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EVALUATING QUAKING ASPEN'S INFLUENCE ON FIRE BEHAVIOR

by

Kristin A. Nesbit

A thesis submitted in partial fulfillment  
of the requirements for the degree

of

MASTER OF SCIENCE

in

Ecology

Approved:

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UTAH STATE UNIVERSITY  
Logan, Utah

2023

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## ABSTRACT

## Evaluating Quaking Aspen's Influence on Fire Behavior

by

Kristin A. Nesbit, Master of Science

Utah State University, 2023

Major Professor: Dr. Larissa L. Yocom  
Department: Wildland Resources

In western North American forests, quaking aspen stands (*Populus tremuloides* Michx.) have long been described as low flammability, “fireproof” forest types that are less likely to burn or burn less intensely than coniferous forests. Paradoxically, however, high-intensity and high-severity fires have been observed to burn through aspen stands and in many cases, aspen requires high-severity disturbance to successfully regenerate. To better understand when and where aspen burn—and when they do not—as well as the factors that affect flammability in aspen forests, I conducted two studies. In the first study, I reviewed evidence for reduced fire occurrence, behavior, and severity in aspen forests via an extensive literature review and a survey of professionals with expertise in aspen-fire encounters. I found evidence that aspen reduces fire occurrence, behavior, and severity, but this effect is dependent on many factors, particularly the relative overstory composition of aspen and conifer trees, type and load of surface fuels, weather, and season. Additionally, I found that research on the effects of specific aspen site and stand characteristics on fire was very limited. I addressed this knowledge gap in the second study, in which I investigated surface and canopy fuel characteristics in 80 aspen stands in Utah, U.S. that spanned gradients of tree species composition from aspen to conifer

dominance and stand development stage from early to late development. Results suggested that pure, late development aspen stands have lower potential flammability during certain surface fuel and seasonal conditions, though also highlighted the high variability of flammability characteristics within aspen forests. While this research supports the claim that aspen forests promote lower flammability conditions under certain conditions, aspen forests are certainly not “fireproof,” and uncertainty remains regarding the future of fire in aspen under a warming and drying climate.

(168 pages)

## PUBLIC ABSTRACT

## Evaluating Quaking Aspen's Influence on Fire Behavior

Kristin A. Nesbit

In western North America, quaking aspen (*Populus tremuloides* Michx.) forests have long been described as low flammability, “fireproof” forest types that are less likely to burn or burn less intensely than coniferous forests. While this assumption has been based on limited scientific research and is largely anecdotal, there is growing interest in the western U.S. to promote aspen near human developments to reduce fire risk. I investigated the available evidence for aspen forests reducing fire occurrence, behavior, and severity, and assessed possible factors that affect flammability in aspen forests to better understand when and where aspen burn, and when they do not. In the first study (Chapter 2), I conducted an extensive literature review and a survey of professionals with expertise in aspen-fire encounters to examine our current understanding of how aspen influences fire. In the second study (Chapter 3), I investigated fuel characteristics in 80 aspen stands in Utah, U.S. that spanned gradients of tree species composition from aspen to conifer dominance and stand development stage from early to late development. I found evidence for aspen forests reducing fire occurrence, behavior, and severity under certain conditions, and results from our field campaign indicated that pure, late development aspen forests were particularly associated with lower flammability conditions. However, I also found that the aspen-fire relationship was complex; factors such as the percentage of aspen vs. conifer trees in the overstory, type and load of surface fuels, weather, and season play important roles in determining how flammable an aspen

forest is. While my research supports the claim that aspen forests promote lower flammability conditions under most conditions, aspen forests are certainly not “fireproof,” and uncertainty remains regarding the future of fire in aspen under a warming and drying climate.

## ACKNOWLEDGMENTS

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Throughout this journey, I was fortunate to be able to work closely with another master's student, Allie Trudgeon. We shared so many laughs with each other, and her constant encouragement and accolades boosted me throughout. Thank you. I would also like to thank my lab mates Alex Howe, Kipling Klimas, Jamela Thompson, Megan Whetzel, Sarah Kapel, and Nadav Mouallem for their advice on classes, insightful ideas about both research and life, and helpful comments on presentations. Thanks also to Keghan Connor, Elle Connor, Chase Gunnell, Emily Lane, and Dylan Lipscomb for their help with collecting data in the field and providing so much amusement.

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Kristin A. Nesbit

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## PREFACE

Because this thesis has been prepared in journal format, there is some redundancy between chapters. Chapter 2 is entitled “Quaking aspen’s influence on fire occurrence, behavior, and severity” and was published as a Tamm Review in *Forest Ecology and Management* in 2023. Chapter 3 will be submitted to a peer-reviewed journal for publication in the near future. Each chapter will be published with co-authors; as such, the pronoun “we” is used throughout the thesis.

## CHAPTER 1

### INTRODUCTION

Historically, western quaking aspen forests (*Populus tremuloides* Michx.) have been considered less flammable than coniferous forests, due largely to anecdotal accounts of high-intensity fires slowing or extinguishing upon encountering an aspen forest (i.e., Fechner and Barrows, p. 15; 1976, Jones and DeByle, 1985; DeByle *et al.*, 1987; Alexander and Lanoville, 2004) and observational studies that found low fire occurrence in aspen forest types in the interior western U.S. (Fechner and Barrows, 1976; DeByle *et al.*, 1987). However, there have also been observations of fires burning in aspen stands with high intensity and high severity (i.e., Kiil and Grigel, 1969; Quintilio *et al.*, 1991; Tepley and Veblen, 2015;), and high-severity fire is considered an essential disturbance agent for regenerating aspen in some western forests (Jones and DeByle, 1985). Therefore, we are left with a paradox: aspen is considered less likely to burn than conifer forests, yet it can burn at high severity and thrives after high-severity fire.

Understanding aspen's influence on fire and the characteristics of aspen forests that affect their flammability is important not only from a basic ecology perspective—as fire-vegetation feedbacks have been identified as an important and growing field (McLauchlan *et al.*, 2020)—but may also be critical in informing forest and fire management to promote aspen around developed areas to reduce fire risk. Possible explanations for reduced fire behavior in aspen forests include fuel characteristics such as high aspen foliar moisture content (Van Wagner, 1977), high understory vegetation moisture content (Brown *et al.*, 1989; Bradley *et al.*, 1992), rapid decomposition of leaf litter (Prescott *et al.*, 2000; Preston *et al.*, 2000; Prescott *et al.*, 2004), and few fine dead



woody fuels (Hély *et al.*, 2000). However, fuel characteristics vary widely in aspen forests—as in any type of forest—depending on stand attributes (i.e., tree species composition, structure, density, age), site features (i.e., topographical features, soil type) and other biophysical factors (i.e., climate and season). Specific information on how these factors affect aspen’s influence on fire is uncertain.

This thesis addresses several uncertainties and knowledge gaps in our understanding of the aspen-fire relationship. In Chapter 2, we report findings from an extensive literature review and a survey of professionals with expertise in aspen-fire encounters. Specifically, our objectives were: (1) review evidence for reduced fire occurrence, behavior, and severity in aspen stands and identify key factors that drive these patterns; (2) conduct a survey of managers, ecologists, and firefighters to gather first-hand information on observed fire behavior in aspen forests; and (3) identify results that could lead to quantitative guidelines for managers interested in using aspen to reduce fire risk. In Chapter 3, we investigated flammability characteristics in aspen stands in Utah, U.S. that varied in stand attributes. Specifically, we examined patterns in (1) surface fuel load, (2) canopy characteristics, and (3) fuel moisture content across 80 aspen stands that varied in tree species composition from aspen to conifer dominance and development from early to late stage. We described each stand’s flammability by calculating a weighted moisture content that combined fuel moisture and load. In all, this thesis provides an important synthesis of knowledge about aspen’s influence on fire and provides key evidence for factors underlying the influence of aspen forests on fire behavior.

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## CHAPTER 2

QUAKING ASPEN'S INFLUENCE ON FIRE OCCURRENCE, BEHAVIOR,  
AND SEVERITY<sup>1</sup>**Abstract**

Quaking aspen (*Populus tremuloides* Michx.) stands have historically been referred to as “firebreak” forest types that can reduce fire activity, but high-intensity and high-severity fires have been observed to burn through aspen stands. Clearly, fire activity in aspen is highly variable, which may be due to the wide variation in aspen stand composition and structure and because the species occurs across wide geographic, environmental, and climatic gradients. In the western U.S., there is growing interest in promoting aspen stands within wildland-urban interface communities to reduce fire risk, but studies that refer to the low flammability of aspen stands rely on limited citations. If promoting aspen to reduce fire risk is a desirable forest management practice, consolidating the available literature is necessary to understand when, where, and how management might achieve this goal. Here, we synthesized literature and conducted a survey of forest and fire managers to assess current understanding of how fire interacts with aspen stands, as well as to examine possible factors that influence fire occurrence, behavior, and severity in aspen communities. We found evidence that the presence of aspen reduces fire occurrence, fire behavior, and fire severity, but this effect is dependent on many factors, including the percentage of aspen vs. conifers in the overstory, load and type of understory fuels, weather, and season. We did not find any quantitative management guidelines on how to create, maintain, or use aspen stands to reduce fire

<sup>1</sup> This article was published in *Forest Ecology and Management*, Vol 531, Kristin A. Nesbit, Larissa L. Yocom, Allison M. Trudgeon, R. Justin DeRose, Paul C. Rogers, “Tamm review: Quaking aspen’s influence on fire occurrence, behavior, and severity,” Copyright Elsevier (2023).

risk. The large gap between “common knowledge” and empirical evidence regarding aspen’s ability to inhibit fire requires further research.

## **Introduction**

Quaking aspen (*Populus tremuloides* Michx.) is the most widely distributed tree species in North America, where it occurs in stands ranging in composition from pure to mixed that are characterized by a broad range of natural fire regimes (Nlungu-Kweta *et al.*, 2017; Shinneman *et al.*, 2013). Western aspen forests have historically been considered less likely to burn compared to conifer-dominated stands. This idea emerged from observations of fires in conifer-dominated landscapes slowing or extinguishing upon encountering an aspen forest (including in Alexander and Lanoville, 2004; DeByle *et al.*, 1987; Fechner and Barrows, 1976, p. 15; Jones and DeByle, 1985), causing these forests to be referred to as “asbestos” forests (DeByle *et al.*, 1987, p. 75). In addition to anecdotal accounts of aspen reducing fire behavior, observational studies that related fire occurrence and forest type across western U.S. forests found that aspen forest types had low fire occurrence from 1960 to 1973 (in Colorado; Fechner and Barrows, 1976) and 1970 to 1982 (across interior western U.S. forests; DeByle *et al.*, 1987). These two studies are often cited for aspen’s relatively low flammability compared to conifer stands. However, there have also been observations of fires burning in aspen stands with high intensity (i.e., Kiil and Grigel, 1969; Quintilio *et al.*, 1991) and high severity (Tepley and Veblen, 2015), so the scientific literature is mixed regarding aspen’s influence on fire activity.

Several ideas have been proposed to explain why aspen stands tend to burn infrequently, over small areas, and with low intensity or severity. These potential

explanations include fuel characteristics such as high aspen foliar moisture content (Van Wagner, 1977), high understory vegetation moisture content (Bradley *et al.*, 1992; Brown *et al.*, 1989), rapid decomposition of leaf litter (Prescott *et al.*, 2000; Prescott *et al.*, 2004; Preston *et al.*, 2000), and fewer fine dead woody fuels (Hély *et al.*, 2000) in aspen stands compared to conifer stands. Similar fuel characteristics have been observed in forests of other North American deciduous tree species—such as red maple (*Acer rubrum* L.; Kane *et al.*, 2021), red alder (*Alnus rubra* Bong.; Worthington *et al.*, 1962), and paper birch (*Betula papyrifera* Marshall; Safford *et al.*, 1990)—and were also linked to lower flammability compared to conifers. In a recent global review of plant traits that influence flammability, moisture content of live and dead plant components was found to be the most important fuel characteristic that directly influences flammability and fire activity in forested communities (Popović *et al.*, 2021). However, in aspen forests, it is uncertain which factor is the most important in influencing flammability.

In any forest type—including in aspen—these fuel characteristics (type, load, and moisture) can vary widely, depending on biophysical factors (such as climate, topographical features, soil type, or season) and stand factors (such as overstory composition, structure, density, or age). Changes to any of these fuel characteristics can modify fuel flammability (Bowman *et al.*, 2014), which in turn can influence fire occurrence, frequency, extent, behavior, and severity (Fig. 1). Because aspen occurs across such a broad ecological amplitude and geographic area, fuel and fire characteristics are expected to vary widely. For example, aspen's occurrence with other tree species (i.e., pure aspen, mixed with hardwood species, or mixed with conifer species) affects the fuel characteristics in that stand, which ultimately affects the stand's

flammability (Fig. 2). Aspen-dominated forests are often defined as containing >50% aspen overstory composition, but aspen can be found across a range of dominance from sparse to pure aspen.



