wagner canopy bulk density criterion for active crown rate of spread was also compared using the lidar-derived arboSense output CBD values. With these values, crown fire propagation was not feasible in the majority (56%) of recently treated stands due to sufficiently lowered canopy bulk density. The outcomes of this study will inform land managers about which fuel components may require maintenance over time in these stand types, as well as potential behaviour and intensity should a fire occur at high weather indices.

3.1 Introduction:

Mechanical fuel reduction treatments of conifer vegetation fuel (hereafter fuel treatments) for wildland fire ignition and spread are considered one of the best lines of defense to protect communities and values at risk from fire. Values at risk within natural vegetated environments can include human life and safety, homes, community buildings, industry infrastructure, recreational infrastructure, and cultural and ecological resources (Calkin et al. 2007). For the forested landscape of the western hemisphere, compounding climate and anthropogenic mediated pressures are increasing fire season intensity and length (Abatzoglou & Williams 2016, Jain et al. 2017), and area burned (Flannigan et al. 2009), thereby impacting ecosystem resilience (Hessburg et al. 2019). Over a century of colonial fire exclusion practices in fire regulated ecosystems have also led to fuel accumulation across much of the western Canadian landscape. This has led to increased potential risk to human life and infrastructure as the amount of interconnected forest and anthropogenic values (the wildland urban interface) (Johnston & Flannigan 2017) grows with the population (Erni et al. 2021). Of the three elements that dictate wildland fire behaviour (fuels, weather, and topography), only fuels can be manipulated to influence potential fire outcomes.

Despite this, long-term effectiveness of fuel reduction at diminishing wildland fire potential is understudied in many regions (Ott et al. 2023, Hood et al. 2024).

3.1.1 Fuel treatments in conifer stands

Fuel reduction treatments can involve many methods of removing and redistributing the combustible fuels on a landscape. These include: mechanical treatments of thinning, pruning, and mastication, chemical control with herbicide, using prescribed fire to reduce surface fuels, or some combination of these techniques (Graham et al. 2004). The basic density and structural aims to reduce crown fire initiation and spread are the reduction of surface fuels, increasing height to canopy base, and reducing canopy bulk density (CBD; Agee & Skinner 2005, Jain et al. 2012). FireSmart Canada guidelines for western Canada are thinning to 3 m crown spacing, raising canopy base height to 2 m, and removal of all dead standing trees and understory vegetation (Partners in Protection, 2003, Schroeder et al. 2010). Less surface fuels combined with increased height to the base of the canopy helps prevent initiation of crown fire, and lower canopy bulk density reduces crown fire spread should it occur (Hoffman et al. 2020). Recognition of local forest composition, prevailing weather, and topographic factors that may influence wildfire behaviour is necessary to correctly apply treatment type and placement (Beverly et al. 2020). Prescriptions of treatment must also consider the trade-off between reducing stem density and increasing solar radiation and wind speed that reaches the forest floor in more open stands, which can increase surface fire spread (Agee & Skinner 2005). The initial reduction in available fuels and changes in forest structure immediately following fuel treatments are well-documented in several forest types (Hirsch & Pengelly 2000, Collins et al. 2007, Vaillant et al. 2015). The efficacy of fuel treatments at reducing potential wildfire behaviour in the short term (1-2 years) has also been well researched

(Hirsch & Pengelly 2000, Stephens & Moghaddas 2005, Stephens et al. 2012). However, long term treatment efficacy in sub-boreal northern forests is less well known.

Fuel reduction treatments are not expected to stop a wildfire, but to reduce rates of spread and intensity sufficiently for suppression to be successful, especially in the WUI (Calkin et al. 2014, Thompson et al. 2020) as well as to prevent crown fire. Though treatments are resource intensive to implement, they have been shown to reduce wildfire intensity (Agee & Skinner 2005), severity (Prichard & Kennedy 2014) and can change the fire type to less hazardous burning conditions (crown to surface) (Agee & Skinner 2005, Prichard et al. 2021, Ott et al. 2023). In comparison, the cost of suppression for the province of British Columbia was $4.16 Billion from 2008 to 2021 (BC Wildfire Service), while just $224 million was spent for fuel mitigation over that time (Hoekstra & Lyumes, 2022). Across Canada, 74.4% of forest-surrounded communities were in a fire deficit (i.e. beyond the historical average time of fire return for a given area and vegetation type), potentially putting them at higher risk of more severe fire; this included many remote indigenous communities (Parisien et al. 2020). Implementation, monitoring and upkeep of fuel mitigation treatments need to be prioritized to keep communities safe (Jain et al. 2012).

Though the initial reduction of fuels and changes in fuel structure immediately following fuel reduction treatments are well documented, the longevity of such effects and reduction in fire hazard are less well known, especially within the mountain forest environments of Canada. Fuel build-up post-treatment is dictated by surface fuel regeneration rates (Collins et al. 2007), which are highly context dependent with varying species composition and climate. Most studies on the topic have focused on the Ponderosa pine – Douglas-fir forests of Western United States, with some differing results. Prichard et al. (2014) found treatments involving prescribed broadcast burning to remove surface fuels were still effective at reducing burn severity after 20 years. A study in western Montana found treatment effects lasting after 15 years, but no difference in surface fuel loading between treated and untreated sites after 23 years, though canopy fuel load was still reduced (Hood et al. 2020). In a study utilizing regeneration simulation, every 550 stems ha^{-1} of seedlings reduced treatment lifespan by five years in terms of reaching a pre-treatment torching threshold wind speed (Tinkham et al. 2016). Research in Canadian forests is limited to boreal (Butler et al. 2013, Thompson et al. 2020, Beverly et al. 2020) or dry interior British Columbia (Rutherford 2023) forest types, and immediate effects (Hirsch & Pengelly 2000). Fuel treatment maintenance is rarely noted in prescription plans across Canada (Mooney 2010), likely due to lack of security in future budget or procedure. Fuel treatment longevity has been identified by the BC Wildfire Service as a pressing research need to keep hazard mitigation effective and economical (LM Forest Solutions, 2020). Difficulties in finding localized answers on treatment maintenance requirements are often due to a lack of long-term funding, current political policies, and public outlooks on fuel reduction (Tymstra et al. 2020).

3.1.2 Fuel treatments and fire behaviour modelling

Forest stands that have been managed for fuel reduction and subsequently burned, with both long-term fuel monitoring and fire behaviour data from the fire event, are difficult to come by. For this reason, fuel treatment effectiveness is often evaluated using fire simulation modelling. However, fire behaviour growth models have been formulated from natural and experimental fires through untreated, natural stands, or traditional harvested (slash) fuels. Thus, the changes in density and stand structure from fuels management has been difficult to model. The Fire Behaviour Prediction (FBP) of the Canadian Forest Fire Danger Rating System (CFFDRS, Forestry Canada Fire Danger Group 1992), for example, utilizes set surface fuel loading, canopy base height, and stand densities within 16 fuel types. The operational standard since implementation, the CFFDRS system provides valuable and timely information to personnel fighting and planning around active fires but is too coarse and static for the myriad compositions of anthropogenically altered (harvested, treated) and disturbed/climate-affected fuels required for evaluation within a research framework.

A long-standing method for assessing fuel treatment efficacy utilizes Byram's fireline intensity equation (Byram 1959, [1]) coupled with Van Wagner's crown fire initiation model (Van Wagner 1977, [2,3]). Surface fire intensity (*I*, kW m^{-1}) is calculated based on hypothetical rate of spread (*r*, m s^{-1}), the low heat of combustion of the fuel (*H*, assumed at 18,000 kJ kg^{-1}), and weight of surface fuel estimated to be consumed in the flaming front (kg m^{-2}):

$$I = Hwr \quad (1)$$

The value for *H* is often converted to 300 so the rate of spread can be kept in the more traditional units of meters per minute. The surface fire intensity required for sufficient heat transfer for ignition of aerial fuels, or critical surface fire intensity (I_0) is dependent on foliar moisture content (FMC) and canopy base height (CBH) and was defined by Van Wagner (1977) as:

$$I_0 = 0.001 \text{ x } CBH^{1.5} \text{ x } (460 + 25.9 \text{ x } FMC)^{1.5} \quad (2)$$

It follows that if the output from Byram's equation for *I* exceeds that of Van Wagner's for I_0, crown fire would be able to initiate. For crown fire to be sustained, however, the canopy fuels must be sufficiently dense. Van Wagner defined a simple empirical model for critical rate of spread for active crown fire spread as:

$$R_o = S_o / CBD \quad (3)$$

where S_o is the mass flow rate of fuel, assumed at 3.0 kg m^{-2} per minute, and CBD is canopy bulk density (kg m^{-3}). The linkage of these three equations allows for evaluation of fuels treatments in the following ways: to see if there was a sufficient reduction in surface fuels available for consumption and/or increase of canopy base height to prevent ignition of the canopy fuel layer (torching) from taking place, and subsequently to calculate if canopy bulk density was reduced enough to prevent crown fire spread if torching is able to occur. These linked models do not take stand or species-specific attributes into consideration except as stand or species determine the relevant input variables – CBH, CBD or FMC.

Fuel treatments in many areas aim to convert stands to more fire-resistant species as this can allow for higher density retention and have ecological benefits (FireSmart Canada 2024). Retaining less flammable overstory species reduces the amount of in-stand solar radiation and wind speed that can increase ignition potential and surface spread after thinning. When evaluating fuel treatment efficacy where stand conversion is an objective, the "fuel is fuel" (Cruz et al. 2022) approach may not be sufficient. Many modelling tools have been developed to simplify the complex interactions taking place in a potential wildland fire so that proactive management can be appropriately planned, and implemented fuel strategies can be evaluated. Fuels Management Analyst Plus (FMA, Carlton 2004), for example, is a practitioner's tool for fuel treatment planning, allowing for dynamic inputs of tree lists, and surface fuel model selection. Another tool, Canadian Conifer Pyrometrics (Perrakis et al. 2020) is a novel modelling framework that incorporates new data linkages between stand-adjusted fuel moisture (Wotton & Beverly 2007), a reanalysis of the crown fire initiation and spread model's (Cruz et al. 2004) fire database including new experimental fires (Perrakis et al. 2023), dynamic canopy fuel inputs (density and CBD), surface fuel consumption based on available fuels and the build-up index (de Groot et al. 2009), and multistrata ladder fuel data (Perrakis et al. *in prep*). These specific inputs will allow us to evaluate the dynamic moisture and fuel interactions needed to properly evaluate fuel treatment effectiveness and longevity.

3.1.3 Research objectives

There have been extensive fuel reduction treatments surrounding the townsite and valuable infrastructure in Jasper National Park, Alberta, Canada due to fuel infilling and the surrounding mountain pine beetle outbreak, which have elevated wildland fire concern. However, it is not known how effective these treatments are at maintaining reduced fire potential over time. This case study demonstrates changes in fuel loading and fire potential from a chronosequence of time since treatment (0 to 19 years) in the wildland-urban interface surrounding Jasper townsite and compares canopy fuel values with similar unmanaged stands along the Athabasca Valley. The following question was asked: how does fuel structure and loading change over time since fuel reduction treatment? To answer this question, the specific objectives were as follows:

1) To assess, based on field data, how fuel varies through vertical strata over time since onset of management;

2) To compare field collected data with remotely sensed plots across comparable managed and unmanaged stands using airborne lidar data derived stem density and canopy metrics; and

3) To assess potential fire behaviour over time since management in field measured and lidar derived stands.

The results of this study answer critical questions associated with how fuels change over time since treatment in interior Douglas-fir and lodgepole pine forests in the montane environments of the northern Rockies. It highlights the use of various modelling methods to interpret mitigation of fire potential in treated stands, and the use of remote sensing techniques to evaluate stand and canopy characteristics over larger managed landscapes.

3.2 Materials and Methods

The study area and field data collection methods are broadly outlined in Chapter 2. Differences and additional details or methodologies follow here.