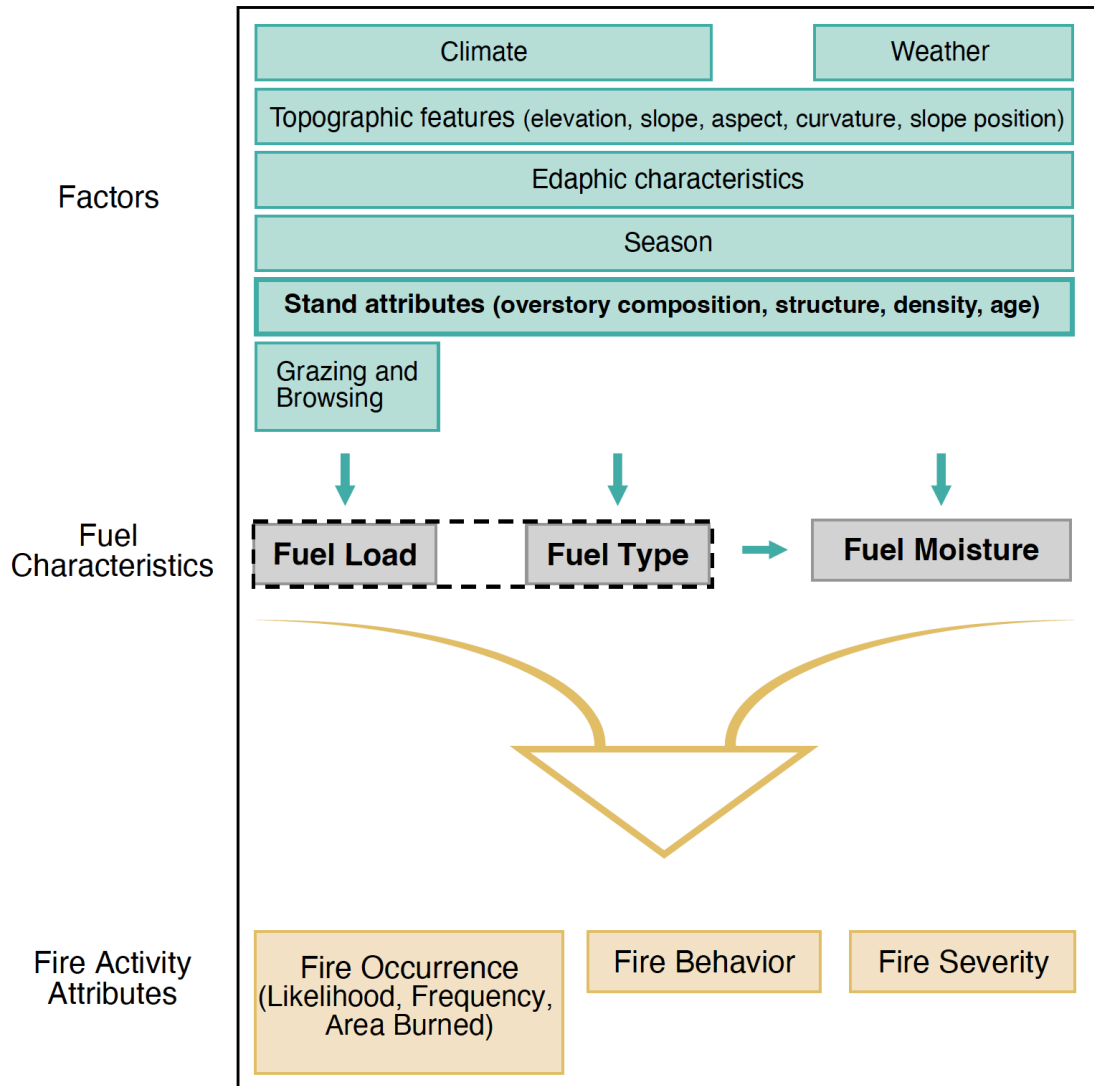


Figure 1: Conceptual model of how fuel characteristics relate to key fire activity attributes discussed in this review. The factors listed in the teal boxes influence the key fuel characteristics (fuel load, fuel type, and fuel moisture; grey boxes), which in turn influence key fire activity attributes (fire occurrence, fire behavior, and fire severity; beige boxes). Fuel load and fuel type are linked (dotted line) because these fuel characteristics are related and are discussed together in the Results and Discussion section. See Table 1 for definitions of fire activity attributes. The width of each teal box indicates which fuel characteristic that factor influences (i.e., stand attributes influence all three fuel characteristics, and grazing/browsing primarily influences fuel load).

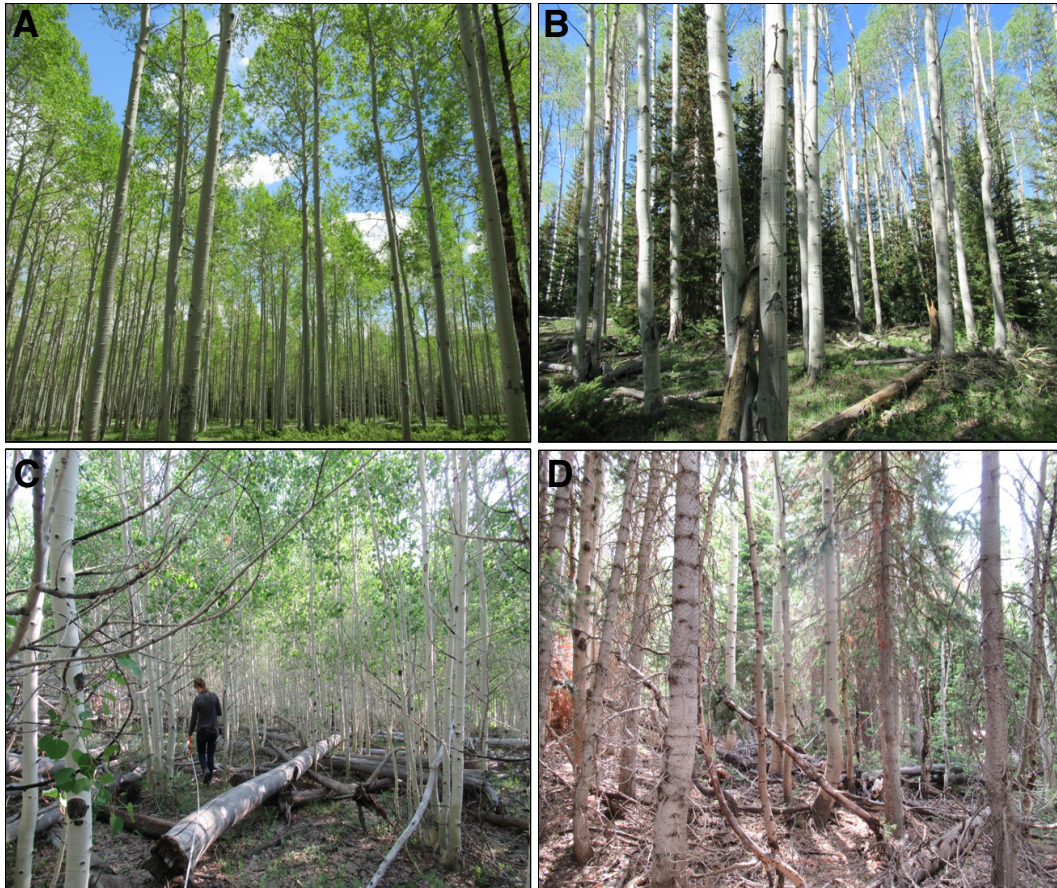


Figure 2: Variation in species composition and structure in western quaking aspen stands. Aspen exists in pure stands (A and C) and in mixed stands with conifer (B and D) or other hardwood species (not pictured). In these pictures, subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) is the main conifer associate, establishing overstory dominance in later successional stages (i.e., D). Pictures were taken on the Tavaputs Plateau, Utah. Photo credits: Kristin Nesbit and Allison Trudgeon.

Fire intensity and fire severity are not always the same in aspen stands. Individual aspen stems are extremely sensitive to fire due to their thin bark that lacks a protective cork layer, and aspen are easily killed even by low-intensity surface fires (Baker, 1925; Bradley *et al.*, 1992; Jones and DeByle, 1985). This can lead to an inverse relationship between fire intensity and severity in aspen stands, where high tree mortality can occur in low-intensity surface fires. Regardless, aspen regeneration after fire can be prolific. Aspen's primary method of reproduction is by vegetative suckering and new suckers can

quickly re-colonize the burned area. Establishment of sexually regenerated aspen seedlings is less common, but can also occur after high-severity fire (Einspahr and Winton, 1976; Kreider and Yocom, 2021a; Kreider and Yocom, 2021b; Turner *et al.*, 2003). This leads to a paradox: aspen stands are considered less likely to burn than conifer stands, yet they can burn at high severity and thrive after high-severity fire.

Understanding the relationship between aspen and fire is interesting not only from a basic ecology perspective, but may also be critical in informing forest and fire management to modify fire activity. Interest has recently increased in forest management in the western U.S. to promote aspen stands around wildland-urban interface areas and areas with high ecological or cultural value (106 Reforestation, 2022; Schlageter *et al.*, 2020). Given the common assumption that quaking aspen stands reduce fire occurrence and fire behavior, and due to the management implications of aspen as “fire break” forests, we saw a need to synthesize available information about fire characteristics in aspen stands and which factors are most important in determining aspen’s potential ability to reduce fire risk. Specifically, we had three objectives: (1) review evidence for reduced fire occurrence, fire behavior, and fire severity in aspen stands and identify key factors that drive these patterns (see Table 1 for definitions); (2) conduct a survey of managers, ecologists, and firefighters to gather first-hand information on observed fire behavior in aspen forests; and (3) identify results that could lead to quantitative guidelines for managers interested in using aspen stands to reduce fire risk. We conclude our review with management recommendations and future research needs.

Table 1: Definitions of fire activity terms used in this review. Definitions are adapted from the National Wildfire Coordinating Group Glossary of Wildland Fire (PMS 205), the United States Department of Agriculture Fire Effects Information System Glossary, and the Canadian Wildland Fire Management Glossary (CIFFC Training Working Group, 2022).

Term	Definition
Fire occurrence	In this review, we use fire occurrence as a term that includes likelihood of fire, fire frequency, and area burned.
Fire likelihood	The probability of a fire occurring in an area of interest.
Fire frequency	The average number of fires that occur within a specified area and time period.
Area burned	The extent of the landscape that is burned by fire. Area burned can be reported in units of area (e.g., hectares) or as a percentage of area burned within an area of interest.
Fire behavior	The manner in which a fire spreads. Fire type (crown, surface, or ground), rate of spread, flame length, and fire intensity are common descriptions of fire behavior.
Fire severity	The effects of fire on vegetation and soils. Aboveground vegetation effects are usually described by the degree of scorch, consumption or mortality. Soil effects are usually described by the depth of burn (or char depth) or degree of organic matter consumed. Synonymous with burn severity in many of the papers reviewed.
	Descriptions of fire severity levels vary among studies, though most studies classify fire severity among three classes: low, moderate, and high severity. Some studies also describe an unburned fire severity category. In this review, high-severity fire indicates near-complete overstory mortality or high soil burn depth. Aspen suckering is not included as a fire severity metric (see Keeley, 2009).

## Methods

We conducted a literature review to assess the current understanding of how fuel type, amount, and moisture affect fire occurrence, behavior, and severity in aspen stands.

We searched the terms “aspen” and “*Populus tremuloides*” in combination with “fuel break,” “fire break,” “fuel characteristics,” “fire severity,” “fire intensity,” “fire occurrence,” “fire frequency,” “fire behavior,” “fuel model,” “prescribed burn or prescribed fire,” “understory or understorey,” “fuel succession,” and “fuel moisture.” We limited our review to *Populus tremuloides* because of its widespread occurrence and ecological importance in North American forests, and particularly because it is one of the

only deciduous trees in many fire-prone forested areas of western North America. Seven databases were used in our search: Google Scholar, Scopus, Proquest, TreeSearch, Utah State University's Aspen Bibliography, Fire Research Institute, and Frames.

In the review of each study or report, we first determined whether the paper was relevant to our review by scanning the abstract. If relevant, we then extracted applicable information. When available, we noted information about the study site (location, latitude and longitude coordinates, incident name of wildfire or prescribed burn), stand characteristics (forest type, overstory and understory characteristics, fuel loads), weather, season, and whether fire occurrence, fire behavior, or fire severity was considered. For each paper, we also determined whether there was evidence for an aspen-related factor being associated with decreasing, increasing, or no change in fire activity (Table 1). We were not able to conduct synthesis methods such as meta-analysis in this review due to the high variability in study designs, the inconsistency in reported measures of factors (such as stand attributes or site characteristics) and fire activity, and the variability in research rigor among studies (McKenzie and Brennan, 2022). However, we were interested in understanding generally how much evidence exists for various factors that might influence fire activity in aspen stands, so we noted any relationships between the specific condition of the factor (e.g., aspen-dominated overstory) and the reported effect (i.e., decrease, increase, or mixed effects in fire activity) for each study. In this part of the analysis, we excluded studies that did not report an effect of a factor on fuels or fire in aspen stands.