3.2.1 Study Area

The townsite of Jasper within Jasper National Park (52.8 N, -118.1 W) is located centrally within the park, and the municipality includes additional residential areas to the northeast around Lake Edith and Lake Annette (Figure 3.1). The townsite population was 4,113 as of 2022 (Alberta Government 2024), and the park hosted over 2.48 million visitors in 2023 (Parks Canada 2024) This region is within Treaty 6 and 8 lands, as well as the traditional territory of the Anishinabe, Aseniwuche Winewak, Cree, Nêhiyawak, Stoney Nakoda, Secwépemc, Dene-zaa, Mountain Métis and Métis peoples for thousands of years. The wildland-urban interface consists of mature *Pseudotsuga menziesii* Franco (Douglas-fir), *Pinus contorta* var. *latifolia* Engelm. (lodgepole pine), *Picea glauca* Voss x *Picea engelmannii* Parry (hybrid spruce) and *Populus tremuloides* Michx. (aspen) (Chavardès & Daniels 2016).

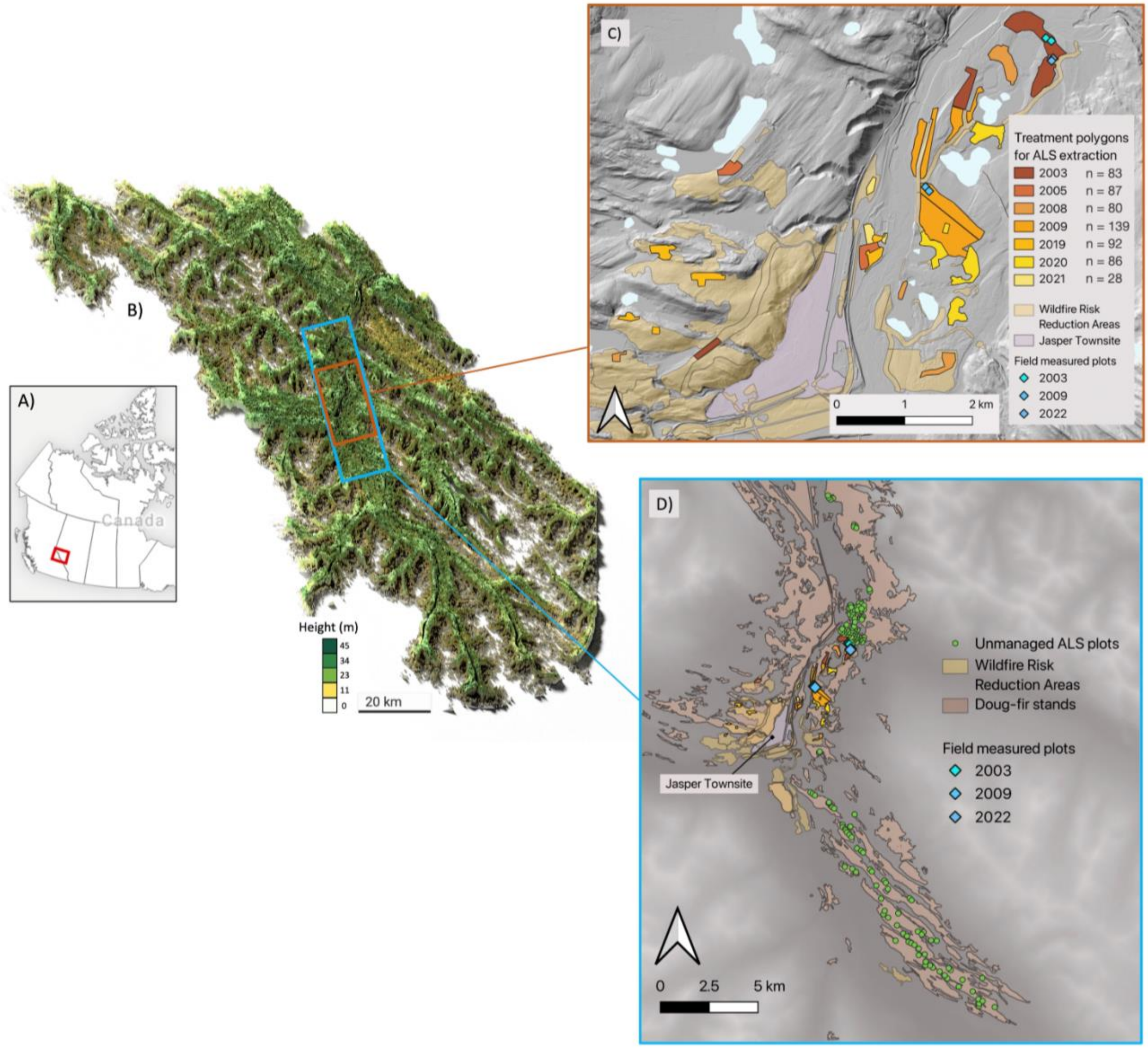

Figure 3.1. Map of study area A) Jasper National Park's location within Alberta, Canada. B) Jasper National Park colourised with canopy height estimated from 10 m resolution tree height distribution from 2020 Sentinel-2 imagery fused with GEDI LiDAR vertical distribution data (Lang et al. 2022). White areas indicate non-vegetated areas. Inset (C) shows locations of 6 fuel mensuration plots in managed stands treated in 2003, 2009, and 2022 (blue diamonds, n = 2 each treatment year). Polygons indicate sampling areas for remotely sensed plots over range of treatment years (n = 595). Inset (D) shows sampling locations of airborne laser scanning (ALS) or lidar remotely sensed plots in unmanaged Douglas-fir stands over the Athabasca Valley (green circles, n = 139).

3.2.2 Study Design

Field data were collected (see Methods section Chapter 2) from forest mensuration plots (Figure 3.1) in July 2021 and 2022 according to the methods outlined with the NG-CFFDRS (Boucher et al. 2023). Six sites that have undergone fuel management were selected over a chronosequence (0, 13, and 19 years since treatment) spanning the range of treatment ages within the park. All management plots underwent similar mechanical thinning treatments. 734 additional plots in treated stands and unmanaged stands in the park with comparable species composition were isolated from lidar data point clouds and processed into stand and canopy level metrics.

3.2.3 Treatment Success Evaluation

Fuel reduction prescriptions were built upon standardized practices from Partners in Protection (1999), the National Fire Protection Association (NFP 1997) and adapted to local fuel environments following similar prescription work in Banff (Arbor Wildland 1991; Westhaver 2003, Table 3.1). Measured plots were assumed to have a starting composition resembling FBP System fuel types C3 (Mature jack or lodgepole pine) and C7 (Ponderosa pine - Douglas-fir) based on retained mature overstory species. To evaluate change over time, the prescription standards were compared with current stand conditions for each measured treated plot. Each fuel component measured in field stands within canopy fuels (Figure 3.2A), ladder fuels (Figure 3.2B), coniferous regeneration (Figure 3.2C) and surface fuel (Figure 3.2D) strata were scored as “exceeds guidelines” or “meets guidelines”.

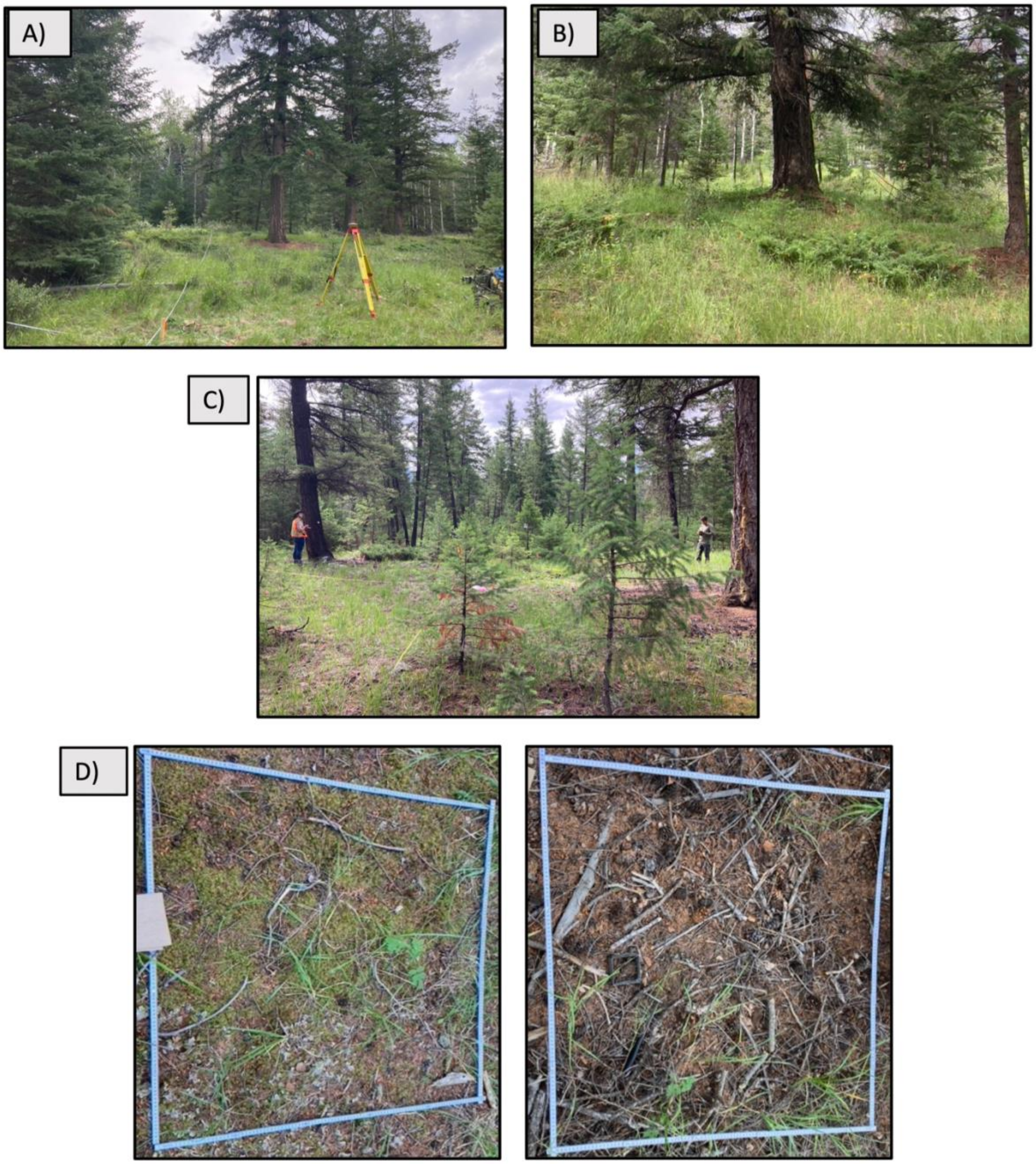

Figure 3.2. Fuel components analyzed against management objectives. A) Mature trees with varying levels of canopy base height B) Common juniper patches located closer together than prescription recommendations underneath coniferous trees (Westhaver et al. 2003), providing potential ladder fuels. C) Coniferous regeneration in foreground with thicket in background D) Surface fuel coverage at approximately 5% fine woody debris (left) and over 5% fine woody debris (right).

Table 3.1. A-D Prescription guidelines for canopy, ladder, coniferous regeneration, and surface fuels in C7 and C3 fuel types utilized for managed stands in Jasper National Park summarized from Westhaver 2003 and Parks Canada).

1A	Canopy	
Component	Diameter / Height	Guideline
Mature Conifers	> 15 cm DBH	Retain all
Legacy trees	Douglas-fir > 50 cm Low limbed lodgepole pine "wolf trees" Deciduous (aspen, poplar) Conifers > 30 cm with fire scars, bole defects, disease (high resiliency and/or wildlife habitat potential)	Retain all
Immature Douglas-fir	10+ m tall	Retain all
Immature Pine, Spruce	10+ m tall	Retain all (in mixed conifer stands
Mountain pine beetle	Beyond 1.5 tree lengths of any infrastructure, road, trail Within 1.5 tree length of any infrastructure, road, trail Stand with low mortality	Grey, Red (reduce to 10 ha^{-1}) Green attack (remove all) Grey, Red, Green (remove all) Thin mature trees to 2-3 crown width (5 – 10 m spacing)
Deciduous Trees (aspen, poplar)	Living or Dead	Retain all in all size classes
Douglas-fir snags	> 15 cm dbh	Retain all
Pre-mountain pine beetle pine snags	Branches off	Retain all
Habitat Trees	Cavities, nesting potential	Retain all
Other ecological features		Use cluster thinning to retain

1B	Ladder Fuels	
Component	Diameter / Height	Guideline
Pruning	> 15 cm DBH Saplings 5 – 12 m tall	2 m clearance from ground to branches; 3 m on slopes > 40%
Conifer dripline for dominant spp.	Mature / Saplings	Remove all ladder fuels within 5 m of dripline (juniper, coniferous regeneration, saplings); 10 m if slope >20 %, 15 if slope > 60%
Pine and spruce in C7 stands	Mature / Saplings	Remove all ladder fuels within 3 m of dripline (juniper, coniferous regeneration, saplings); 10 m if slope >20 %, 15 if slope > 60%
Juniperus communis (Juniper)		Remove beneath trees

1C	Coniferous Regeneration	
Component	Diameter / Height	Guideline
Saplings	< 12 cm DBH Saplings 5 – 10, 12 m tall	Reduce density to 25 ha^{-1}
Advanced regeneration	2 – 5 m Doug-fir > Pine > Spruce spp preference	Reduce density to 25 ha^{-1}, remove ladder fuels underneath
Spruce (in C7)	Regen to Sapling	Remove all
Douglas-fir thickets	2 – 5 m	Retain 2 – 3 healthy individuals, well spaced
Regeneration	0.5 – 2 m Doug-fir > Pine > Spruce spp preference	Reduce density to 36 ha^{-1} If in thickets, thin to 2 m diameter

1D	Surface Fuels	
Component	Diameter	Guideline
Fine woody debris	< 5 cm	Max 5% ground coverage
Recent deadfall	> 25 cm	Reduce to 5 ha^{-1}, remove branches if promoting ladder connectivity
	< 25 cm	Reduce to 15 ha^{-1} or 35 m spacing
Coarse woody debris (reduced branches)	> 20 cm	Reduce density to 50 ha^{-1} or 15 m spacing – count standing gray mountain pine beetle in this amount
	< 20 cm	Reduce to 15 ha^{-1} or 35 m spacing
Juniper		Reduce density to 35 patches ha^{-1} or 20 m spacing (patch 1-2 m^{-2})

3.2.4 Airborne lidar analysis

To compare managed and unmanaged canopy fuels across the landscape with the limited number of field collected plots, point cloud data from airborne lidar surveys were utilized. To capture conditions along the temporal range within the park's treatment areas, 734 further 400m^2 plots were extracted from three airborne lidar (or airborne laser scanning; ALS) surveys conducted in 2021 and 2022. Lidar "plots" (extracted vegetation structural data) were located in treatment years 2003, 2005, 2008, 2009, 2019, 2020, 2021 as well as unmanaged stands. These were classified into "Unmanaged", "Old" (Treatment 17 – 19 years prior), "Intermediate" (Treatment 13 – 14 years prior), and "Recent" (Treatment 0 – 3 years prior) treatment age. Potential qualifying treatment polygons were limited to areas of low topographic relief and Douglas-fir, hybrid spruce, and lodgepole pine species composition for comparability with plot measurements. The surveys were flown using a Teledyne Optech Inc. Titan Airborne Laser Terrain Mapper equipped with multispectral channels at wavelengths 1550 nm (shortwave infrared), 1064 nm (near infrared), and 532 nm (green) (Hopkinson et al. 2016; Chasmer et al. 2017). Survey specifications were as follows: pulse repetition frequency 75 kHz per channel for a total of 225 kHz, the flight altitude 1200 m, the scan angle 25°, overlap 50%, and the point density was 5 - 6 points m^{-2}. Flight and survey specifications were the same for both flight survey years. The point clouds were combined from all wavelengths (to increase point density) cleaned and classified within TerraScan (Terrasolid, Finland). Returns were then normalized to ground, and digital elevation models (DEM) and canopy height models were derived within LAStools (rapidlasso GmbH, Germany).

To isolate "plots" for tree density extraction, digital elevation models for each polygon were resampled to a 20 m by 20 m cell resolution using the average, and slope was calculated. A new slope raster was calculated to isolate the areas with negligible topographic relief to be representative of measured plots. The Jasper 2020 Vegetation Resource Inventory and Wildfire Risk Reduction vector layers were then rasterized with the overstory species attribute value. Areas of Douglas-fir and lodgepole pine species composition with little to no topographic relief (< 3°) for unmanaged stands were identified. For managed stands, overstory species composition, little topographic relief also overlapped with a treatment polygon. A grid-based stratified random sampling was performed with a minimum distance of 30 m to place plot centres across the geographic extent of the resulting suitable areas for each treatment year and unmanaged Douglas-fir stands and extrapolated to 400 m^2 circular plots using 11.28 m radius shapefiles (Figure 3.1D).

When the shape files were extracted for a polygon, the 1 m resolution canopy height model was interrogated in R using the package "lidR" (Roussel et al. 2020) and clipped to each plot extent. Each plot extent was then analyzed for individual tree detection and segmentation using a variable window filter, with a minimum height of two meters to exclude understory, within the ForestTools package (Popescu & Wynne, 2004, Plowright 2023). This resulted in the heights and coordinates for 15,597 identified trees which allowed for stem density (per ha) calculations.

Mature stems were distinguished from saplings using a minimum height threshold of 12 m as per prescription guidelines (Table 3.1). Canopy metrics (CFL, CBH, canopy coverage, and CBD) were isolated for each extracted plot from outputs derived from the "arboSense" lidar canopy scaling tool via a collaboration between Hatfield Consultants and University of Lethbridge (Chen et al.; Chasmer et al. *in prep*). This modelling tool ingests point cloud data and based on training data from NG-CFFDRS (Chapter 2, Figure 2.3) field plot measurements from the eastern slopes of the Canadian Rockies and utilizes a decision tree approach based on the selection of the highest correlate within 15 parameter groups to compare the inputs from lidar data with field data. This is repeated with different lidar height metrics as inputs to compute canopy fuel metrics with the optimal combination determined when the model outputs reach an optimized stable accuracy. As canopy coverage was not estimated in the field, the arboSense outputs were obtained for field plot locations as well. If the located plot resulted in values indicating a non-forested stand (canopy height ~ 2 m, canopy cover < 5, CBD < 0.001), this observation was omitted as this is assumed to indicate a more intensive clearing or fuel break operation as opposed to stand thinning. This resulted in n = 83 plots for 2003 treatments, n = 87 plots for 2005, n = 80 plots for 2008, n =139 plots for 2009, n = 92 plots for 2019, n = 86 for 2020, and n = 28 for 2021. The number extracted and retained was also constrained by varying treatment polygon sizes over the years limiting suitable areas for extraction. If a circular plot was not centred on a 20 x 20 m arboSense output pixel, the value of the majority cell was used. Deviation of modelled from measured was calculated for arboSense outputs by extracting lidar canopy metrics from field measured plot locations for comparison.

3.2.5 Fire behaviour modelling

Three models were used to evaluate the efficacy of fuel treatments reducing fire behaviour potential, which also allowed for comparison between these tools. One stand for each field measured treatment year was evaluated for fire potential using the Byram & Van Wagner, Conifer Pyrometrics, and Fuels Management Analyst models. The Van Wagner canopy bulk density criterion for active crown rate of spread was also compared using the arboSense output CBD values, with a maximum cut-off spread rate of 40 m min^{-1} (C7 fuel type, FBP 1992) used to evaluate if, under the most severe fire weather, that stand could sustain active crown fire spread.

3.2.6 Fire Weather

Nine fire weather scenarios were used as inputs for the models. To obtain fire weather values for the 90^{th}, 95^{th}, and 97^{th} percentile fire weather conditions within the study area, daily fire season (April 12 – September 30^{th} for Southern Cordillera, Wang et al. 2015) weather data from 1994 to 2022 were extracted from the Jasper Warden station (52.93, -118.03). Temperature, relative humidity, wind speed and 24 – hour precipitation at the 1300-hour standard were extracted for each day. A range for 90^{th}, 95^{th}, and 97^{th} percentiles fire weather index values were calculated, with a low, intermediate, and high wind speed and corresponding fine fuel moisture code (FFMC), duff moisture code (DMC), and build up index (BUI), components of the fire weather index (FWI) recorded using the 'cffdrs' package in R (Wang et al. 2017, Table 3.2). Some literature highlights 80^{th} percentile or 90^{th} alone as a threshold for moderate risk, but the 95^{th} and 97^{th} conditions are useful to signal conditions potentially increasing in occurrence with a warming and drying climate (Vaillant et al. 2009). FMA uses relative humidity, temperature, and wind speed as direct inputs instead of the FWI components, and consequently these weather inputs were also extracted (Table

3.2). Wind speed inputs utilized in FMA are at a height of twenty feet instead of ten meters, and so a correction factor of was applied by dividing the 10 m windspeed by 1.15 (Andrews 2012).

Table 3.2. Fire weather inputs for 90th, 95th, and 97th percentiles used in Byram & Van Wagner linked and Conifer Pyrometrics modelling framework (wind, Fine Fuel Moisture Content, Duff Moisture Code, Build Up Index) and Fuels Management Analyst (wind, relative humidity (%), temperature °C) from the Jasper Warden Station.

	Weather Indices	Low wind	Intermediate wind	High wind
90th	Wind (km hr^{-1})	5	8.9	12.8
	FFMC	93.9	93.1	92.2
	DMC	75	70.2	65
	BUI	100.6	90	82.4
	rH (%)	24.6	25.8	28.2
	Temp (°C)	25.7	22.8	21.4
95th	Wind (km hr^{-1})	5.3	9.6	13.4
	FFMC	94.2	93.2	92.7
	DMC	88.7	84.0	73.4
	BUI	119.2	107.2	91.7
	rH (%)	22.5	25.1	27.4
	Temp (°C)	26.0	23.9	22.2
97th	Wind (km hr^{-1})	6.4	8.7	14
	FFMC	94.8	94.4	93.2
	DMC	99.7	88.3	77.5
	BUI	129.1	116.2	102.0
	rH (%)	21.3	23.1	27.2
	Temp (°C)	27.3	25	24

3.2.7 Prevailing wind speed and direction

A wind rose, or frequency of directional count diagram was made for each fire weather percentile to showcase the influence of winds at these higher weather hazard scenarios. Analysis of wind conditions from fire season normal at Jasper Warden station show the highest occurrence and strength of wind from S or SSW at high fire weather indices (Figure 3.3). At the 97th fire weather scenario, however, wind often also originates from a north-westerly direction, or from directly north or south when wind speeds are highest. This analysis shows the influence of topography and wind channeling at the location of this weather station (west of Jasper townsite, 1020 m elevation, 52.93, -118.03) within the montane environment and impacts potential fire hazard, and risk mitigation planning. The maximum recorded wind speed was 37 km h^{-1}, but wind gusts can be up to 61 km h^{-1} (Government of Canada 2024). This was used to determine a crowning threshold at which point the stand is considered resistant to crown fire initiation.

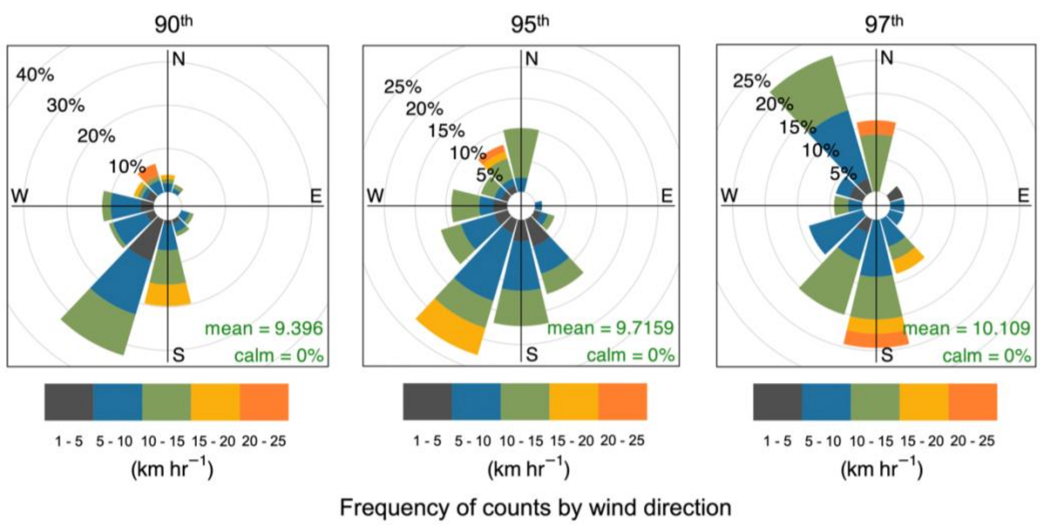

Figure 3.3. Wind roses for Jasper Warden weather monitoring station showing frequency of counts by wind direction at 90th, 95th, and 97th fire weather percentiles.