For each paper, we also classified the forest type(s) discussed in each study based on the authors' descriptions. We differentiated five forest types (pure aspen, aspen-

dominated, mixed aspen-conifer, conifer-dominated, and mixed aspen-hardwood) and a “general cover type” for studies that examined broad classes of land cover types over large spatial scales (Table 2). The aspen-dominated, mixed aspen-conifer, and conifer-dominated forest types refer to stands that included both aspen and conifer species. We acknowledge that ecological contexts and fire regimes differ widely across studies in this review; however, we were interested in understanding the aspen-fire relationship in the context of fire events in aspen forests, and were not focused on the nuance of natural fire regimes for particular aspen forests that studies discussed. Specific species discussed in papers are listed in the summary of studies table (Appendix C).

Table 2: Forest type classes discussed in 84 papers. Five forest types were classified: aspen-dominated, mixed aspen-conifer, conifer-dominated, pure aspen, and mixed aspen-hardwood. While some papers only focused on a single forest type, many papers discussed more than one forest type and are counted in multiple rows. The “general cover type” category refers to studies that were regional- or landscape-wide and defined more general forest cover classes. Five studies did not specify a forest type.

<b>Forest Type</b>	<b>N papers</b>
Aspen-dominated (with conifer)	35
Mixed aspen-conifer	28
Conifer-dominated (with aspen)	25
Pure aspen	14
General cover type	13
Mixed aspen-hardwood	8
Did not specify*	5

\*Includes Fisher (1986), Loomis and Roussopoulos (1978), Philpot (1969), Sando and Wick (1972), and Van Wagner (1977).

In addition, we conducted a survey of professionals with expertise in fire-aspen encounters to gather first-hand information on fire behavior in aspen stands. The survey (Appendix A) was implemented using the survey software Qualtrics (Provo, UT, last accessed 09-2021), and responses were gathered anonymously from November 2020

through March 2021. One major section of the survey asked respondents to recall fuel, weather, and fire characteristics during the most recent incident that they had observed fire interact with an aspen stand. Respondents who affirmed that they had observed fire moving into an aspen stand from a different cover type were asked what change (if any) in fire behavior they observed. Additionally, the survey asked respondents if they had observed fire interacting with aspen stands on multiple occasions or a single incident. Respondents who indicated that they had observed multiple fires in aspen stands were asked to estimate the percent of fires that stopped, decreased in intensity, did not change in fire behavior, or exhibited other behavior. Finally, respondents were asked to provide descriptions of fire behavior in aspen stands (i.e., fire type, spread, flame length, intensity). The survey was distributed through email, by contacting program managers and fire management officers who worked for U.S. federal and state agencies, fire science exchange networks, fire-focused nonprofit organizations, and university extension programs in the Intermountain West, Southwest, and Rocky Mountain regions.

### **Summary of literature reviewed**

A total of 84 studies were found to be relevant to our review (Appendix C). The papers reviewed cover most of the distribution of quaking aspen in North America, with a notably low number of studies in the Midwest and northeastern U.S. (Fig. 3). Most studies (n=45) were conducted in boreal forests in Alaska and Canada, 29 papers focused on the western U.S., 9 papers were focused on the Great Lakes region (1 of these studies included results from Massachusetts), and 1 paper discussed aspen stands in western North America more broadly.

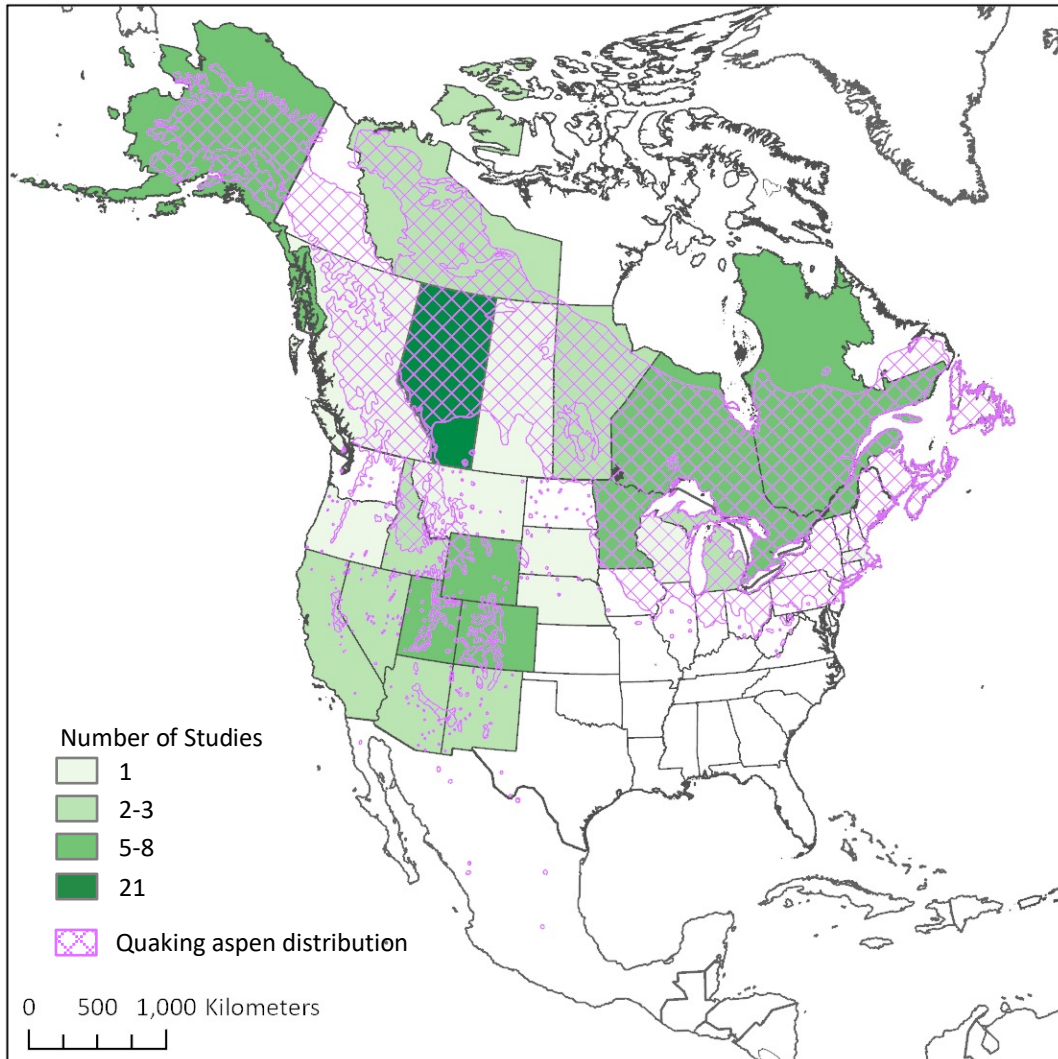


Figure 3: Location of studies in North America and geographic distribution of quaking aspen. The hue of shaded U.S. states and Canadian provinces indicates the number of studies located in that state or province. Forty-five studies were conducted in the boreal region (39 in Canada, 6 in Alaska), 29 studies in the western U.S. region, 9 studies in the U.S. Great Lakes region, and 1 study was broadly in western North America. Quaking aspen distribution map was downloaded from [databasin.org](http://databasin.org) (originally from Little, 1971).



Most papers (n=63) discussed factors (teal boxes, Fig. 1) in aspen forests that influenced fire activity attributes (beige boxes, Fig. 1). Of these, the most commonly studied fire activity attribute was fire behavior (n=37 papers), followed by fire severity (n=20 papers) and fire occurrence (n=20 papers; Table 3). Many papers discussed more than one fire activity attribute. Seventeen papers discussed one or more factors (teal boxes, Fig. 1) that influenced fuel characteristics (grey boxes, Fig. 1) in aspen forests, but did not specifically refer to any of the fire activity attributes (Table 4). Four papers did not specifically discuss factors or fire activity attributes in aspen stands. Of these, two papers discussed methods of planting aspen seedlings as a fuel break (Fisher, 1986; Johnson, 1975), and two papers measured crown fuels of aspen trees and conifer trees (Loomis and Roussopoulos, 1978; Sando and Wick, 1972).

Table 3: Number of papers that discussed factors (teal boxes, Fig. 1) that influenced three fire activity attributes (fire occurrence, fire behavior, and fire severity; beige boxes, Fig. 1). See Table 1 for definitions of fire activity terms. Many papers studied more than one fire attribute and/or factor and are counted in multiple rows or columns.

<b>Factor</b>	<b>Fire Occurrence (20 papers)</b>	<b>Fire Behavior (37 papers)</b>	<b>Fire Severity (20 papers)</b>
Overstory composition	18	29	14
Weather	9	18	3
Season	3	10	3
Grazing	2	5	-
Stand age	2	2	1
Edaphic characteristics	1	2	2
Stand structure	1	2	1
Slope	-	1	3
Aspect	-	-	2
Phenology	-	1	-
Stand density	-	-	1

Table 4: Number of papers that discussed factors (teal boxes, Fig. 1) that affected fuel characteristics (fuel type and load, fuel moisture; grey boxes, Fig. 1) in aspen stands. Papers summarized here did not specifically study any fire activity attribute. Many papers studied multiple factors or fuel characteristics and are counted in multiple rows.

<b>Factor</b>	<b>Fuel Type and Fuel Load (8 papers)</b>	<b>Fuel Moisture (11 papers)</b>
Overstory composition	5	2
Edaphic characteristics	2	6
Stand density	3	2*
Stand age	3	1*
Season	-	3
Phenology	-	3
Stand structure	-	3*
Weather	-	2
Slope	-	2
Aspect	-	1

\*Includes papers that measured microclimate attributes (e.g., wind speed, air temperature, soil temperature) in aspen stands (Chesterman and Stelfox, 1995; Powell and Bork, 2007). These microclimate attributes influence fuel moisture.

## Results and Discussion

### *Fire Occurrence*

As defined in Table 1, we used the term fire occurrence as an overarching term to include the likelihood of fire, fire frequency, and area burned. Several studies that compared pre-fire vegetation cover types with fire occurrence over large spatial or temporal scales found that aspen-dominated or mixed aspen-hardwood cover types were less likely to burn, had fewer fire ignitions, burned less frequently, or had less area burned than other forest types, particularly conifer forest types. This included studies in Alberta, Canada (Cumming, 2001; Krawchuk *et al.*, 2006); the Canadian Great Lakes-St. Lawrence region (Drever *et al.*, 2008); the interior western U.S. (DeByle *et al.*, 1987); and Colorado, U.S. (Ryan, 1976; also in Fechner and Barrows, 1976). Additionally, Alexander (2010) cited several studies that found lower fire occurrence and area burned in aspen stands compared to conifer stands in western and eastern Canada and northeast

and north-central U.S. (e.g., Haines *et al.* 1970, 1973, 1975, 1978; Tymstra *et al.*, 2005; Wein and Moore 1977). Another study of a single wildfire in northwest Colorado found that aspen stands were 200 times more likely to be classified as unburned than Englemann spruce-subalpine fir (*Picea engelmannii* Parry ex Engelm. - *Abies lasiocarpa* [Hook.] Nutt.) stands and 8 times more likely to be classified as unburned than lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands (Bigler *et al.*, 2005). The correlation between aspen stands and lower fire occurrence probability compared to conifer cover types was also demonstrated in a fire simulation modeling study in Alberta (Beverly *et al.*, 2009).

In contrast to studies that estimated extremely low annual burn rates or area burned in aspen-dominated forest types (i.e., DeByle *et al.*, 1987; Cumming, 2001; Ryan, 1976), two more recent studies conducted in aspen's northern range reported aspen stands burning at high rates (in Ontario, Canada from 1996-2006, Podur and Martell, 2009; in interior Alaska from 2001-2015, Wehmas, 2018). Another study in Alberta found that aspen-dominated forest types had higher fire frequency than white and black spruce forest types, though the author attributed this finding to the aspen stands being significantly farther from bodies of water (i.e., presumably had lower soil moisture) than conifer stands (Larsen, 1997). While the finding of aspen burning at high rates in the more recent studies (Podur and Martell, 2009; Wehmas, 2018) may indicate that there has been a shift in the influence of aspen on fire occurrence (perhaps due to a changing climate), there could also be other factors at play. For example, Podur and Martell (2009) noted that aspen forests were relatively rare in their study area (comprised 8% of the study area), whereas aspen forests comprised a greater proportion of the study areas in

the previous studies (~14% in Ryan, 1976 and 24% in Cumming, 2001). The patch size of each aspen stand could also be a complicating factor; a majority of the broadleaf patches in Wehmas' (2018) study were relatively small (<4 ha), so these stands may have been more easily overwhelmed by fires. We did not find any studies in this review that explicitly described the effect of landscape heterogeneity (*sensu* Turner and Gardner, 2015) on aspen forests that burned, and how that may affect fire occurrence; this presents an important research opportunity for future study. For example, across large landscapes, the size of an aspen stand could influence fire occurrence, especially when located adjacent to more flammable conifer-dominated stands. Because of aspen's widespread distribution this influence may vary by topography, climate, and geography.