3.2.8 Byram & Van Wagner linked surface and crown fire initiation

FWI values were input into the FBP rate of spread models to estimate surface fire rate of spread at all isolated wind speeds and nine weather scenarios. Maximum surface fuel consumption was estimated using field measured values of litter, herbaceous and woody surface fuels, and fine woody debris < 3 cm. Consumption of woody debris over 1 cm diameter in the flaming front is not always expected but at these fire weather indices, is highly probable (Prichard et al. 2014, Hanes et al. 2021). These surface fuel consumption and rate of spread values were input into Byram's intensity equation to find predicted fireline intensity. Van Wagner's critical surface intensity was then calculated using FMC (assumed 100% as seasonal average, Beverly et al. 2020) and CBH. Critical active rate of spread was calculated using CBD values. CBH threshold values, or the pruning heights required to avoid crown fire initiation were calculated using Van Wagner's critical surface fire intensity equation with the predicted intensity from Byram.

3.2.9 Conifer Pyrometrics

To show differences in potential wildfire behaviour at high to extreme fire weather conditions, stand level values were input into the Conifer Pyrometrics (CP, Perrakis et al. 2023) wildfire modelling framework. CP is a stand-level fire behaviour model that initially calculates probability of crown fire using a new empirical model (updated from Cruz et al. 2004). If a surface fire is predicted, a new empirical surface model is used to predict surface rate of spread. If crown fire is predicted, Van Wagner criterion for active crown fire and an expansion of the CFIS crown fire and spread model Cruz et al. (2005) is used to identify passive or crown fire type as well as crown fire rate of spread. Fire type and rate of spread is calculated with dynamic inputs of canopy fuels, stand density, and stand adjusted moisture contents. More specifically, CP allows for stand specific inputs of surface fuel loading, canopy bulk density and vertical fuel continuity. The dynamic structural modifier of the "fuel strata gap", or the effective distance between surface and ladder fuels, and the surface fuel contribution of fire intensity to the initiation of crown fire if midstory strata has a sufficient density (> 1200 stems ha^{-1}) can also be utilized instead of CBH. However, in our field stands, saplings only reached a maximum density of 475 stems ha^{-1}, and so live crown base height was used (Perrakis et al. 2023) instead of the fuel strata gap.

CP predicts fire type (surface, passive crown (torching), or continuous crown), rate of spread (m min^{-1}), and torching and crowning thresholds (km hr^{-1}). Necessary inputs include stand density, fuel strata gap (based on overstory CBH, midstory height and CBH, and midstory canopy fuel load), surface fuel consumption scaled to the heat flux threshold contribution of the ladder fuels, and stand canopy bulk density.

3.2.10 Fuels Management Analyst Plus

Fuels Management Analyst Plus (FMA) is a tool that allows managers to evaluate potential fuel treatments by the dynamic input of tree lists. Inputs for each tree includes species, DBH, height, crown ratio, crown class (dominant, codominant, intermediate, or suppressed), and crown condition. A surface fuel model must also be appropriately selected. The grass and understory model 2M (Anderson 1982) was selected based on composition (open conifer, > 30% grass/moss coverage as primary carrier of fire) and fuel loading selected based on field measurements. Surface fuel did not display major differences in fuel loading and so the 2M surface fuel type was utilized for each stand. Fire weather inputs were 1 hr, 10 hr, 100hr fuel moisture, relative humidity, temperature, and wind speed. The outputs of FMA plus include flame length, fire type, torching threshold, crowning threshold, and scorch height. Torching thresholds and fire type were compared between CP and FMA outputs.

3.2.11 Statistical Analyses

To better understand how the distribution of canopy fuels vary between treatment year stands and untreated stands, comparisons were applied across stand density, sapling proportion, canopy cover, canopy bulk density, and canopy base height. The Kruskal-Wallis rank test with Dunn’s pairwise comparison as well as the Anderson-Darling pairwise distribution test was used (see Chapter 2 methods, KW; Kruskal & Wallis 1952, AD; Anderson & Darling 1952). Each arboSense derived variable was right-skewed and not normally distributed, even after attempts at transformation. KW was again used due to the skewed nature and unequal variances of numerous variables. The Levene's test for equal variance was employed for heteroskedasticity and was found significant (unequal variance) for sapling proportion, canopy length and canopy bulk density. The non-normal distribution and unequal variances meant that non-parametric tests were necessary for statistical comparisons. When a KW test was significant (i.e. the mean ranks between treatment year blocks were significantly different), a Dunn's test (Dunn 1964) for pairwise comparison was performed. For each pair of treatment blocks (Old, Intermediate, Recent, and Unmanaged), the difference in mean rank scores divided by the rank pooled variance estimate (from the KW test) is calculated with the Holm correction for multiple comparisons (Holm 1979). The Dunn's test allows for evaluation of which treatment periods were statistically different from one another for each canopy characteristic derived from lidar. All KW, Dunn's, and AD tests were performed in R (R Core Team 2023) using the "rstatix" (Kassambara 2023) and "PMCMRplus" packages (Pohlert 2023). Due to the limited amount of field data available and the inherent assumptions within each fire modelling framework, statistical analyses were not performed on field stand comparisons or modelling outputs.

3.3 Results

3.3.1 Field measured plot characteristics and canopy fuels

Field measured stands were located 5 – 8 km northeast of the Jasper townsite around Edith and Trefoil Lakes (Figure 3.1C). The oldest treatment, completed in 2003, covered approximately 32 hectares and was the furthest from the community (~8 km). The 2009 treatment covered 19 hectares and was 2.5 km east of the townsite. The most recent treatment covered 10 hectares and is a linear design along an access road. All stands, managed and unmanaged, were composed of lodgepole pine, Douglas-fir, spruce and aspen (Table 3.3). The overstory of both stands treated in 2003 were classed as 100 years old, 2009 treatments were 145 years old, and 2022 treatments 90 years old within the Jasper National Park vegetation resource inventory.

Current overstory stand density was 55% lower in recent treatments than old treatments. The difference between recent and intermediate age treatments overstory density was just 9% (Table 3.3). Stands treated in 2022 had 63 (SE = 13) stems ha^{-1} in the midstory sapling cohort, 50% fewer than the oldest treatments. However, intermediate age stands had 34% more saplings than the oldest treatment stands with 363 (SE = 113) stems ha^{-1}. Fuel reduction in the most recently treated stands is most notable in the loss of canopy cover, and subsequent decrease in canopy bulk density (Table 3.3). The intermediate age treatments retained more CBD with a mean of 0.12 (SE = 0.03) kg m^{-3} than recent and older treatments. This is influenced by older, large-stemmed Douglas-firs present in these stands. Canopy base height varied less than one meter between treatment years, though it was highest in the most recently treated stands (Table 3.3).

Table 3.3. Mean (± SE) stand structural characteristics and canopy fuel loading in field measured managed stands over time since treatment in Jasper National Park, AB. All values refer to measurements taken in 2022.

Stand Characteristics					
Treatment Age	**Trees**	**Saplings**	**Live Basal Area**	**Quadratic Mean Diameter**	**Species Proportions**
	stems ha^{-1}	**stems ha^{-1}**	**m^2 ha^{-1}**	**cm**	
Recent Treatment 2022	**175** (0)	**63** (13)	**8.1** (1)	**24.2** (1.5)	**Douglas-fir** 36% **Pine** 36% **Aspen** 14% **Spruce** 14%
Intermediate Treatment 2009	**188** (38)	**363** (113)	**30.2** (2.7)	**46.2** (6.7)	**Douglas-fir** 75% **Pine** 10% **Aspen** 10% **Spruce** 5%
Old Treatment 2003	**388** (63)	**125** (25)	**13.8** (0.6)	**21.5** (1.3)	**Douglas-fir** 48% **Pine** 16% **Aspen** 25% **Spruce** 11%
Canopy Characteristics					
	Canopy Cover	**Height**	**Canopy Base Height**	**Sapling Height**	**Canopy Bulk Density**
	%	**m**	**m**	**m**	**kg m^{-3}**
Recent Treatment 2022	**15** (5.7)	**15.1** (0.75)	**3.5** (0.54)	**4.7** (0.7)	**0.03** (0.003)
Intermediate Treatment 2009	**44** (7.3)	**19.5** (2.53)	**3.4** (0.46)	**3.9** (0.9)	**0.12** (0.03)
Old Treatment 2003	**45** (0.1)	**14.8** (0.57)	**2.7** (0.5)	**4.9** (0.4)	**0.06** (0.02)

3.3.2 Surface fuel composition and loading

Surface fuels between measured stands were generally consistent. Ground coverage was notably dominated by grassy vegetation. Shrubs were sparse, with 5-15% area coverage. Recently treated stands had slightly lower values of the smallest diameter fine and medium woody debris, litter loading and live woody fuels (shrubs and seedlings) (Table 3.3). Duff loading was highest in the oldest treatment stands (Table 3.3). Both intermediate treatments and older treatments had twice as many coniferous seedlings as recent treatments. One stand in the oldest treatment block contained only aspen seedlings. Coarse woody debris loading was highest in old and recent treatments (1.59 (0.61) and 1.53 (0.61) kg m^{-2} respectively) and fine woody debris loading was highest in intermediate age stands (0.49 (0.14) kg m^{-2}).

Table 3.4. Mean (± SE) surface and ground fuel loading and structural characteristics in field measured managed stands over time since treatment in Jasper National Park, AB. All values refer to measurements taken in 2022.

Surface fuel loading										
Management Status	**Fuel bed depth**	**FWD (0 – 0.99 cm)**	**FWD (1 – 2.99 cm)**	**MWD (3 – 7 cm)**	**CWD (7 cm+)**	**Litter**	**Duff**	**Herbaceous material**	**Live Woody fuels**	**Conifer Seedlings**
	m	**kg m^{-2}**	**kg m^{-2}**	**kg m^{-2}**	**kg m^{-2}**	**kg m^{-2}**	**kg m^{-2}**	**kg m^{-2}**	**kg m^{-2}**	**stems ha^{-1}**
Recent	**0.28**	**0.09**	**0.18**	**0.10**	**1.53**	**1.65**	**2.68**	**0.06**	**0.04**	**1100**
Treatment 2022	(0.02)	(0.0)	(0.02)	(0.03)	(0.61)	(0.1)	(1.52)	(0.02)	(0.0)	(300)
Intermediate	**0.30**	**0.16**	**0.16**	**0.17**	**0.51**	**1.76**	**3.52**	**0.04**	**0.07**	**2700**
Treatment 2009	(0.01)	(0.02)	(0.01)	(0.15)	(0.51)	(0.09)	(0.34)	(0.01)	(0.01)	(100)
Old	**0.26**	**0.11**	**0.12**	**0.13**	**1.59**	**1.74**	**3.92**	**0.06**	**0.05**	**2100**
Treatment 2003	(0.02)	(0.03)	(0.04)	(0.02)	(0.61)	(0.08)	(0.73)	(0.0)	(0.05)	(2100)

3.3.3 Fuel accumulation over time each vertical fuel strata

The oldest treatments exceeded recommended density or continuity in each vertical fuel strata (Figure 3.4) and was the only treatment age with overstory components (individual trees) that did not meet current prescription recommendations. These trees were mature stems impacted by the mountain pine beetle outbreak. Each stand measured had multiple trees with branches below the two-meter ladder fuel threshold. The intermediate age treatment stands had the highest proportion of saplings exceeding the recommended density, even when accounting for cluster retention guidelines of thicket regeneration. This proportion was similar to levels in oldest treatment stands (Figure 3.4), suggesting 10-15 years is sufficient regeneration time to raise understory density above recommended levels. Both old treatments and intermediate treatment areas had over 5% coverage of fine woody debris. All stands had a higher than recommended density of coarse woody debris with < 20 cm diameter.

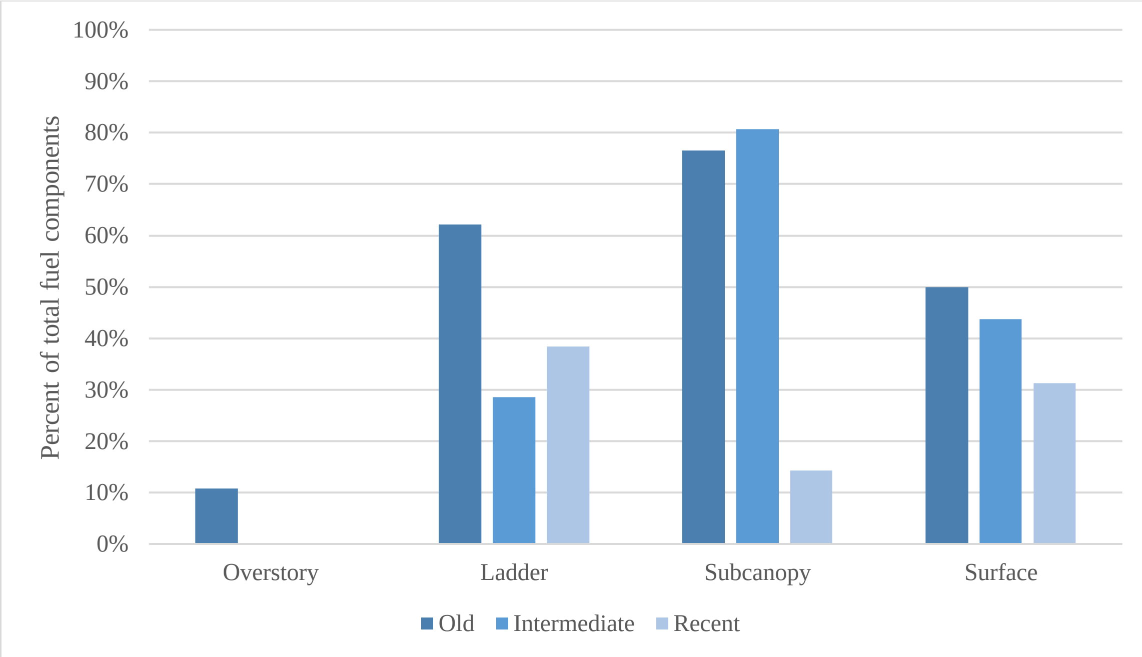

Figure 3.4. Proportion of each measured fuel component within a vertical fuel strata level that exceeds current prescription recommendations over time since treatment. Overstory components refer to individual mature trees; Ladder fuel components refer to branches below two meters, regenerating conifer seedlings and saplings and juniper beneath mature trees; Subcanopy components refer to regenerating conifer spacing and density; Surface fuel components refer to downed woody debris and juniper (Table 3.1A-D).

3.3.4 Canopy fuels and stand densities across the larger landscape

Canopy metrics, vegetation resource inventory stand age, and tree density values were populated for 734 plots using airborne lidar point cloud data exterior to the field measured plots, with 139 in unmanaged stands and 595 across managed stands with comparable species composition. Each treatment age block had between 170 and 219 plots (Old n =170, Intermediate n = 219, Recent n = 206). Stands treated recently had the highest mean (SE) stand age at 147 years (2.7), and unmanaged stands had the lowest (125 (2.2)). Management significantly lowered stem density (KW H = 92.3, $p < 0.001$) with a mean of 635 (13) stems ha^{-1} in unmanaged stands, 1.4 times higher than the most recent treated stands. Error propagated between field measured and lidar modelled outputs were lowest for stand density, and increased with more complex canopy metrics, especially the canopy base height (Table 3.5). Interestingly, all three treatment age blocks had a significantly higher proportion of immature trees (< 12 m height) to total stems than unmanaged stands, with the highest proportion in the recent treatment period at 55% of total stems as saplings. Canopy coverage significantly increased over time since management and was significantly different between managed and unmanaged stands (Figure 3.5), though coverage was not different between intermediate and old treatment ages. Canopy base height from lidar outputs had an inverse relationship to the field measured plots, with the highest CBH in unmanaged stands, and significantly lower CBH in recently treated stands (Figure 3.6). All treatment age blocks exhibited a significant reduction in canopy bulk density comparted to unmanaged stands (Figure 3.7). Canopy bulk density trends aligned with field measured data (significantly lower in 2019-22 treated stands), but the difference in lidar derived values were not as extensive (Figure 3.6).

Table 3.5. Accuracy of prediction between field collected data and canopy metrics from lidar data output by arboSense.

Field vs. arboSense canopy metric agreement			
Metric	**R^2**	**RMSE**	**RMSPe**
Stand density	**0.78**	**87 stems ha^{-1}**	**0.15**
Canopy base height	**0.38**	**0.79 m**	**0.23**
Canopy bulk density	**0.54**	**0.03 kg m^{-3}**	**0.37**

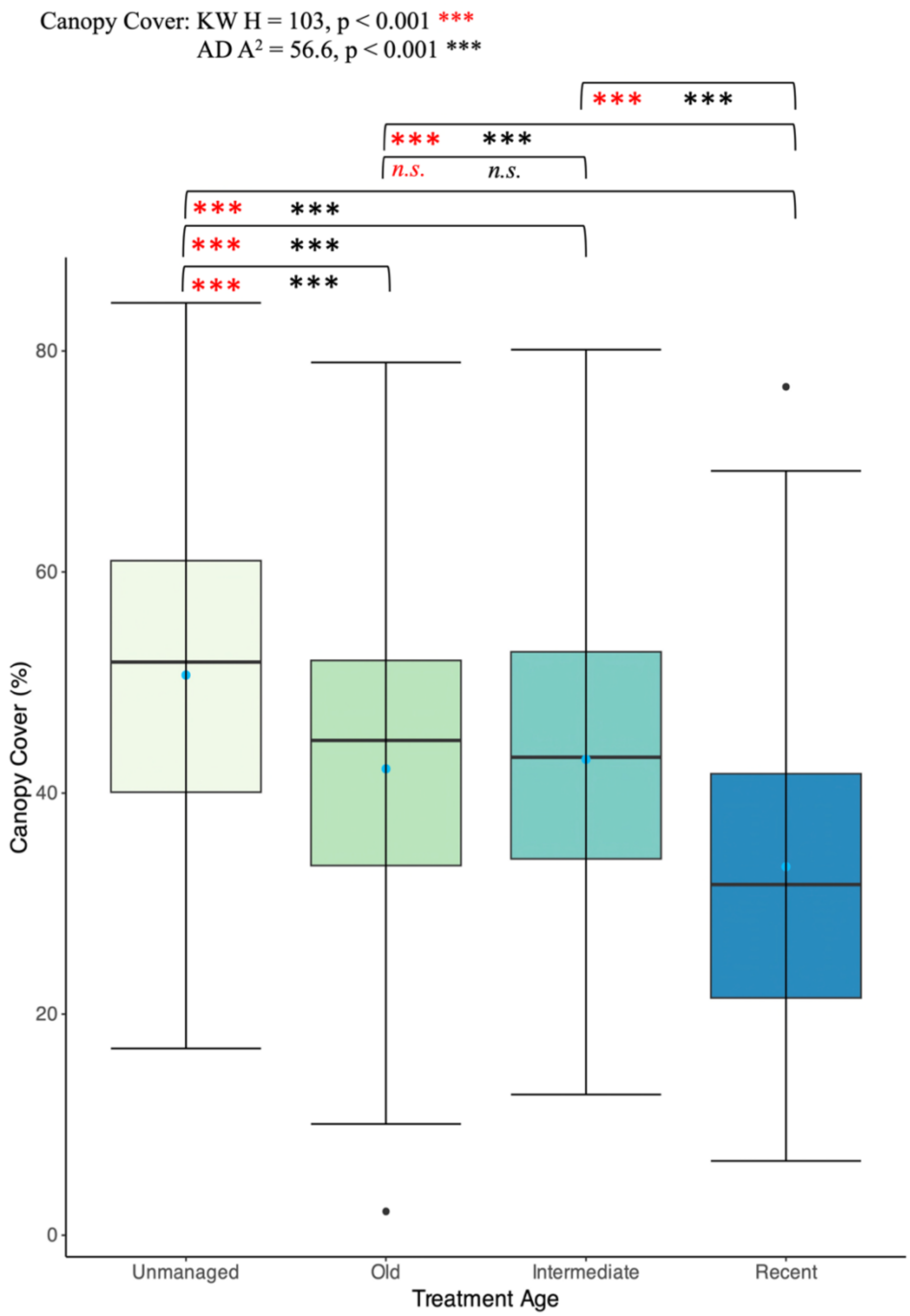

Figure 3.5. Canopy cover modelled from 734 airborne lidar data plots and 6 field plots across unmanaged and a chronosequence of time since management in Jasper National Park. Means are denoted in blue; median as the horizontal line; interquartile range (rectangle), and $5^{th}/95^{th}$ percentiles as whiskers. Pair-wise significance is denoted by red asterisk (Kruskal Wallis with Dunn's pairwise comparison) and black asterisk (Anderson-Darling).
n.s. = not significant