The proportion of aspen in the overstory has also been noted to affect fire occurrence (i.e., Novák *et al.*, 2022), since aspen stands mixed with conifers have been observed to be more susceptible to burning or experience higher area burned than pure aspen stands or mixed aspen-hardwood stands (e.g., in Cumming, 2001 and DeByle *et al.*, 1987). In addition, higher conifer composition in aspen stands was associated with higher fire susceptibility and increased fire occurrence and size in modeling experiments (Beverly *et al.*, 2009; Drever *et al.*, 2008; Ouarmim *et al.*, 2016). However, the specific composition of overstory aspen in mixed aspen-conifer stands that translates into lower fire occurrence is uncertain and requires further research.

Finally, several studies noted that weather (primarily fuel moisture and wind) played a key role in determining fire occurrence and area burned in aspen stands. Studies largely concluded that aspen stands reduced fire frequency or area burned more during moderate weather conditions (Dash *et al.*, 2015; Wehmas, 2018). However, during

extreme fire years, aspen and conifer forests were found to have the same probability of carrying surface fire during extreme fire years in northern Canada (Dickinson and Johnson, 2003), and large areas of pure aspen and aspen-dominated stands were found to burn easily during two large wildfire events in Alberta (the Chisholm Fire in 2001, Ember Research Services Ltd., 2003; and the Lesser Slave Lake fire in 1968, Kiil and Grigel, 1969). Conversely, Cumming (2001) found that mixed aspen-hardwood stands burned less frequently and with less area in Alberta wildfires from 1961-1996, even during extreme fire years, and Krawchuk *et al.* (2006) found that the effect of forest composition was *stronger* in years with more severe fire weather, in which aspen-dominated stands continued to have fewer ignitions in Alberta wildfires from 1983-1993.

#### *Fire Occurrence Summary*

We found that overstory composition and weather were the most commonly discussed factors influencing fire occurrence in aspen stands (Fig. 4A). Purer aspen stands were largely associated with decreased fire occurrence (except see Larsen, 1997; Podur and Martell, 2009; Wehmas, 2018), while mixed aspen-conifer or conifer-dominated stands were associated with increased fire occurrence. In many studies, aspen-dominated stands were associated with decreased fire occurrence only during moderate weather conditions, while during extreme weather events, large areas of aspen-dominated stands were observed to burn (except see Cumming, 2001, Krawchuk *et al.*, 2006). Other factors influencing fire occurrence in aspen forests that were discussed included the age of a stand (mixed results whether young aspen stands were more likely or less likely to burn; Bigler *et al.*, 2005; Dickinson and Johnson, 2003), the presence of grazing (grazing reduced fire frequency; Baker, 1925; DeByle *et al.*, 1987), the presence of high duff or

soil moisture (higher duff or soil moisture reduced area burned or fire frequency; Larsen, 1997; Smith *et al.*, 1993), and the season the fire occurred in (fires were less likely in aspen stands during summer; Alexander, 2010).

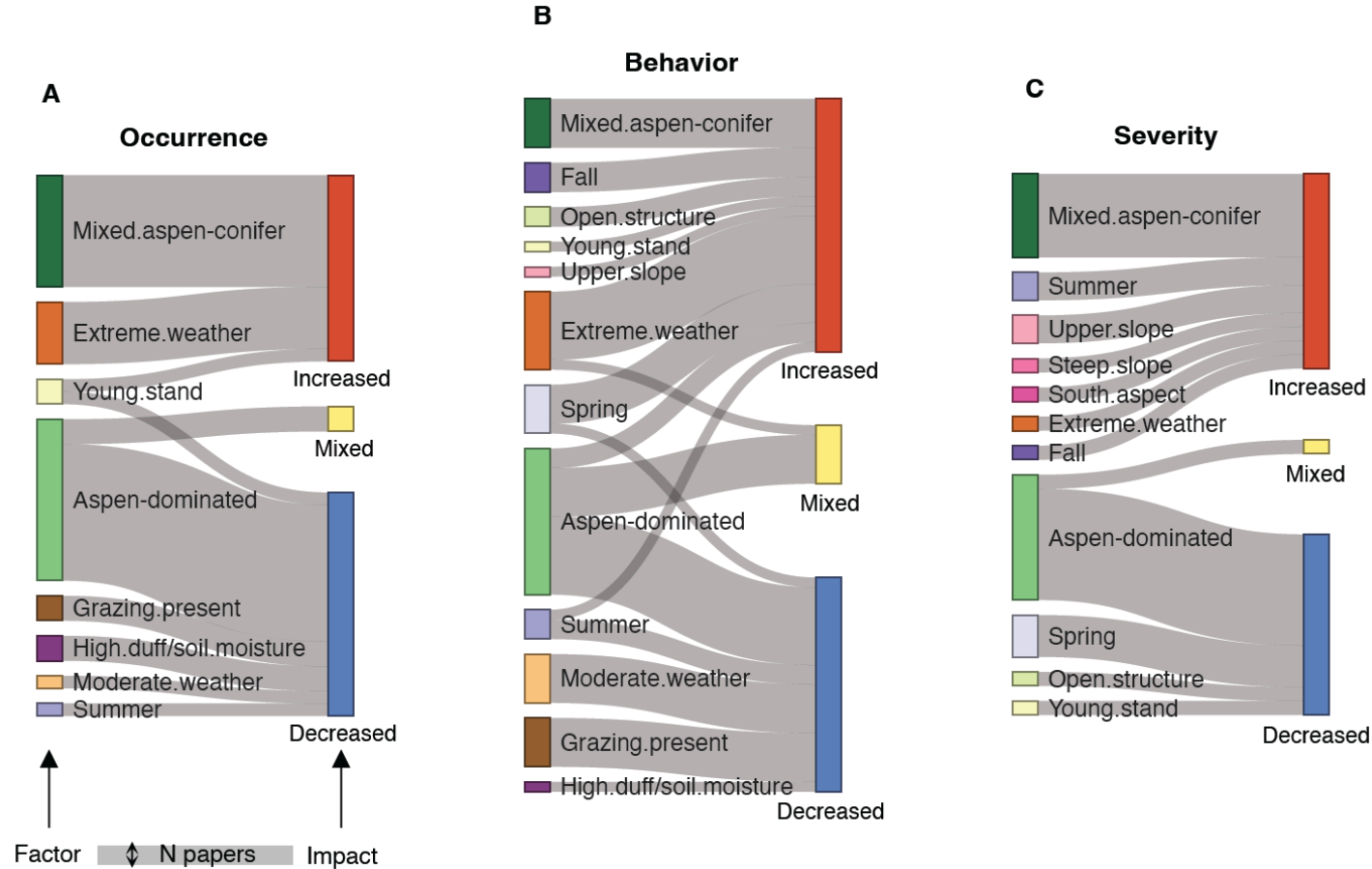


Figure 4: Sankey diagram of relationships between factors in aspen stands and fire occurrence, fire behavior, and fire severity that were discussed in the papers reviewed. The height of each colored bar and the height of the gray link bars are sized according to the number of papers (reference scale height is 1 paper) that specified how a factor (colored bars on left side of each panel) influenced fire occurrence (A), fire behavior (B), or fire severity (C). Fifty-five studies are represented in these diagrams; the other studies reviewed did not specify a particular factor (i.e., mixed aspen-conifer) or did not discuss how that factor affected fire activity (i.e., increased or decreased). Many papers discussed multiple factors or fire activity attributes and are included in multiple links (gray bars) or in multiple diagrams.

### *Fire Behavior*

Fire behavior (defined in Table 1) in aspen stands was addressed in 38 papers. Many studies attributed differences in fire spread and intensity among different forest types (i.e., overstory composition) to variability in fuel types and loads, which also may vary in terms of fuel moisture. The sections that follow describe differences between aspen-dominated and conifer-dominated stands in fuel types and loads of specific fuel components (i.e., live and dead vegetation, dead woody, litter and duff, and foliage) and fuel bed strata (i.e., surface fuels vs. canopy fuels).

### *Fire Behavior and Surface Fuels*

Pure aspen stands are often associated with high biomass of understory grass, herbaceous and shrub layers (Cavard *et al.*, 2011; Mueggler, 1985; Qian *et al.*, 2003), which may be due to factors such as greater understory light availability (Lieffers and Stadt, 1994) and increased water availability (LaMalfa and Ryle, 2007) when compared to conifer stands. Many studies reported that an accumulation of senesced, dry understory vegetation or dry, dead woody surface fuel in aspen forests led to fast-moving, high-intensity fires—particularly in combination with hot, windy, and dry conditions—in prescribed fires and wildfires (Alexander and Sando, 1989; Bailey and Anderson, 1980; Bartos and Mueggler, 1981; Baxter, 2003; Bradley *et al.*, 1992; Brown *et al.*, 1989; Brown and DeByle, 1989; Ember Research Services Ltd., 2003; Gordon, 1976; Jones and DeByle, 1985; Kiil and Grigel, 1969; Perala, 1974; Quintilio *et al.*, 1991; Simard *et al.*, 1983; Weber, 1990) and in modeling studies (Beales, 1998; Brown and Simmerman, 1986). While absolute values of moisture content have been shown to differ between species of grasses, forbs and shrubs, understory plants within aspen stands were observed



to follow typical seasonal trends in two studies, in which plants emerged with high moisture content in the spring then dried out over the season as they senesced (Brown *et al.*, 1989; Loomis *et al.*, 1979). Variability in moisture content of understory plants due to phenological changes has important implications for the variability and seasonality of fire behavior in aspen-dominated stands with understory vegetation as the primary fuel component (Alexander, 2010). Aspen forests exhibited higher rates of spread and fire intensity in spring or fall (when trees are leafless and understory vegetation is dead or dried) compared to summer (when trees are leafed out and understory vegetation is green) in modeling studies (Hély *et al.*, 2000, 2001) and prescribed fires (Perala, 1974). In several studies, aspen stands in summer had reduced wind speeds, increased shading, decreased air temperature, and increased relative humidity than stands in spring (Frederick, 1961; Kiil *et al.*, 1977; Marston, 1956; Wright and Beall, 1934); these characteristics are associated with lower fire intensity or spread. Several other studies noted that seasonality was important in determining fire behavior in aspen stands, though no empirical data was provided (e.g., Brown and DeByle, 1985; Brown *et al.*, 1989; Ember Research Services Ltd., 2003; Lieffers and Stadt, 1994).

While pure aspen stands have been associated with greater understory vegetation biomass, these types of stands also tend to have fewer small dead woody fuels (generally classified as <7.6 cm in diameter) than mixed aspen-conifer or conifer-dominated stands (Brown *et al.*, 1989; Brown and Simmerman, 1986; Hély *et al.*, 2000; Ouarmim *et al.*, 2016), which Brown and DeByle (1989) attributed to aspen crowns producing less fine-sized twigs compared to conifers. A lack of fine woody fuels in purer aspen stands may explain why aspen stands are often associated with decreased fire behavior compared to

conifer stands (Hély *et al.*, 2000), as fine woody fuels dry out quickly and are easily ignitable. However, aspen stands that have an accumulation of large woody fuels (generally >7.6 cm in diameter)—particularly in older pure aspen stands (Lee *et al.*, 1997; Beales, 1998) or in stands mixed with conifer (Bartos, 2007)—have been correlated with higher intensity fires and high flame lengths during fires (Bradley *et al.*, 1992; Brown and DeByle, 1989; Ember Research Services Ltd., 2003; Margolis and Farris, 2014; Quintilio *et al.*, 1991).

Overstory composition also affects the amount, quality, and type of litter, as well as the moisture content of litter and duff fuels. Hély *et al.* (2000) suggested that increased conifer composition in aspen stands should lead to less compact (i.e., more aerated) litter because of the inclusion of needles in the litter bed, leading to higher probability of fire spread and longer flame lengths. However, while one study found lower duff depths and higher bulk densities in pure aspen stands compared to mixed aspen-conifer stands in Alberta (Otway *et al.*, 2007b), two other studies found no difference in litter and duff load, depth, or bulk density between aspen-dominated stands and conifer stands in northern Minnesota, U.S. (Loomis, 1977) and in Quebec, Canada (Hély *et al.*, 2000). Litter and duff characteristics were also found to be highly variable in aspen stands depending on season (de Groot *et al.*, 2009) and understory vegetation type (Smith *et al.*, 1993). Finally, multiple studies demonstrated that aspen leaf litter decomposes faster than conifer needle litter, particularly in the first year (i.e., Prescott *et al.*, 2000; Prescott *et al.*, 2004; Preston *et al.*, 2000). Higher litter decomposition rates decrease the fuel bed depth, which decreases flame height (Varner *et al.*, 2015), so a higher rate of litter decomposition in aspen-dominated stands compared to conifer-dominated stands may

indicate a mechanism for reduced fire behavior in aspen-dominated stands.