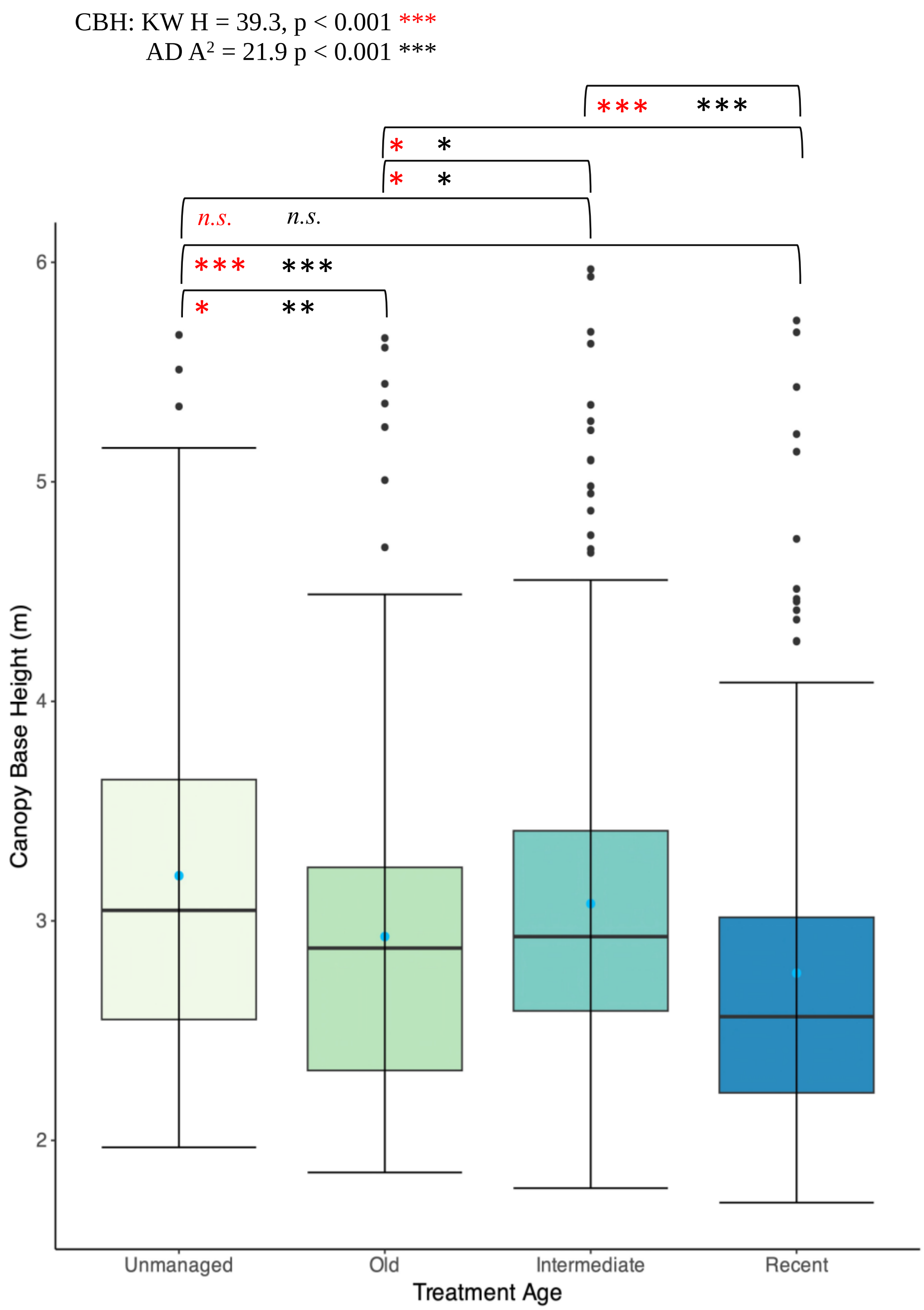

Figure 3.6. Canopy base height modelled from 734 airborne lidar data plots and 6 field plots across unmanaged and a chronosequence of time since management in Jasper National Park. Means are denoted as blue dot; median as the horizontal line; interquartile range (rectangle), and $5^{th}/95^{th}$ percentiles as whiskers. Pair-wise significance is denoted by red asterisk (Kruskal Wallis with Dunn's pairwise comparison) and black asterisk (Anderson-Darling).
$p < 0.05$ = *; $p < 0.01$ = **; $p < 0.001$ = ***; n.s. = not significant

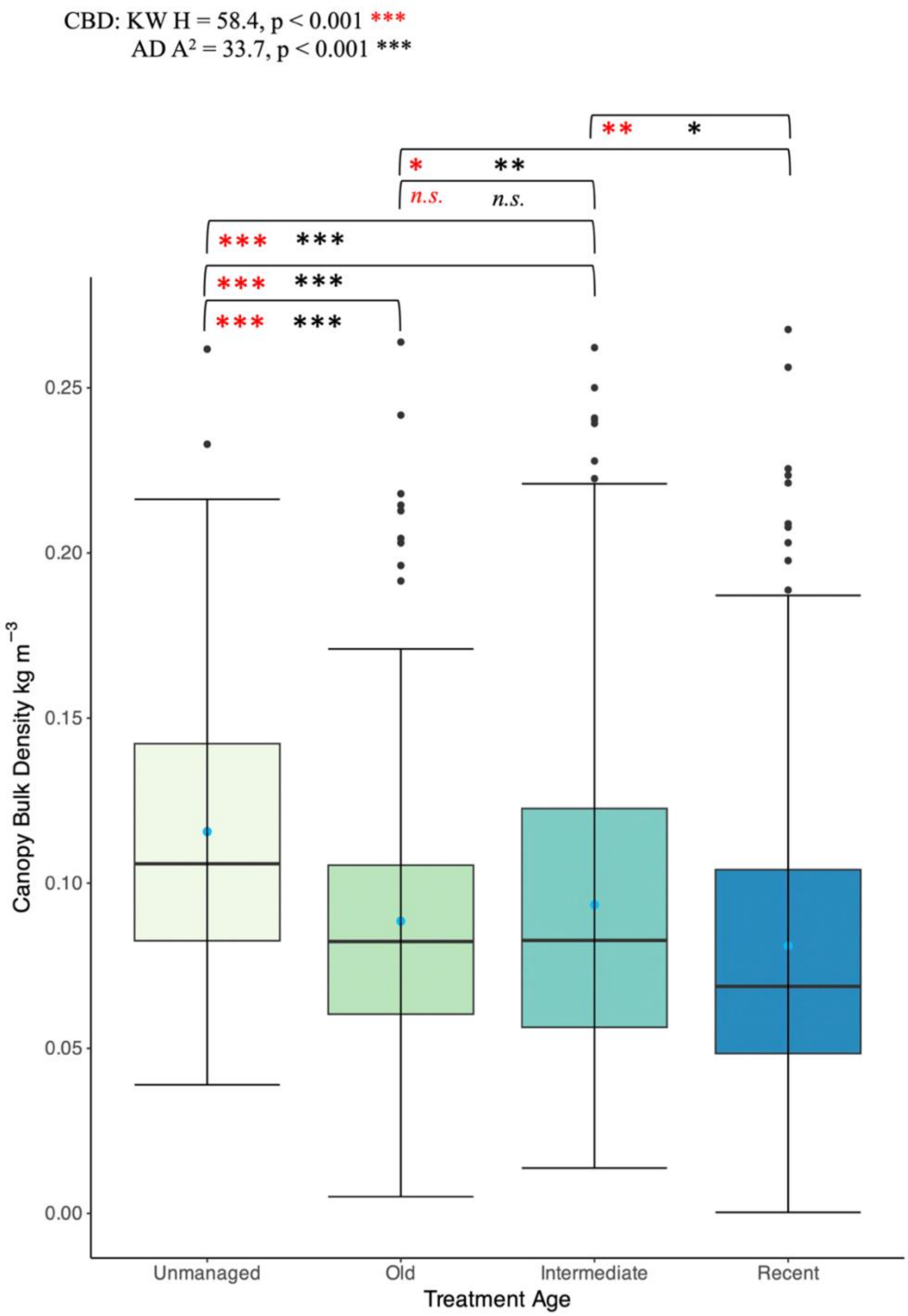

Figure 3.7. Canopy bulk density modelled from 734 airborne lidar data plots and 6 field plots across unmanaged and a chronosequence of time since management in Jasper National Park. Means are denoted in blue; median as the horizontal line; interquartile range (rectangle), and $5^{th}/95^{th}$ percentiles as whiskers. Pair-wise significance is denoted by red asterisk (Kruskal Wallis with Dunn's pairwise comparison) and black asterisk (Anderson-Darling).
$p < 0.05$ = *; $p < 0.01$ = **; $p < 0.001$ = ***; n.s. = not significant

3.3.5 Fire modelling

The reduction in stand density and canopy bulk density due to thinning showed active crown fire spread could not be supported across all treatment years. However, due to the low CBH across treated stands, torching could occur in most of these higher fire weather scenarios.

3.3.6 Fire type and torching threshold – Conifer Pyrometrics and Fuels Management Analyst

Conifer Pyrometrics predicted surface fire in the "low wind" scenario at 90^{th} and 95^{th} percentiles, but only for the most recently treated stand. Passive crown fire or torching fire behaviour was predicted for each other fire weather and stand combination. As time since management increased, the torching threshold (threshold at which aerial fuels may be ignited) at these weather conditions decreased (Table 3.6). Fuels Management Analyst predicted less potential for passive crown fire behaviour. In the recently treated stand, surface fire was predicted for all scenarios of nine fire weather combinations. In the intermediate stand, surface fire was predicted at low wind for the 90^{th} and 95^{th} weather percentiles, but the torching threshold was met for all other scenarios. The oldest treatment stand predicted passive crown fire behaviour for all fire weather conditions but could not sustain crown fire. The average torching threshold predicted by FMA showed a much larger range than CP (Table 3.6).

Table 3.6. Predicted wind speed threshold for crown involvement of individual trees as time since treatment increases using Fuels Management Analyst (FMA) and Conifer Pyrometrics (CP).

Torching Threshold (km hr^{-1})			
	Fire Weather	**FMA**	**CP**
Recent Treatment 2022	**90th**	**13.3**	**6.3**
	95th	**13.1**	**6.3**
	97th	**12.3**	**6.0**
Intermediate Treatment 2009	**90th**	**6.8**	**5.0**
	95th	**6.7**	**5.0**
	97th	**6.0**	**5.0**
Old Treatment 2003	**90th**	**2.5**	**4.0**
	95th	**2.3**	**4.0**
	97th	**1.6**	**4.0**

3.3.7 Thresholds for crown fire initiation – Byram and Van Wagner model linkage

Van Wagner's formula for critical surface fire intensity for crown fire initiation decreased from 1391.1 kW m^{-1} in the recent treatment to 844.4 m^{-1} in the intermediate treatment, to 529.0 kW m^{-1} for the oldest treatment (Table 3.7). This is largely dependent on the low CBH found in the oldest treatment stand. The intermediate age treatment stands exhibited the highest surface fire intensity due to slightly more total surface fuel expected to be available for consumption in the flaming front. All predicted headfire intensities exceeded that of the critical surface fire intensity, suggesting torching and passive crown fire behaviour was possible in all stands at these weather conditions. Based on these critical surface fire intensities, to prevent canopy involvement in the fire, the oldest treatment age stand would require the CBH to be elevated by 3.63 m, the intermediate treatment age stand CBH would need to be raised by 2.94 m, and the most recently treated stand by 1.35 m.

Table 3.7. Predicted headfire intensity (HFI), critical surface fire intensity (I_0), canopy base height (CBH), and canopy base height required to prevent aerial fuel involvement (CBH_0) as time since management increases.

Surface Fire Intensity					
	Fire Weather	**HFI**	**I_0**	**CBH**	**CBH_0**
		(kW m^{-1})	**(kW m^{-1})**	**(m)**	**(m)**
Recent Treatment 2022	**90th**	**1816**	**1391.1**	**4.09**	**5.43**
	95th	**1977**			
	97th	**2649**			
Intermediate Treatment 2009	**90th**	**2041**	**844.4**	**2.93**	**5.87**
	95th	**2221**			
	97th	**2977**			
Old Treatment 2003	**90th**	**1990**	**529.0**	**2.1**	**5.77**
	95th	**2166**			
	97th	**2902**			

3.3.8 Crown fire spread critical rate of spread – Van Wagner

The simple empirical model Van Wagner identified for sustained crowned fire spread was applied to the three field plots modelled above as well as all lidar derived plots, as CBD values are the only input. The recently treated stand would require a rate of spread of 106 m min^{-1} to exceed the threshold for active crown fire spread based on Van Wagner's criterion for active crowning (Van Wagner 1977). These fuels (Douglas-fir dominated) typically reach an equilibrium spread between 40 and 50 m min^{-1}, requiring low foliar moisture content and wind speeds over 50 km hr^{-1} (Forestry Canada Fire Danger Group 1992). Jasper winds rarely gust over 60 km hr^{-1}, with wind speeds usually below 30 km hr^{-1} (Figure 3.3, Government of Canada 2024). The intermediate and oldest treatment stands had critical spread rates of 41.7 and 42.8 m min^{-1}, respectively. Under these empirical models, given a conservative cut off critical rate of spread of 40 m min^{-1}, 43.8% of stands treated recently could sustain crown fire. Intermediate and oldest age treatments ranged from 57.5 – 59.3% potentially able to sustain crown fire, respectively. This is a substantial reduction from unmanaged stands, of which 82.7% could propagate crown fire spread. With a more moderate cut off of 30 m min^{-1}, the amounts for both recent and oldest treatment ages were reduced to 27% able to sustain crown fire, intermediate age at 35%, as opposed to unmanaged at 56.2%.

3.4 Discussion

This study examined how fuel structures change over time since fuel management and the impact these changes have on potential wildland fire behaviour. Regional knowledge of how treatments impact fuels over time is essential as vegetation as a fuel source is dynamic, and treatments must be regarded as transitory in nature. Modelling results from CP and FMA suggest that stand density and canopy fuels remained sufficiently reduced over the 19-year span of treatments to prevent active crown fire. However, at the high fire weather hazard values presented here, the saplings and lower branches maintaining fuel continuity into the overstory resulted in torching and passive crown fire behaviour in most scenarios presented. Reassessment of stands against management objectives suggest that mechanically raising the canopy base height is not often fully achieved in these stands. Ladder fuel objectives are not always met at the time of prescription; some vertical fuel connectivity may be retained and further increases during post-treatment regeneration. Stands treated in 2022 exhibited deviations from prescription recommendations in ladder fuels and surface strata which was due to higher retention than is recommended for coarse woody debris under 20 cm in diameter (Figure 3.4). By the time treatments reached intermediate age (13 years), enough regeneration had occurred to have significant levels of subcanopy trees over the conservative density recommendations, but these stands exhibited less ladder fuel connectivity (branches below 2 meters) than the oldest treatment stands (Figure 3.4). The absence of sufficient canopy fuel density for active crown fire spread and the presence of aspen and large diameter Douglas-fir signal the successful selection for conversion to more fire-resistant stands in treated areas.

Across the larger landscape, lidar derived canopy metrics showed significant reduction in stand density, canopy cover, and canopy bulk density over time since management, and in comparison to unmanaged stands (Figure 3.5-7). Using lidar derived information, canopy base height increased over time since treatment (Figure 3.6), but the opposite trend was found in the field measured plots (Table 3.3). Modelling the fire type and torching threshold with differential accounting for surface fuel consumption (measured fuels with FBP spread rate, for CP versus reliance on most similar fuel model selection, FMA) led to variance in fire type in some instances and higher relative difference in torching threshold, most notable in the recent and oldest treatment stands. The reduction of canopy bulk density in the fuel type independent Byram and Van Wagner linked equations suggest very extreme weather conditions would be required for active crown fire spread in these treated stands, but these models were developed using fire behaviour data from much more moderate conditions. In very extreme conditions, fire may create and be influenced by other processes such as fire-induced wind, pyro-cumulonimbus storms, and extreme spotting (McRae et al. 2015, Fromm et al. 2022), but these factors are beyond the scope of this research. This thereby suggests treatments here could remain successful at preventing active crown fire spread for ~20 years, but intensity still increases with fuel aridity and wind values conducive to torching, which can pose safety risks to nearby values and firefighting personnel.

3.4.1 Evaluation of fuel treatment efficacy and longevity

Though a combination of thinning and burning of surface fuels is accepted as being the most effective at reducing potential fire rate of spread and intensity (Schwilk et al. 2009, Lyderson et al. 2017), mechanical treatments are also highly valuable and meet less public resistance (Brunson 2023). The efficacy of fuel reduction at reducing crown fire potential immediately and short term (1-3 years) post management is well documented (Hirsch & Pengelly 2000, Vaillant et al. 2009, Collins et al. 2013). Though long-term data are hard to come by: in low productivity forests where regeneration is slow, modelled fire length and torching potential has been noted to remain low for around 10 years and could last for 20 years with some maintenance (Stephens et al. 2012). Phelps et al. (2022), in the Alberta Wildland Fuels Inventory Program, also found that mechanically treated stands had comparable litter and fine woody debris fuel loads compared to untreated stands. In the research presented here, the lack of change in surface fuels over time (Table 3.4) resulted in the critical surface fire intensity being reached at each treatment age (Table 3.7). This ambiguity and likelihood of torching in each stand makes it difficult to determine fuel treatment efficacy, but at extreme weather indices, some crown involvement is expected in most conifer stands (Beverly et al. 2020). At a stand level, fuel treatments are typically evaluated through wildfire behaviour simulation such as this, to see if the prevention of crown fire spread and a reduction of headfire intensity lasts over time. At a landscape level, fire effects such as burn depth and scorch height are often evaluated as indicators of severity when wildfire interacts with prior treatments (Ott et al. 2023). However, if models do not produce strong signals due to the inherent assumptions on fuel and their relationship to spread and intensity, practical physical monitoring of treated stands over time remains a valuable tool for management personnel. Monitoring and upkeep of past treatments has been identified by the BC Wildfire Service in a review as one of the most important research objectives for wildland fire management (LM Forest Solutions, 2020). Reassessing fuel accumulation and density targets is a recommendation in the BC Wildfire Service Fuel Management Practices Guide (2023), but these must be localized to fuel and weather conditions. The results of the reassessment preformed here indicate that stand conversion to retain large-stemmed Douglas-fir and aspen trees is occurring. In lower fuel strata, by 13 years post-treatment, however, maintenance would be required involving the removal of fine woody debris on the surface, pruning of ladder fuels, and lowering density of subcanopy trees (Figure 3.4). Interestingly, the 2022 treatments met management goals on juniper and fine woody debris but had a larger density of coarse wood boles retained on the forest floor. There must be concession here that there are more nuanced or site-specific ecological aims that may not perfectly align with the generalized objectives.

3.4.2 Utilization of remote sensing techniques for landscape level fuel assessment

The significant differences found between treatment period blocks for stand density, canopy coverage, and canopy bulk density (Figure 3.5-7) would not have been found with field measures alone. Traditional field data collection consumes substantial resources in time and money. Remote sensing techniques are valuable for extracting information across larger landscape, and lidar derived canopy metrics (especially height and cover) have been proven for high-accuracy results (Hopkinson et al. 2005, Hall et al. 2005, Hopkinson & Chasmer 2009), but these can only be used (e.g. without enhanced modelling of duff and surface fine fuels, etc. using machine learning) to evaluate canopy metrics for crown fire potential. When extracted stem densities and heights were used to classify trees versus subcanopy or saplings, a higher proportion of saplings was found in more recently treated stands. However, this may be accounted for by the significant loss in canopy cover in the most recent treatment areas. With species that can have tall, large canopies such as Douglas-fir, or tighter spacing between crowns such as lodgepole pine, subcanopy trees may be occluded from measurement from the air or included in a density profile with a larger stem (Donager et al. 2021). As the stand is thinned, smaller trees are more readily detected and measured. This increased detection may be occurring with the decreasing canopy base height in recent treatments as well, as accuracy improves with less interference from higher points. In addition, it is notable that with the lidar derived plots, negligible differences were seen in canopy cover, canopy base height, and CBD between the intermediate and oldest treatment ages. With canopy fuel metrics that are interdependent such as canopy bulk density (reliant on the estimate of canopy base height), the confidence and error propagation must be taken into account (Table 3.5). Canopy base height is difficult for airborne lidar to accurately measure, especially in dense stands, due to occlusion from the higher branches, and intermixing with immature trees and regeneration (Hall et al. 2005, Arkin et al. 2021). As the crown fire critical rate of spread is based on lidar derived CBD (which involves CBH), these results come with some inherent uncertainty (Anderson et al. 2005).

3.4.3 Interpretability of results from various fire modelling systems

There is no panacea for simulating fire behaviour, with fuels and climate inhabiting such regional spaces and the difficulty of acquiring empirical validation, especially for fuel treatment evaluation. Multiple modelling methods and combinations of fire behaviour tools were used here to highlight this, each of which have their limitations and strengths. The Byram – Van Wagner linkage for crown fire initiation is thoroughly researched and reviewed (Cruz et al. 2004) and embedded in many subsequent modelling systems used today (Forest Fire Danger Rating Group 1992, Finney 1998, Scott and Reinhardt 2001). It provides a straight-forward, fuel type and arrangement independent approach to evaluate the influence of surface fuel availability and crown base height on crown fire occurrence. It does not, however, account for vertical heat flux transfer, and relies on a constant based on one experimental fire in a red pine plantation (Van Wagner 1977, Alexander & Cruz 2016). Utilizing this model required surface rate of spread as an input. This has been done with a hypothetical number (Hirsch & Pengelly 2000), but the aim here was to model surface fire spread as accurately as possible with the given weather conditions. Rate of spread was estimated using the FBP system empirical C7 spread model. The fuels in this study area vary greatly from the interior BC dry forest Ponderosa pine-Douglas-fir stands that characterize the C7 fuel type. For example, the static CBH for the C7 fuel type is 10 m, though this assigned value is known to be a compromise between measured and observed crown fire involvement values; The C7 forest floor layer is also described as “shallow to non-existent” (Forest Fire Danger Group 1992). The CBH recorded here in the field and modelled by lidar clearly show the influence the mountainous topography has on fuel structural complexity and loading (Figure 3.6). However, because rate of spread was an initial weather-based point to be able to input estimated surface fuel consumption and CBH based on stand measurements, these differences do not impact the results overly. The finding that each stand modelled here could result in torching places importance on ensuring the height to the crown is raised when treated.

The FMA tool was developed for the evaluation of tree removal and crown length change so land managers could predict potential changes in fire behaviour (Carlton et al. 2004). The dynamic input of individual trees lends benefit especially when planning stand conversion thinning treatments (i.e. it can model leaving in more deciduous trees, different densities and crown classes) with a constant surface fuel model to show a range of outcomes. For the modelled stands in this case study, however, it was impossible to highlight the influence of slight differences in surface fine fuel loading, as they were close enough in values to remain closest to the same surface fuel model. Though the canopy inputs are more fuel and stand complex specific, the linkages utilized between Rothermel’s (1972, 1991) surface and crown fire spread models and Van Wagner’s crown fire initiation has been criticized for underprediction of crown fire initiation and spread (Cruz &

Alexander 2010). This underprediction is potentially evident in the higher instance of surface fire predicted and higher torching wind speeds for the 2009 and 2022 treated stands when compared to CP results (Table 3.6).

Conifer Pyrometrics is a relatively new modelling framework that incorporates new experimental data, stand adjusted moisture content, estimated surface fuel consumption, and a combined empirical and physical approach to conifer fire behaviour prediction. This system is still being finalized, but will be valuable for linking several dynamic variables that have not yet been easily incorporated into operational research programs. Despite this valuable linkage, the CP source data is almost entirely from boreal forests, and as such it may be inaccurate for low density, open grass surface fuel types. The cordilleran fuel complexes found in western Canada have been less well represented by traditional fuel types (Perrakis et al. 2018, Baron et al. 2024) and fire spread models, and require more attention going forward. This is compounded in this study area by inherent structural diversity in a montane environment.

3.4.4 Levels of influence on fire behaviour by fuels and weather

Though fuel accumulation and structure play a large part in how a fire spreads and behaves, this can be superseded by extreme weather conditions. The "fuel effect", or the influence that the physical characteristics of a fuel complex has on fire behaviour (Keane et al. 2015), has been found to have diminishing impact as fire weather becomes more extreme (Cruz et al. 2022). Rate of spread at higher fire weather indices is largely dictated by wind speeds, so much so that a 10% of the 10-m wind speed rule generally applies to sufficiently dry fuels, regardless of conifer, eucalypt, or shrubland in composition (Cruz et al. 2020). However, fuel reduction treatments remain successful at reducing burn severity even under extreme conditions, which can aid in forest resiliency (Lydersen et al. 2017). The feedback interactions between weather conditions and fuels are difficult to uncouple. Weather prior to a fire event influences moisture conditions within the fuels, which influences ignition and spread potential within the fuels, which can then be overtaken by strong winds as the main spreading driver during the fire event. Barring strong wind-domination in a fire event, however, fuels reduction treatments can substantially lower intensity and severity and lessen resistance to control.

3.5 Conclusion

Based on detailed surveying and fire modelling, conifer fuel treatments in Douglas-fir and lodgepole pine stands within Jasper National Park, Alberta appear effective at reducing risk of active crown fire behaviour. Across the larger landscape, as measured by airborne lidar, active crown fire is predicted to be possible in 43.8% of recently treated stands, compared with 82.7% of unmanaged comparable stands. Torching or passive crown fire, however, are still likely under dry conditions with moderate or high wind speeds (90^{th}, 95^{th}, and 97^{th} fire weather percentiles) and across all treatment years. This is stated as a suggestion bearing in mind the many and considerable limitations and assumptions of fire modelling, the use of lidar derived metrics with higher uncertainty, and a minimum number of field sample points. Height to the canopy base increased as more time since treatment had passed in field measured plots, but the opposite was seen when evaluating lidar-derived metrics. However, this may be a measurement artefact, as lidar introduces more uncertainty in CBH than field measures, which subsequently propagates into CBD estimates. CBH had a large influence on crown fire initiation within the models used here. The reassessments of managed stands suggested ladder fuels and canopy base height failed to meet current management objectives often. This could be remediated by subsequent prescribed fire after mechanical treatment, which would raise CBH and reduce surface fuels, though this is not always achievable near residential areas. The reassessment also indicated that many stand elements, mainly sapling density and ladder fuels, exceed treatment guidelines by the time 13 years had passed. These findings recommend light maintenance may be required on a more regular basis to maintain full fire hazard mitigation aimed for by park managers.