While no clear trends in litter and duff load, depth, or bulk density between aspen and conifer stands was established, several studies found that pure aspen forests had high litter and duff moisture (e.g., Samran *et al.*, 1995; Otway *et al.*, 2007a); even higher than previous predictions by the Canadian Forest Fire Weather Index (Otway *et al.*, 2007b). High duff moisture was identified as a key factor in lowering the probability of fire ignition and spread in duff layers during ignition tests in one study (Otway *et al.*, 2007a). Additionally, while soil moisture content was found to be highly variable depending on site and weather conditions, there was evidence that aspen-dominated stands had higher soil moisture content than conifer-dominated stands in western Canada (Powell and Bork, 2007) and the interior western U.S. (Buck and St. Clair, 2012; LaMalfa and Ryle, 2008). Soil moisture content does not directly impact fire behavior, but it influences the moisture content of duff and litter layers, which impacts fire spread and intensity (Samran *et al.*, 1995), and is important in determining the species and amounts of associated vegetation (or lack thereof) within a forested area. The difference in soil moisture between aspen and conifer stands has been attributed to greater winter snowfall accumulation (LaMalfa and Ryle, 2008) and higher soil moisture retention due to the formation of a mollic horizon (enriched in organic matter) in the upper mineral soil (Bartos and Amacher, 1998) in aspen-dominated stands compared to conifer stands. Soil moisture also varies based on proximity to water sources, topography, and soil texture (Rogers *et al.*, 2014). Additionally, aspen have been found to exhibit hydraulic redistribution (or hydraulic lift), in which deeper soil water taken up by roots is passively released from shallower roots during low evaporative demand at night (Brown *et al.*, 2014; Depante *et al.*, 2019).

Hydraulic redistribution allows for the maintenance of increased soil moisture in upper soil layers during drought periods as well as provides water for understory vegetation; both of these factors may promote decreased fire behavior in aspen stands.

### *Fire Behavior and Canopy Fuels*

Attributes of canopy fuels—which affect crown fire behavior and wind speed through a stand (Andrews, 2012)—also differ between pure aspen and conifer stands, due to differences in tree form and branch and foliage size, retention, and distribution. Using species-specific allometric equations that relate tree diameter to crown biomass, aspen trees were found to have less branch and foliage weight than most conifer tree species (Brown, 1978; Jenkins *et al.*, 2003; Loomis and Roussopoulos, 1978; Sando and Wick, 1972). This indicates that aspen trees have fewer small diameter canopy fuels (foliage and branches) available to burn in a crown fire, which reduces the potential for crown fire spread. Aspen stands that have a conifer component may be more likely to spread crown fire, particularly in older mixed aspen-conifer stands, due to the increased crown fuel loading and vertical continuity of crown fuels from conifer trees (Thompson *et al.*, 2017). In addition, purer aspen stands were found to have lower canopy bulk density and higher canopy base height compared to stands with higher conifer composition in a study in northern Utah (DeRose and Leffler, 2014). As anticipated, the likelihood of crown fire spread was predicted to be less in aspen-dominated stands compared to conifer-dominated stands, and the likelihood of torching was less in stands with greater canopy base height (DeRose and Leffler, 2014).

In addition to having less available canopy fuel, less canopy bulk density, and greater canopy base height than conifer-dominated stands, aspen-dominated stands

appear to have overall greater foliar moisture content, at least during the late spring and throughout the summer. Aspen leaves had higher moisture content than conifer needles throughout the growing season in one study (Van Wagner, 1967); leaves emerged in the spring with about 250% moisture content, leveled off by early July to about 140%, and maintained high moisture even during leaf abscission in the fall (about 128-147%). Conversely, conifer foliage fluctuated around 100-115%, with the lowest moisture content in early spring (Van Wagner, 1967). Observations of high moisture content in aspen foliage led Van Wagner (1977) to note that "aspen stands do not crown" (p.31) in the development of crown fire initiation models and was indicated as a mechanism to explain the low-intensity fire behavior often observed in aspen-dominated stands during summer (Alexander, 2010; Alexander and Lanoville, 2004). One other study examined the effect of aspen leaf chemistry on fire behavior, though no relationships were found (i.e., flammable extractives in aspen leaves did not diminish ignition; Philpot, 1969).

#### *Fire Behavior and Other Factors*

As described in the previous sections, overstory composition in aspen stands is important in influencing fuel type, load, and moisture. These conditions have been shown to be highly variable depending on site and stand characteristics, which creates high variability of fire behavior in aspen stands (i.e., see Beales, 1998; Brown and Simmerman, 1986; Ember Research Services Ltd., 2003). However, the relative importance of fuels and weather in affecting fire behavior in aspen stands is uncertain. Several studies in this review noted that more extreme weather (drier fuels and greater wind speed) was necessary for fire to spread through pure aspen stands; under more moderate weather conditions, fires were observed to not spread at all or spread at a low

rate and intensity (Alexander and Sando, 1989; Brown and DeByle, 1989; Hinzman *et al.*, 2003; Quintilio *et al.*, 1991). In two modeling studies, extreme weather conditions were also predicted to result in high-intensity fire behavior in pure aspen stands (DeRose and Leffler, 2014; Crouse, 2005). These studies show support for the “weather hypothesis” (that weather has a greater effect on fire behavior than fuel; Bessie and Johnson, 1995). In contrast, the “fuels hypothesis” indicates that differences in fuel type and load in different cover types influences fire spread and intensity, even under extreme weather conditions. Evidence for this hypothesis in aspen forests was shown in a forest composition analysis of fires in western Canada (Cumming, 2001) and in an experimental crown fire initiated in a mixed-conifer stand in northern Canada that spread into an adjacent pure, fully leafed-out aspen stand and “dissipated into a slow moving, gentle, low-intensity surface fire” (Alexander and Lanoville, 2004, p.222).

The effects of stand age, density, or structure in aspen forests on fire behavior is uncertain and has not yet been well-studied. It is uncertain whether younger or older pure aspen stands have greater understory plant biomass (e.g., see Beales, 1998 and Lee *et al.*, 1995), and no differences in microclimate factors of wind speed, soil temperature, and air temperature were found in aspen stands of different ages (Chesterman and Stelfox, 1995). No studies were found that directly examined the impacts of an aspen stand’s age on fire behavior, however, Tepley and Veblen (2015) noted evidence for young aspen stands that initiated in 1878/79 acting as a fire break for a fire in 1899 in Colorado. Only one paper related aspen stand density to understory biomass, though did not specify how this may affect potential fire behavior (Woods *et al.*, 1982). The open stand structure of typical mature, pure aspen stands has also been related to higher midflame wind speeds when

compared to conifer-dominated stands (Norum, 1983; Ziegler *et al.*, 2020). Higher midflame wind speeds in addition to higher loads of understory vegetation in aspen-dominated stands with open stand structure could promote high spread rates, though this has not yet been demonstrated.

### *Fire Behavior Summary*

We found that overstory composition, weather, and season were the most commonly discussed factors influencing fire behavior in aspen stands (Fig. 4B). Variation in overstory species composition was associated with variation in surface fuel type (i.e., woody vs. live understory fuel), surface fuel load, litter and duff attributes, and canopy fuel attributes. While fuel characteristics were highly variable among aspen forests, aspen-dominated stands were generally associated with greater understory vegetation biomass, fewer fine dead woody fuels, less canopy bulk density, and higher canopy base height compared to stands mixed with conifer or dominated by conifers. These attributes generally resulted in lower-intensity fire behavior in aspen-dominated stands, especially during summer, when understory plants and aspen foliage had higher moisture content. High moisture content in aspen foliage and understory plants was commonly cited as a mechanism that reduces the likelihood of crown fire behavior in aspen-dominated stands (e.g., Alexander, 2010; Van Wagner, 1977). The season in which a fire occurred, and the weather during a fire, were key factors that explained why fast-spreading and high-intensity fire was observed in aspen forests in spring or fall (when aspen trees are leafless, understory vegetation has not yet emerged or has senesced and is dry, and litter layers are drier) and during extreme weather conditions. Additionally, while only discussed in a few papers, the presence of grazing or browsing was found to

reduce potential fire spread and intensity in pure aspen stands when herbaceous fuels were the primary fuel type (Beales, 1998; Brown and Simmerman, 1986; DeByle *et al.*, 1987; Jones and DeByle, 1985). Finally, there was limited evidence for the effects of stand characteristics (such as age, structure, and density) on fire behavior, and a quantitative amount of conifer trees within mixed aspen-conifer forests that resulted in higher-intensity fire behavior was unclear. Further research of how these stand characteristics influence fire behavior will be essential to inform aspen management decisions.

### *Fire Severity*

Several studies discussed the influence of aspen stands on fire severity (defined in Table 1). A majority of studies concluded that fire severity was greater in conifer-dominated stands compared to aspen-dominated stands, despite the fact that aspen trees are not fire-resistant. Only one study reported an explicit value of overstory composition that resulted in higher severity, in which aspen stands with just 25-50% of black spruce and balsam fir (*Abies balsamea* [L.] Mill.) resulted in fire severity levels similar to pure conifer stands (Carlson *et al.*, 2011). Four studies in Canadian boreal forests correlated pre-fire stand composition with fire severity and found that fire severity increased with increasing conifer composition and decreasing aspen composition (Carlson *et al.*, 2011; Leduc *et al.*, 2007; Wang, 2002; Whitman *et al.*, 2018). Similarly, several studies in the western U.S. anecdotally noted that mixed aspen-conifer stands tended to exhibit greater fire severity than pure aspen stands (e.g., in Bartos, 2007; Rogers *et al.*, 2014; Shinneman *et al.*, 2013), though there were no studies that provided quantitative evidence. In contrast, one study—a fire reconstruction in montane forests of Colorado—found that fire



severity was historically highest in aspen stands compared to conifer stands (Tepley and Veblen, 2015). They also observed multiple pure multi-cohort aspen stands in a portion of the study area, which were attributed to the presence of fires that burned at lower severity, allowing some aspen to survive and recruit into the overstory (Tepley and Veblen, 2015). Another explanation for multi-cohort aspen stands is that episodic regeneration occurs independent of fire disturbance, as has been suggested in other studies (e.g., Betters and Woods, 1981; Kurzel *et al.*, 2007; Rogers *et al.*, 2014).

The effect of other factors—including weather, topography, fuel moisture, season, stand structure, stand age, and surface fuel types—that influenced fire severity in aspen forests were discussed in only a few papers. The effect of extreme weather was shown to overwhelm the effect of aspen forest cover on fire severity in a spatially explicit modeling experiment in Alaskan boreal forests in which fire severity increased under extreme weather conditions in deciduous forest types (Johnstone *et al.*, 2011); this effect of extreme weather overwhelming other factors has been demonstrated in other studies and vegetation types (e.g., Bigler *et al.*, 2005). Consistent with our knowledge of how topography influences fire severity, aspen stands on steeper slopes (Brown and DeByle, 1987; Paragi *et al.*, 2007), on south-facing slopes (Paragi *et al.*, 2007), and on the upper topographic positions of slopes (Carlson *et al.*, 2011) were found to have longer char lengths on aspen boles and higher aboveground aspen mortality. Additionally, low moisture content in soil, litter, and fine dead fuels during prescribed fires (Bates *et al.*, 2006, de Groot *et al.*, 2009; Tucker and Jarvis, 1967; Weber, 1990) and wildfires (de Groot *et al.*, 2009; Kiil, 1970) was cited as a major factor that led to locally higher fire severity in aspen forests. Low moisture content was related to season in several of these

studies, though with mixed results regarding which season resulted in higher severity (Bates *et al.*, 2006; de Groot *et al.*, 2009; Weber, 1990). While evidence was limited regarding aspen stands in particular, stands with open structure (Whitman *et al.*, 2018) and younger stands (Bigler *et al.*, 2005) may be correlated with lower fire severity. Finally, an accumulation of large dead woody fuel was cited as a key contributor to locally high burn severity in litter and duff fuels in one prescribed fire study in aspen stands (Margolis and Farris, 2014).

### *Fire Severity Summary*

We found that overstory composition was the most commonly discussed factor that influenced fire severity in aspen stands, with fewer studies discussing the effects of topography, season, extreme weather, and stand structure or age on fire severity (Fig. 4C). A majority of studies found higher fire severity with increased conifer composition in aspen stands (except see Carlson *et al.*, 2011, Johnstone *et al.*, 2011, and Tepley and Veblen, 2015). However, the effects of topography, extreme weather, and season—all of which influence fuel moisture availability—may overwhelm the influence of aspen forests on fire severity. More research is needed to further assess the influence of stand characteristics (i.e., age, structure, and density) in aspen forests on fire severity.

### *Survey Results*

A total of 137 respondents completed the survey. Of these, 110 respondents completed the section that asked participants to recall stand, fuel, weather, and fire characteristics during the most recent incident that they had observed fire interact with aspen stands. Respondents were asked what type of fire behavior they had observed in

aspen stands (surface, torching, or crown) during this incident, and could select multiple options. In the results that follow, respondents who indicated they had only observed a surface fire were grouped into the *low-intensity* category, respondents who indicated that they had observed torching and/or crowning behavior in addition to observing a surface fire were grouped into the *mixed-intensity* category, and respondents who indicated that they had observed torching and/or crowning fire but did not observe a surface fire were grouped into the *high-intensity* category. Low-, mixed-, and high-intensity fire behavior was observed across all categories of overstory composition, fuel load, slope, season, and understory fuel type, illustrating the high variability of fire behavior in aspen stands (Fig. 5). While this variability could reflect recall bias, which can be common in survey research, a few patterns emerged. For instance, a greater number of respondents observed low-intensity fire behavior in pure aspen and aspen-dominated stands, in stands with low or moderate surface fuel load, in stands on mild slopes, and during fires in the spring and fall seasons. On the other hand, a greater percentage of respondents observed mixed- or high-intensity fire behavior in mixed aspen-conifer and conifer-dominated stands, in stands with heavy surface fuel load, in stands on moderate or steep slopes, and during fires in summer. There was not a clear pattern between the understory fuel type and observed fire behavior, with all fire intensities observed across all fuel types.