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CHAPTER 4: CONCLUSION

4.1 Summary of Research

This research contributes to a deeper understanding of fuel distributions in the northern Rocky Mountains of Canada. With increasing prevalence of climate-mediated and anthropogenic disturbance, wildland fuel structural and loading characteristics in many areas have deviated from the traditional fuel types that have been used for fuel classification and fire behaviour prediction for many decades. The warming and drying climate has increased the frequency and impact potential of wildland fire; it is thus imperative that altered fuel complexes and their influence on fire behaviour are understood.

The mountain pine beetle outbreak of the past two decades is the largest natural disturbance for the forested landscape in western Canada outside of wildland fire itself, and the interactions between these fuels and fire behaviour are complex and long-lasting. Beetle-killed fuels can significantly increase surface fuel loading and create difficult terrain as trees fall, and lowered fuel moisture in dead vegetation mixed with live vegetative regeneration can increase fire ignition and spread potential. The proportion of mortality due to mountain pine beetle can significantly influence the distribution and composition of fuels, illustrated in Chapter 2.

In addition to increased disturbance, a century of colonial fire exclusion practices has altered fire regimes, increased fuel loading, and encouraged the infilling of coniferous species across much of the forested regions of western Canada. Landscapes that have always been fire-mediated have experienced significant departures from their regular fire return intervals. The resulting fuel accumulation has increased fire intensity and severity potential and susceptibility to disease and disturbance. To remediate this, especially in the wildland urban interface where human lives, property and infrastructure are at risk, fuel reduction treatments through programs such as

FireSmart have been implemented over the last few decades. However, regionally specific regeneration rates and fire environments have made the longevity and efficacy of these reduction treatments difficult to evaluate. Changes in fuel as time since mechanical fuel reduction treatment increases, as well as the impact this has on potential surface fire intensity and crown fire initiation are assessed in Chapter 3. This research provides critical insights into the range of variability fuels present in altered states (disturbed and managed stands) in the montane environment and the implications on potential fire behaviour.

In Chapter 2, the impact of gray-phase mountain pine beetle outbreak on fuel structure and loading was examined using *in situ* field data. Specifically, the objectives were to: a) assess if severity levels significantly impact fuel community structure, composition, and loading across vertical fuel strata using field data, and b) place these findings within the range of variability of infestation using airborne lidar data derived stem density and tree height in additional remotely sensed plots across the larger landscape. The results here indicate that mortality levels within the same temporal phase of outbreak have significant impacts on the vertical distribution and composition of fuels. Severely impacted stands exhibited significant loss of initial canopy fuels, mortality and canopy fuel loss in the sapling cohort, more forest floor coverage by herbaceous material, and less seedling recruitment than both moderately and lightly impacted stands. Though the loss of overstory canopy fuels in gray-phase outbreak is consistent with past literature, (Schoennagel et al. 2012, Donato et al. 2013), the more pronounced loss within the subcanopy cohort found here provides a strong indicator of fuel variation as outbreak severity increases. Light and Moderate stands displayed more structural heterogeneity and the interspersal of dry standing dead vegetation and live fine fuels may present high hazard in case of fire (Talucci et al. 2022). Prospective regeneration will be of particular interest as outbreak severity increases as both

Moderate and Severe stands exhibited less than half the number of coniferous seedlings as Light stands, aligning with findings in proximal locations (Astrup et al. 2008, McIntosh & Macdonald, 2013, Leiffers et al. 2023). The opening of the canopy as severity increases has led to an increase of herbaceous vegetation coverage which follow more seasonal moisture retention, affecting ignition potential depending on curing level. The lack of difference in coarse woody debris suggest no substantial snag fall has occurred yet. The placement of the field measured plots within the range of stand densities and heights across the mountain pine beetle outbreak range increases confidence that these measurements can reasonably represent stands across the larger landscape. These results build upon past work detailing differences in fuel along a temporal "time since beetle" outbreak and indicate a potential shift to other stand types in the most severely impacted areas, barring a spur of regeneration from fire.

Chapter 3 addressed the objective of quantifying fuels and fire hazard mitigation as time since fuel reduction treatment increases. Specifically, the objectives were: to assess how fuel varies through vertical strata over time since onset of management, to compare field collected data with remotely sensed plots across comparable managed and unmanaged stands using airborne lidar data derived stem density and canopy metrics, and to assess potential fire behaviour over time since management in field measured stands. Six field plots over the range of treatment years (0, 13, and 19 years since mechanical treatment) were examined in detail, and 734 further plots derived from airborne lidar data were analyzed for canopy characteristics and stand similarity across management areas. Fire potential was examined in select field plots using a standard surface fire intensity (Byram 1959) to crown fire initiation model (Van Wagner 1977), a canopy input modelling tool for land managers (Carlton 2004), and a forthcoming modelling framework that allows for stand specific moisture and fuel inputs (Perrakis et al. 2023, Perrakis et al. *in prep*). This study indicates that canopy cover and canopy bulk density were sufficiently reduced to prevent active crown fire spread in most situations, but vertical continuity and surface fuel levels provided opportunity for torching, or crown involvement in individual trees, in all stands at intermediate and high wind speeds for high fire weather indices. Field data indicate that by the time since treatment reaches thirteen years, maintenance is required for many stand elements, mainly in saplings, advanced regeneration, and ladder fuel continuity. Similarities in these maintenance action items and derived canopy metrics for treatments that occurred 13 (intermediate age) and 19 (oldest age) years prior suggest regeneration has significant impact on managed stands by 13 years post treatment. Overall, this study suggests that some fire behaviour mitigation (prevention of active crown fire spread) may persist around two decades after treatment, but more emphasis may need to be placed on routine maintenance to elevate the canopy from regenerating fuels.

The overall objectives of the thesis examined in Chapters 2 and 3 were based on the hypothesis that fuels will accumulate in the surface or understory strata after fuels are removed from the canopy, as regeneration accrues after disturbance or fuels management. Both studies provided surprising results in terms of surface fuels. Surface fuels were not significantly different in composition or loading for most elements in both mountain pine beetle and managed stands across treatment years. Sensitivity of fire spread and intensity models to surface fuel consumption make this an important consideration. Shifts in surface level composition to herbaceous and grass vegetation and lack of coniferous seedling recruitment as mountain pine beetle severity increases indicate potential stand recovery trajectories away from dense conifer stands. Likewise, selection for large-stemmed, fire-resistant species such as Douglas-fir and moisture-persistent species such as aspen, and recruitment of seedlings of these species in past treatment areas may signal successful stand conversion to less hazardous stand types. Fuel baselines, shifts, and signals such as these are essential to identify for risk recognition and operational adjustments going forward. Conditions during a fire event are of course highly specific, and extreme weather and aridity combinations can cause significant fire spread, superseding the influence of fuel distributions on fire behaviour.

4.2 Recommendations

- Continued monitoring of post-mountain pine beetle stands will identify areas with increasing fuel loads, fuel connectivity, successional trajectories, and landcover change as regeneration continues into "Old" phase of outbreak.
- Identification of areas with downed woody debris "jackpots" in higher density Moderate and Severe areas as dead standing stems fall over the next 5-10 years may require monitoring or clearing if in high-traffic areas for the public or parks personnel due to increased fire intensity potential and reduced navigability.
- Continued monitoring of treated stands is recommended especially in areas directly adjacent to homes and infrastructure. Light maintenance removing ladder fuels and advanced regeneration density of saplings around 10 years post treatment could preserve protection from fire spreading to structures and individual trees torching if fire occurs.
- In management areas further from homes and infrastructure, pairing mechanical thinning with prescribed burning could reduce surface fuels and thus surface fire rate of spread and intensity. This work highlights that without a reduction in surface fuels, critical surface fire intensity thresholds for crown involvement remain low, even in the most recently treated stands, and can be reached at high fire weather indices.
- Establishment of monitoring programs for fuel accumulation and connectivity can identify small areas within treated stands that may require light maintenance and prevent the need

for more resource and time intensive strategies if regeneration becomes too sizeable and dense.

- In recognition of the Jasper Complex Wildfire, which burned the community of Jasper in August 2024, the research presented here will provide a baseline for fuel distribution and improved understanding of the complex drivers of fire behaviour in the months and years to come.

4.3 Limitations & Future Directions

The scope of these findings may be constrained by some inherent limitations. These studies are observational in nature, and therefore limits the results to areas of similar species composition, climate, and terrain. Logistics and time constrained the field data collection to 24 plots, with 18 across mountain pine beetle stands and six across managed stands. Despite field measured stands spanning very similar ranges in density and height as field-derived lidar plots, conclusions may be restricted by this number of measured and modelled values for surface and ground fuels. Plots were also limited to areas at lower elevations throughout the valley, though mountain pine beetle occurs throughout a larger elevational range (newer outbreaks), and managed stands occur on sloped terrain surrounding the town. Lidar plots were selected within the topographical range of field collected data for comparability. Future research could examine the range of variability found across the topographical gradient from valley up to the treeline.

Though lidar has been proven to be a reliable method of deriving canopy characteristics (Hopkinson et al. 2005, Hall et al. 2005, Hopkinson & Chasmer 2009), confidence decreases lower in the canopy when there is overlap between overstory and understory vegetation. Lidar is also limited by point density for the ability to characterize fine details that can be recorded within field plots. Occlusion from overstory points makes canopy base height more difficult to accurately predict (Arkin et al. 2021). The importance of canopy base height accuracy for wildland fire models, especially crown fire initiation, makes this uncertainty a notable consideration when utilizing lidar derived values within these predictions. Using each modelling system also involves many inherent built-in assumptions, and spread rates based on fuels in natural and unmanaged stands, which together result in a propagation of error (not examined in this thesis). Generalizations of fire potential based on these results should be approached with an abundance caution. Lastly, the use of the vegetation resource index provided by Jasper National Park for stand age and mountain pine beetle severity for lidar plot extraction may have propagated error from time of data collection.

Opportunity for future research and monitoring of fuels is present across this landscape as mountain pine beetle stands move into “Old” designation, and standing dead vegetation falls to the surface. Removal may be required in key areas that collect “jackpots” of fallen stems to prevent intense surface fire potential and hazardous terrain. The baseline of mortality due to mountain pine beetle established here can be used to examine how these fuels, and regions that have experienced similar levels of disturbance, will shift and accumulate over the coming decades. There is also opportunity to use these data to evaluate potential fire hazard over the variability in these stands if appropriate measures are used to account for the variable fuel moistures and influence of interspersed dead standing and live vegetation. Future work following from Chapter 3 could involve similar evaluation in different treatment types over time, such as prescribed burning, which would present lowered surface fuels and more consistently raise the canopy base height, or a combination treatment (mechanical thinning prior to prescribed burn). Jasper National Park has been conducting a wide range of fuel reduction strategies for decades and so a comparison of these strategies in these fuel types would be a natural next step to build upon this research. The findings here can inform similar studies on fuel treatment longevity, both further observational and experimental in design.

4.4 Concluding Statement

This research has successfully characterized and quantified fuels across a range of gray-phase mountain pine beetle outbreak severity and a range of time since fuel treatment in the cordilleran montane forests of Jasper National Park, Alberta. Beetle-induced mortality levels impacted surface fuel composition, seedling recruitment, and canopy fuels (especially in the subcanopy cohort). Fire hazard may present highest in stands designated “Moderate” severity, as these stands exhibited high intermixing of live and dead standing vegetation. Severity designations suggested here can provide insight into fuel structure and composition in areas with similar outbreak.

As time since fuel treatment increased, canopy cover and canopy bulk density significantly increased, though surface fuels remained consistent. Critical surface intensity was reached at all weather indices (90^{th} – 97^{th} percentiles), so torching fire behaviour is possible in these weather scenarios, but canopy fuels remained sufficiently reduced to prevent active crown fire based on these modelling systems. This research provides critical insight into the distribution of disturbed and managed fuels over time, and the potential impact on fire behaviour as high fire weather indices occur more frequently in a warming climate.

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