These attributes were similar to our findings from the scientific literature with a key difference: the attribute of season. Survey respondents observed more mixed- and high-intensity fire behavior during the summer, while the literature suggested that fire behavior in aspen stands was least intense during the summer. This may be explained by the type of incident (a prescribed fire or a wildfire) that survey respondents had observed;

a greater number of respondents observed high-intensity fire behavior during a wildfire incident, while only a few respondents observed high-intensity behavior during a prescribed fire incident (Appendix B). When the season in which respondents observed the fire incident was considered, a greater number of respondents reported that they had observed a wildfire in the summer (when weather conditions were likely more extreme), while prescribed fires (likely during less extreme weather conditions) were more often observed in the spring and fall seasons (Appendix B). Prescribed fires are often managed in aspen stands during spring or fall—before or after the growing season when canopy and surface vegetation is drier—and these types of fires are typically controlled to be low-intensity surface fires. This could explain why survey respondents observed lower-intensity fire in aspen stands during the spring and fall.

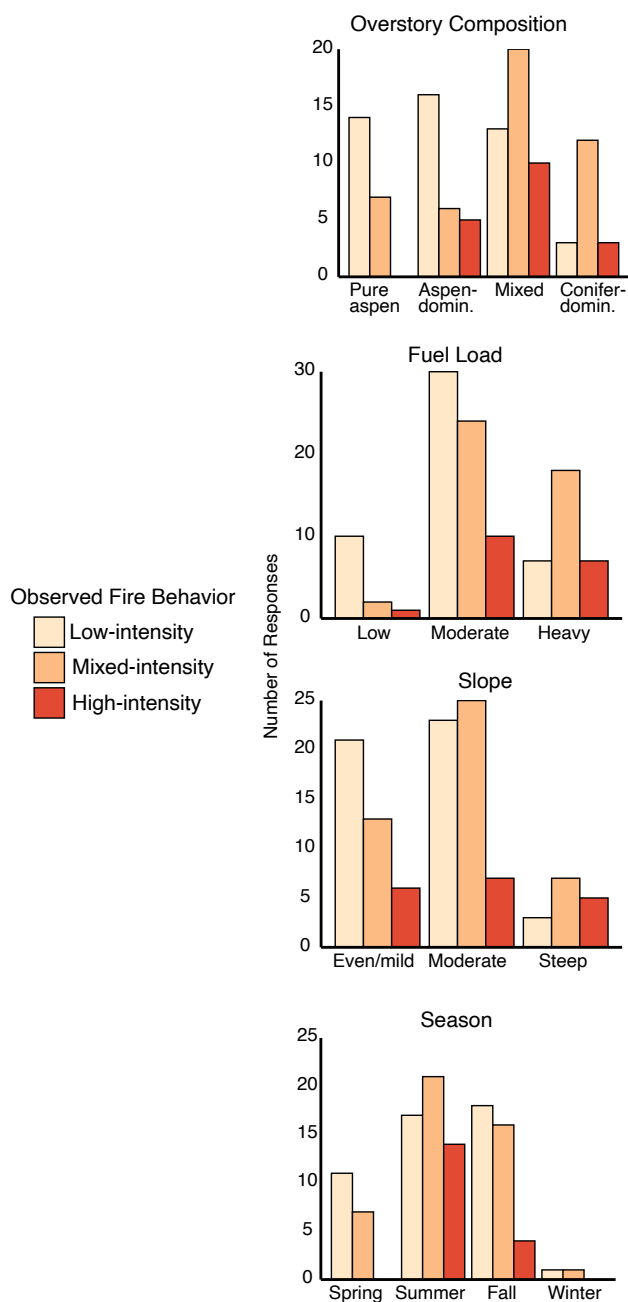


Figure 5: Observed fire behavior related to stand and site characteristics in a survey sent to fire and land managers. Respondents had to select one option per factor (x-axis categories). Respondents could select multiple options of observed fire behavior (surface, torching, or crowning); respondents who selected only surface fire are grouped into the low-intensity category, those who selected torching and/or crowning in addition to surface fire are grouped into the mixed-intensity category, and those who selected torching and/or crowning only are grouped in the high-intensity category. A total of 110 respondents completed this section of the survey.

Eighty-three respondents indicated that they had observed fire moving into an aspen stand from a different cover type. Of these, 63 noted that they had observed a decrease in fire intensity, 11 noted that they had observed an increase in fire intensity, and 9 noted that they had observed no change in fire intensity (Fig. 6A). One-hundred-and-eight respondents indicated that they had observed multiple fire incidents in aspen stands across their careers and provided rough estimates of the percentage of fires that either: (1) stopped upon entering an aspen stand, (2) decreased in intensity, (3) did not change in fire behavior, or (4) exhibited other fire behavior. Many of the respondents who input a percentage in the “other” category clarified that they had observed an increase in fire intensity. Of the 108 respondents who observed multiple fires in aspen stands, 76 managers observed that a majority ( $\geq 50\%$ ) of fires decreased in intensity when they encountered an aspen stand, 15 managers observed that a majority of fires stopped, 7 managers observed that a majority of fires exhibited other changes in fire behavior (mostly increased intensity), and 7 managers observed that a majority of fires exhibited no change in fire behavior (Fig. 6B). While greater numbers of respondents reported decreased fire intensity after fire moved into an aspen stand during a single fire or across multiple fires, the fact that a small number of respondents reported increased intensity or no change in fire behavior reflects the variability of observed fire behavior in aspen forests, and that aspen stands do not always reduce fire intensity.

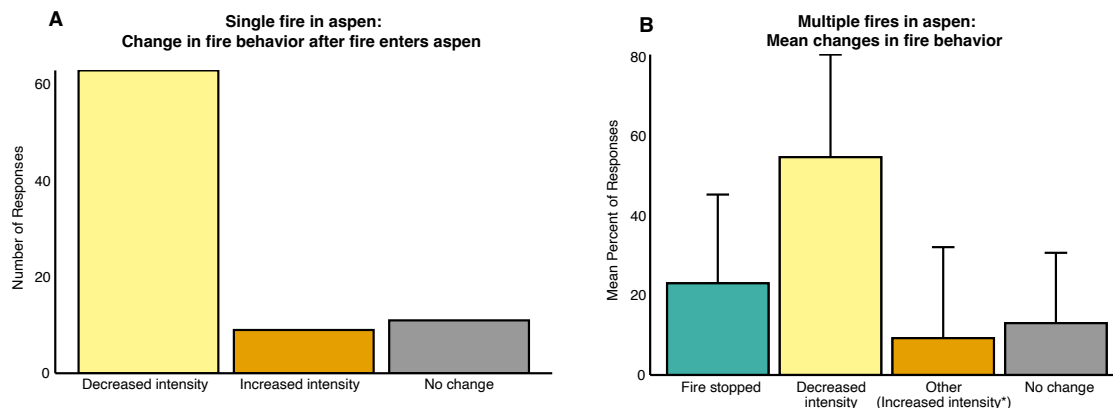


Figure 6: Reported changes in fire behavior observed by fire and land managers in the survey. (A) Observed changes in fire behavior from respondents who observed fire entering an aspen stand from a different cover type (83 total responses). (B) Observed fire behavior from respondents who indicated that they had observed multiple fires (>2 fires) in aspen stands over their careers (108 total responses). The number of respondents who indicated that they had observed  $\geq 50\%$  of fires in aspen stands in each category are depicted. \*Respondents who selected the “other” category could clarify via a text fill-in option; many of these respondents indicated that they had observed increased intensity.

In open-ended questions, respondents overwhelmingly described the complexity of fire behavior in aspen stands. Many respondents referred specifically to weather conditions, season, understory fuel conditions, overstory composition, stand type, and fuel moisture as important factors in the likelihood of an aspen stand burning or determining fire behavior in aspen stands. Respondents mentioned that fire behavior in aspen stands was “highly variable,” and that aspen stands were not “end-all solve-all fire breaks,” highlighting the complexity of this issue and interpretation of qualitative responses. Importantly, at least four respondents emphasized that fire behavior in aspen stands has changed over the last few decades, noting that “aspen is not so much a fire break as it used to be,” “fire activity has increased in aspen stands [over the last decade],” “fires do not seem to ‘hang up’ in aspen as much as they used to,” and that aspen is not as much of a “heat sink” as in past decades. These observations of the potential implications

of changing future fire conditions in aspen forests are interesting and warrant further research.

### **Synthesis**

While we found evidence for reduced fire occurrence, fire behavior, and fire severity in aspen stands, we also consistently found complex relationships among the factors reviewed and fire activity in aspen stands. Aspen stands inhabit a wide range of geographic, environmental, and climatic conditions, existing in both pure stands of variable density or with a variety of other overstory and understory species, and are characterized by huge variability in natural fire regimes (Nlungu-Kweta *et al.*, 2017; Shinneman *et al.*, 2013). Not surprisingly, the claim that aspen stands are firebreak or “asbestos” forests (DeByle *et al.*, 1987, p. 75) is too general, and more specificity on site and stand characteristics, and their relative influences on fire, is needed. Managers who responded to the survey reiterated this point, indicating that conditions in aspen stands were highly heterogeneous, and expressed that the specifics of these characteristics (i.e., species composition, stand age, understory fuel type, or understory fuel load) influenced the degree of fire behavior or severity.

#### *Fire behavior modeling in aspen*

While there have been numerous observations of crown fires in forests adjacent to aspen stands dropping to the ground when they encounter aspen, a common method of studying crown fire behavior is through fire behavior modeling. An important assumption in the algorithm used to model crown fire behavior in North American forests is that “aspen stands do not crown” (Van Wagner, 1977, p. 31). Models that predict crown fire



spread in the U.S. and Canada use Van Wagner's (1977) crown fire initiation and spread equations; these equations were specifically developed for conifer forests, as Van Wagner noted that "in Canada only conifer forests support crown fire" (p. 30). Observations of high-intensity crown fire behavior in aspen stands, while rare, have been noted, so further research of crown fire potential in aspen stands is needed to evaluate the use of Van Wagner's model in aspen. For example, future research could explore under what specific conditions (i.e., extreme weather conditions or adjacent vegetation) crown fires spread through pure aspen stands.

Fire behavior models are also used to predict surface fire spread, which require users to input a representative fuel model. Models require users to choose among a finite amount of fuel models that may not always accurately reflect of the complexity within that system. Additionally, models used in the U.S. and in Canada differ in how fuel types are represented. The surface fire model used in Canada (as well as boreal forests in Alaska)—the Canadian Forest Fire Behavior Prediction System (FBP)—specifies 18 fuel types common to the boreal forest system, based on overstory species composition. These fuel types include 4 that represent a range of aspen (and other deciduous trees) composition, from pure aspen to mixed aspen-conifer forests (Forestry Canada Fire Danger Group, 1992). Surface fire spread models in the U.S., on the other hand, use a defined set of 53 standard fuel models (Anderson, 1982; Scott and Burgan, 2005) that do not explicitly specify overstory species composition. Therefore, it is often unclear which U.S. fuel model best represents aspen stands, considering the variety of conditions in which they exist. To address this issue, Brown and Simmerman (1986) developed a fuel model guide specifically for western U.S. aspen stands that differentiated between aspen-

dominated and mixed aspen-conifer stands. However, Brown and Simmerman's (1986) aspen fuel models have not yet been fully incorporated into many U.S. fire behavior models. Developing and including fuel types that better represent aspen stands in U.S. fire behavior models is advised in order to increase the accuracy of fire behavior predictions. Including Brown and Simmerman's (1986) aspen fuel models in fire behavior models used in the U.S. could achieve this, though further validation of these fuel models is needed, particularly to assess the validity of the models to aspen forests outside of the U.S. Intermountain West, where the empirical studies to develop the model were conducted.

#### *Quaking aspen fire regimes: past, present, and future*

The differences in aspen forest types and fire regimes across aspen's distribution have important implications for when, where, and how fire interacts with aspen (Nlungu-Kweta *et al.*, 2017; Shinneman *et al.*, 2013). Aspen forests across North America have distinct differences in species composition, stand structure, physical environment (e.g., topography, climate, hydrology, and soils), and disturbance regimes (Rogers *et al.*, 2014). Boreal (northern latitudes in Canada and Alaska) and montane (montane western U.S.) aspen forests, specifically, have been noted to have disturbance regimes dominated by mixed-severity and stand-replacing fire, depending on the amount of conifer present in the overstory (Flannigan *et al.*, 2001; Kulakowski *et al.*, 2004; Stocks *et al.*, 2002). Western boreal forests tend to have higher fire frequency than eastern boreal forests (Kneeshaw and Gauthier, 2003). However, in "stable aspen," fire was not identified as the dominant disturbance regime (Rogers *et al.*, 2014). It is likely, though, that stable aspen types also support fire under specific—though uncommon—conditions, either at

very long return intervals (Morris *et al.*, 2019; Whitlock *et al.*, 2010), or at low intensity (Novák *et al.*, 2022).

Fire regimes in aspen forests have changed since European and Euro-American settlement, and will continue to change with increasing human activity and a warming climate. The current distribution of aspen-dominated stands in western North America has been attributed to the period of early Euro-American settlement, in which there was an increase in ignition sources (Kashian *et al.*, 2007; Kulakowski *et al.*, 2004; Rogers *et al.*, 2011; Wadleigh and Jenkins, 1996; Zier and Baker, 2006). Reconstructions and sediment core studies in aspen forests have additionally indicated that historical stand-replacing fires due to lightning ignitions during droughts created large expanses of aspen-dominated forest before Euro-American settlement (Margolis *et al.*, 2007; Carter *et al.*, 2017). In western forests in the twentieth century, however, fire suppression, herbivory, and elevated climatic moisture—all favoring successional replacement by conifers, particularly in western aspen forests—led to a shift towards conifer dominance (Jones and DeByle, 1985; Kay, 1997; Rogers *et al.*, 2020). This shift towards conifer dominance, in combination with current warming and drying climates, has resulted in conditions in which stands in some areas are now at risk of both higher intensity and higher severity fires (Bartos, 2007; Morris *et al.*, 2019).

An increase in fire frequency, fire severity, and area burned across western North America has been projected to result from climate change (Westerling *et al.*, 2006). The effect of changing fire regimes on future fire conditions and on the extent of deciduous and coniferous forests is uncertain, and will differ by geographical region (Morelli and Carr, 2011). Several studies have suggested that increased fire frequency and fire severity

will increase the extent of deciduous forest types in North America (e.g., Chen *et al.*, 2009; Foster *et al.*, 2022; Hansen *et al.*, 2021; Johnstone *et al.*, 2011; Kulakowski *et al.*, 2013; Mekonnen *et al.*, 2019; Terrier *et al.*, 2013). A few studies have concluded that an increase in deciduous forest cover would act as a negative feedback on increased fire activity (e.g., Johnstone *et al.*, 2011; Terrier *et al.*, 2013; Foster *et al.*, 2022): however, these studies relied on the assumption that aspen forests were less flammable than other forest types. Our review found that conditions in aspen forests are highly variable, leading to high variability of flammability in aspen forests. Furthermore, we found evidence for extreme weather conditions overwhelming the relative effects of low flammability aspen fuel types, in which pure aspen forests burned intensely and severely during extreme weather (e.g., Foster *et al.*, 2022; Johnstone *et al.*, 2011; Terrier *et al.*, 2013). This is an example of top-down (i.e., climate) control of fire regimes overriding the effect of bottom-up (i.e., fuel) controls (*sensu* Turner and Gardner, 2015). The relative influence of bottom-up vs. top-down controls on aspen fire regimes likely varies in time and space (Whitlock *et al.*, 2010), but is an area of research requiring further investigation. Other studies have concluded that an increase in deciduous forest cover would not decrease future fire frequency and severity due to increased frequency of extreme weather under future climate (e.g., Hart *et al.*, 2019; Krawchuk and Cumming, 2011; Wehmas, 2018). This was mirrored by survey respondents, in which several managers indicated that they have observed an increase in fire occurrence, frequency and intensity in aspen stands in the last few decades, attributing this change to changing climate conditions (i.e., more drought) in the western U.S.

### *Aspen and fire around the world*

We focused our review on quaking aspen due to aspen's widespread occurrence and ecological importance in North American forests, as well as the common perception of the species being an "asbestos" forest type in western North America. In our original literature search, we found one paper written in English that discussed fire behavior in European or Eurasian aspen, though this study was primarily focused on fire effects on tree regeneration and did not discuss aspen's influence on fire behavior (Ascoli *et al.*, 2006). European aspen is widespread throughout the European and Asian continents and its autecological and phenological characteristics are similar to quaking aspen, so it may be reasonable to assume that it has a similar relationship to fire, at least under certain environmental conditions. Searching for additional literature that addresses fire activity in other aspen species around the world (*sensu* Rogers *et al.*, 2020) would enhance our understanding of fire susceptibility in aspen.

### *Management implications and areas of future research*

One objective of our review was to identify results that could lead to quantitative guidelines for managers interested in using aspen stands to reduce fire risk (e.g., near structures or other high-value areas). In this aim, and in consideration of the available literature, we identified one primary commonality that can inform management actions immediately. Specifically, pure aspen and aspen-dominated stands were likely to reduce fire behavior, fire occurrence, and fire severity, except in the most severe weather conditions (Fig. 4). The change in fire activity in aspen-dominated stands appeared to be driven by the indirect control of the aspen overstory on understory fuel and moisture conditions (Fig. 1), which can also be altered by management. Both the literature and

managers who responded to the survey suggested that pure aspen or aspen-dominated stands, particularly stands with understories consisting of live, green vegetation, were more likely to reduce fire spread and fire intensity. Promoting aspen-dominated stands may not be a viable management action in regions where aspen does not achieve canopy dominance. Secondly, seasonality in the timing of burning must be considered, as reduced moisture content in aspen leaves and understory vegetation in the spring and fall may promote higher intensity or severity fires. As with any type of fuel treatment, continued reduction of accumulating fuel loads and fuel continuity is required to maintain function (Fechner and Barrows, 1976; Ember Research Services Ltd., 2003). Thus, as is true for most fuel treatments, using aspen stands as a fuel treatment should be viewed as increasing the *probability* of slowing, diminishing, or inhibiting fire, but the effectiveness of this fuel treatment may be greatly reduced under certain seasonal, windy, or dry conditions. Further research on the effects of aspen forest patch size, adjacent vegetation, and topographical features on fire occurrence, fire behavior, and fire severity remain a key knowledge gap. Additionally, the effects of aspen stand age, structure, and density warrant further research in order to understand the types of aspen stands that are more likely to reduce fire activity. Looking forward, there is a need for research on how fire activity in aspen may change in the future with a changing climate (*sensu* Yang *et al.*, 2015).

Another important consideration for management is the scale at which aspen forests may reduce fire activity. In many of the landscape-wide fire occurrence studies reviewed here (e.g., Cumming, 2001; DeByle *et al.*, 1987; Krawchuk *et al.*, 2006; Ryan, 1976), aspen forest types were associated with decreased fire occurrence when compared

to conifer forest types. Similar findings have been demonstrated for broader classes of deciduous forest types in interior Alaska forests (Barrett and Kasischke, 2013; Kasischke and Hoy, 2012) and across North America as a whole (Pu *et al.*, 2007). Further research in other geographical regions, in particular those that were underrepresented or not represented in our review such as northeastern and midwestern U.S. (Fig. 3), and over different time periods (especially over more recent decades) would be valuable (e.g., see Podur and Martell, 2009 and Wehmas, 2018, who both found high rates of aspen burning). These findings could be important for managers who are interested in implementing fuel treatments at the landscape scale, for example, promoting aspen forests in “strategically placed landscape area treatments” (i.e., SPLATs; Finney *et al.*, 2001; Tubbesing, 2019; McKinney *et al.*, 2022).

Finally, we propose a mechanistic pathway for how flammability may be affected in aspen stands based on overstory composition, fuel moisture, surface fuel type ratio (ratio of live to dead fuels), and canopy fuel load. Under average climatic moisture conditions and with typical understory fuel types, pure aspen stands tend to have low flammability due to high moisture in foliage and live understory vegetation, a greater proportion of live-to-dead surface fuels, and low canopy fuel load. Under the same average climatic conditions, conifer stands tend to have higher flammability due to lower fuel moisture, a greater proportion of dead surface fuels, and higher canopy fuel load. With increasingly dry conditions (or during seasons before or after green-up), flammability of all forest types increases, though the literature suggests that unusually hot, windy, and dry conditions are necessary to cause a pure aspen stand to become highly flammable. Given that climate is warming and drying, better understanding of how

fire interacts with aspen stands under different climate scenarios is needed. Integrating this understanding with clear and prescriptive methods of how stand and site characteristics in aspen stands affect aspen's susceptibility to fire would improve understanding of the aspen-fire relationship and would benefit managers interested in using aspen stands as a fire risk reduction method.

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## CHAPTER 3

STAND COMPOSITION AND DEVELOPMENT STAGE AFFECT FLAMMABILITY  
OF QUAKING ASPEN FORESTS IN UTAH, USA**Abstract**

In western North American forests, quaking aspen stands (*Populus tremuloides* Michx.) have long been described as low flammability, “fireproof” forest types, even though paradoxically, aspen regenerates vigorously after fire and in some cases requires high-severity disturbance to successfully regenerate. A better understanding of how specific aspen site and stand characteristics may influence fire behavior is needed. We investigated surface and canopy fuel characteristics in 80 aspen stands in Utah, U.S. that spanned gradients of tree species composition from aspen to conifer dominance and stand development stage from early to late development. Fuel type, load, and moisture content were measured, and a value representing the overall flammability of surface fuels in different aspen forest types (called a ‘weighted moisture content’) was calculated for each stand. High variability of fuel type and load was observed across stands, though late development, conifer-dominated stands had significantly higher loads of fine dead fuels (~5 times higher litter and ~2 times higher woody 1-h fuel load in one study area) and significantly lower loads of live understory vegetation (~2 times lower grass and ~5 times lower forb load) compared to pure aspen stands. Fuel moisture content did not vary among stands; however, the differences in load of specific fuel components among stand types led to significant differences in weighted moisture content, in which in one study area, pure, late development aspen stands had 48-104% higher weighted moisture content than mixed aspen-conifer stands. In addition, weighted moisture content decreased

through the growing season, particularly in pure aspen stands that had high understory vegetation load and low fine dead fuel load. Results from this study provide evidence for lower seasonal flammability of pure, late development aspen stands under certain surface fuel conditions, though also highlight the high variability of combustible elements within aspen forests.

## **Introduction**

Quaking aspen (*Populus tremuloides* Michx.) is ecologically important throughout its wide range in North America and is particularly valued in the Intermountain West because it is one of the only deciduous tree species in montane environments and supports many ecosystem services (DeByle and Winokur, 1985; Perala, 1990; Kuhn *et al.*, 2011;). In addition, western aspen forests have been anecdotally characterized as “asbestos” (DeByle *et al.*, 1987, p. 75) or “firebreak” forest types, meaning that fires in adjacent conifer stands have been observed to slow or extinguish upon entering an aspen forest (Fechner and Barrows, 1976; Jones and DeByle, 1985; Alexander and Lanoville, 2004). During prescribed fires, aspen stands have been noted to be difficult to burn due to the prevalence of live (i.e., moist) understory vegetation, sparseness of fine dead (i.e., dry) fuels, and/or high moisture content in aspen foliage (Bailey and Anderson, 1980; Jones and DeByle, 1985; Brown and Simmerman, 1986; Brown and DeByle, 1987; Brown *et al.*, 1989). However, fires have been observed in aspen, including at high intensity and high severity (i.e., Kiil and Grigel, 1969; Quintilio *et al.*, 1991; Tepley and Veblen, 2015), which challenges the “common knowledge” that aspen stands inhibit fire. To date, the scientific literature is mixed regarding aspen’s influence on fire, in part due to the great variability in site and

stand characteristics of aspen continentally (Rogers *et al.*, 2014), and there is a need for empirical research of fire-related characteristics in aspen stands (Nesbit *et al.*, 2023).

Wildlands have different types of fuel (combustible live and dead plant components) of various sizes, loads, moistures, and spatial arrangements. These fuel characteristics vary among vegetation types due to differences in flammability-related plant traits, vegetation composition and structure, and season (Bowman *et al.*, 2014). Traits of aspen trees, such as tree architecture and leaf moisture content, have been proposed as mechanisms that reduce the probability of crown fire in which mature aspen trees have low canopy bulk density, high canopy base height, and high leaf moisture content (Van Wagner, 1977; Brown, 1978; DeRose and Leffler, 2014;). Surface and ladder fuel conditions within aspen stands have also been shown to vary depending on tree species composition. Pure aspen forests are typically associated high loads of understory vegetation and few fine woody fuels (Mueggler, 1985; Qian *et al.*, 2003; Cavard *et al.*, 2011) and with rapid decomposition of aspen leaf litter (Prescott *et al.*, 2000; Preston *et al.*, 2000; Prescott *et al.*, 2004), while aspen forests that are mixed with conifers have higher fine woody fuel load, a more aerated litter bed, and greater canopy bulk density and vertical continuity (Hély *et al.*, 2000; DeRose and Leffler, 2014). These traits of mixed aspen-conifer forests lend themselves to increased fire intensity and spread.

Fuel type (i.e., live or dead, herbaceous or woody) is intrinsically tied to moisture content, and fuel moisture content is considered a critical factor that influences fire ignition and propagation (Rothermel *et al.*, 1986). Several studies have demonstrated differences in microclimate and fuel moisture between deciduous and

coniferous forests (e.g., Pinto and Fernandes, 2014; Schunk *et al.*, 2017), but to our knowledge no studies on fuel moisture have been conducted in aspen compared to conifer forests. In addition, the seasonality of fire behavior in aspen forests is an important consideration, due to phenological changes in aspen trees and associated understory vegetation that results in varying moisture conditions seasonally (Alexander, 2010). Higher fire occurrence, intensity, and rate of spread has been modeled and observed in aspen stands in spring and fall—when leaves, understory vegetation, and litter are senesced or dry—compared to summer (Perala, 1974; Hély *et al.*, 2000, 2001). Most studies that investigate the influence of fuel moisture on fire behavior typically only focus on dead fuel moisture (particularly fine dead fuels such as litter and small-sized wood particles), while moisture content of live fuels (leaves and needles of trees, shrubs, forbs, and grasses) and its effect on fire behavior has not been as well-studied, but are likely a very important component affecting fire behavior (Countryman, 1974; Finney *et al.*, 2013; Rossa *et al.*, 2016).

Because natural fuel beds are inherently complex and include a variety of dead and live fuels, there is a need to characterize the ratio of live to dead fuels and their associated moisture content in the field to assess the flammability of different vegetation types more completely. Several laboratory experimental studies have been conducted to predict fire behavior in more realistic fuel beds and have proposed an empirical model, called a weighted or composite fuel moisture content equation, that accounts for different ratios of live and dead fuels (Viegas *et al.*, 2013; Rossa, 2017; Rossa and Fernandes, 2017). This model has been applied in simple fuel beds consisting of one live and one dead fuel component (Viegas *et al.*, 2013), live shrub and litter fuels

(Marino *et al.*, 2012), litter and quasi-live tree branch fuels (Rossa and Fernandes, 2017), and live and dead grass fuels (Hoffa *et al.*, 1999). To our knowledge, applying the weighted moisture content in more complex fuel beds with several live and dead fuel components in the field has not yet been conducted.

The objective of this study was to investigate differences in flammability characteristics in aspen stands along two gradients: tree species composition from aspen to conifer dominance and development from early to late stage. Specifically, we examined patterns in (1) surface fuel load, (2) canopy characteristics, and (3) fuel moisture content across 80 aspen stands in Utah along both gradients. We calculated the weighted moisture content of each stand to describe stand flammability and compared weighted moisture content among stand types. Assessing how stand characteristics alter flammability in western aspen forests will provide crucial evidence for the potential mechanisms underlying the influence of aspen forests on fire behavior.

## **Methods**

### *Study area*

We had two study areas; one was in central-east Utah in the Tavaputs Plateau region (hereafter, Tavaputs) on private land and the other was in northern Utah in the Bear River Mountain Range (hereafter, Bear Rivers) on the Uinta-Wasatch-Cache National Forest (Fig. 7). Elevation at plots in the study areas ranged from 2600 to 3043 m in the Tavaputs and from 1903 to 2550 m in the Bear Rivers. Annual precipitation in the Tavaputs study area averages 564 mm and follows a bimodal distribution, with higher precipitation falling in early spring (March) and autumn (September and October), while annual precipitation in the Bear Rivers study area averages 652 mm and falls primarily

during the winter (PRISM Climate Group, 2022). Both study areas cover a wide range of daily temperature means, ranging from approximately -5°C in January to 18.5°C in July (PRISM Climate Group, 2022). Forested stands in both study areas range in composition from pure aspen to conifer-dominated. Conifer species include subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex. Engel.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Mirb.] Franco), and lodgepole pine (only in Bear Rivers; *Pinus contorta* Dougl. ex. Loud.). Grazing and browsing pressure—which affects the load, height, and continuity of herbaceous fuel (Strand *et al.*, 2014)—differs between the two study areas. In the Tavaputs, grazing and browsing pressure is primarily from wild horses, deer, and elk, but specific numbers and timing of animals is difficult to quantify. In the Bear Rivers, grazing and browsing pressure is primarily from domestic livestock, as well as deer and elk. All of the stands selected in the Bear Rivers were located in a grazing allotment, but only 38% of the plots were likely grazed by cattle (7.5% of plots; ~550-1000 animals) or sheep (30% of plots; ~700-1200 animals) prior to data collection.

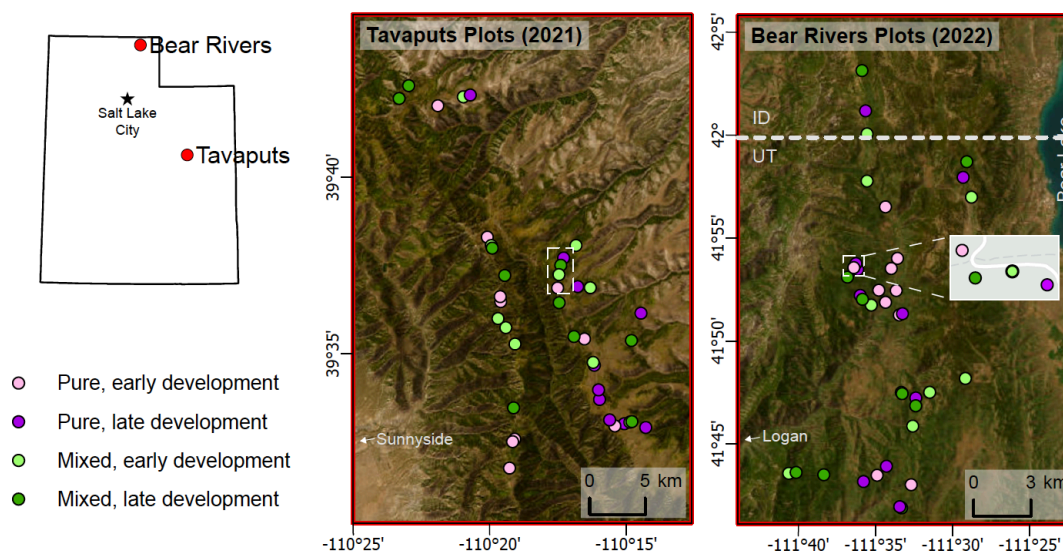


Figure 7: Map of plots at two study areas in Utah, color coded by aspen composition and development stage. Eighty plots were surveyed across the two study areas (40 in each). Dashed white boxes indicate the plots in which fuel moisture content was measured.

### *Stand selection*

To select representative stands along gradients of species composition and development stage, we classified stands into four categories (i.e., stand types). These stand types included: (1) pure aspen, early development; (2) pure aspen, late development; (3) mixed aspen-conifer, early development; and (4) mixed aspen-conifer, late development. In part, these stand types were intended to characterize compositional changes as would be expected under the typical succession model for seral aspen types (Bartos *et al.*, 1983). Pure, early development stands had lower quadratic mean diameter, higher understory aspen (trees <10 cm diameter at breast height [DBH]) basal area, and lower mean height than pure, late development stands (Table D.1). Mixed, early development stands were characterized by mature overstory aspen trees (> 10 cm DBH) with shorter, sub-dominant conifer trees, had high relative stand density indices, and

ranged in composition from 30 to 100% aspen (Table D.1). Mixed, late development stands were characterized by co-dominant aspen and conifer trees, high relative stand density indices, and ranged in composition from 0 to 45% aspen (Table D.1). Mixed aspen-conifer stands could have 0% or 100% aspen composition because overall stand composition was defined only for the live trees greater than 1.37 m in height (i.e., mixed stands characterized by 0% aspen had standing dead aspen trees in the plot, and mixed stands characterized by 100% aspen had standing dead conifer trees or conifer trees that were less than 1.37 m in height).

Site, stand, and fuel characteristics were measured in 80 plots (10 plots in each stand type per study area). Fuel moisture content was measured in four stands (one of each stand type) in each study area through the growing season (in 2021 in the Tavaputs and 2022 in the Bear Rivers).

#### *Plot design and sampling methods*

At each plot, we measured overstory and understory trees, woody surface fuels, and non-woody surface fuels (grasses, forbs, and shrubs). Overall plot attributes of elevation, aspect, and slope were collected at the center of each plot. Each plot was also field-assigned to two fuel models: one standard fuel model (Anderson, 1982 or Scott and Burgan, 2005) and one aspen fuel model (Brown and Simmerman, 1986). Overstory trees (> 10 cm DBH) were inventoried in a 200 m<sup>2</sup> plot. For each overstory tree, species and status (live or dead) were recorded and DBH and height were measured. Understory trees (<10 cm DBH) were inventoried in a 100 m<sup>2</sup> subplot. For each understory tree that was at least 1.37 m tall (i.e., had a measurable DBH), species, status, DBH and height were recorded. Understory trees <1.37 m tall were tallied by species and height class.



Dead woody surface fuels were measured on two 22.9 m transects, one oriented towards north and the other at a randomly generated azimuth that was not within 15° of north. Woody 1-h, 10-h, 100-h, and 1000-h time lag fuels were quantified on each transect following the protocols in Brown (1974), and two duff and litter depth measurements were taken along each transect. Fuel load of shrubs, forbs, and grasses were estimated in four 1 m<sup>2</sup> subplots located at 8 m from plot center in each cardinal direction using the Photoload Sampling method (Keane and Dickinson, 2007). For a subset of these live surface fuel subplots, we used a double sampling approach to develop calibration relationships. In three plots per stand type per study area, one subplot was selected to destructively sample. After the visual estimates of fuel load were recorded for each fuel type in the subplot using the Photoload Sampling method, we collected and sorted the shrubs, forbs, and grasses that were present. These samples were oven-dried at 100°C for 24 h and weighed. We developed calibration relationships between visually estimated load and destructively sampled load and adjusted each visually estimated load from the regression estimate (Fig. D.1; Tinkham *et al.*, 2016). Calibration relationships were developed separately for each fuel type (i.e., shrub, forb, and grass).

#### *Fuel and soil moisture content sampling*

Moisture content of dead woody fuel, live fuel, litter, and mineral soil was measured in one of each of the four stand types from June through September in 2021 (Tavaputs Plateau) and 2022 (Bear Rivers). Moisture sampling plots were located 140 to 700 m apart and 40 to 70 m from a road for ease of repeat sampling. Woody fuel moisture was measured about once per week and live fuel, litter, and soil moisture was measured every two weeks. Samples were collected during the warmest part of the day

between the hours of 1100 and 1600.

Three woody fuel stations per stand type were established for repeat measurements throughout the season. Each station included one sample of each woody fuel size class (10-h, 100-h, and 1000-h time lag classes), and stations were situated throughout the stand in various shady and sunny areas (Fig. 8). Standard 10-h fuel moisture sticks (four connected dowels, each 1.27 cm in diameter, oven dry weight of 100 g) elevated 25 cm above the litter surface on metal brackets were used. The 100-h and 1000-h samples were cut from existing dead and downed wood in each stand with lengths ranging from 11 to 46 cm and diameters ranging from 2.5 to 7 cm for the 100-h samples and from 8.1 to 21 cm for 1000-h samples. The bark from these large woody samples was removed and the samples were placed on the litter surface. A spring scale (300 x 2 g capacity, Pesola AG, Feusisberg, Switzerland) was used to weigh the 10-h fuel sticks and a digital scale (3000 x 0.1 g capacity, Brecknell, Smethwick, U.K.) was used to weigh the 100-h and 1000-h samples to acquire the weight in the field ( $W_{et,wt}$ ). At the end of the sampling season, the 100-h and 1000-h samples were collected, oven dried at 100°C until they reached a constant weight and weighed ( $D_{ry,wt}$ ).

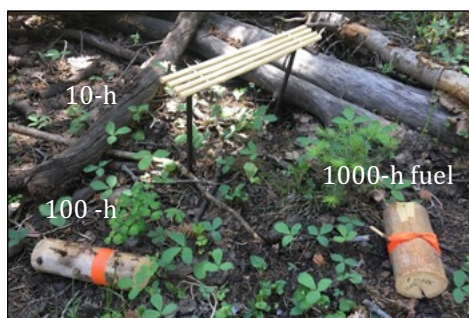


Figure 8: Woody fuel station setup to measure moisture content. Three stations (each with a 10-h, 100-h, and 1000-h fuel sample) were established per stand type in each study area.

Live fuel, litter, and soil moisture sampling protocols followed Norum and Miller (1984) and Zahn and Henson (2011). Three paper bags, each with at least 20 g of material, were collected for each fuel type in each stand. The entire suite of fuel types that were sampled, where available, were: aspen and conifer overstory foliage (> 2 m above the ground), aspen and conifer understory foliage (< 2 m above the ground), shrub foliage, forb, grass, and litter (Table D.2). Mineral soil was also collected in each stand type. Duff was minimal in all of the stands, so was not collected. Not all fuel types were sampled in each stand, due to insufficient amounts of certain fuels. Each sample was weighed in the field ( $Wet_{wt}$ ) to 0.1 g on a digital scale (3000 x 0.1 g capacity, Brecknell, Smethwick, U.K.), oven-dried for 24 h at 100°C, and reweighed ( $Dry_{wt}$ ). Percent moisture content (MC) was calculated for each woody fuel, live fuel, litter, and soil sample using the equation:

$$MC (\%) = \frac{Wet_{wt} - Dry_{wt}}{Dry_{wt} - bag_{wt}} * 100$$

#### *Weighted moisture content calculation*

To describe each stand's flammability throughout the growing season, we calculated the weighted moisture content (WMC) of fine live and dead surface fuels from late June to early October. We chose to only include these fuel components in the WMC calculation because we were interested in quantifying flammability of the surface fuels that are most important in driving fire behavior (Bennett *et al.*, 2010). Coarse woody fuels are less important for initial fire spread and intensity in surface fires, and canopy fuels are only important in determining crown fire behavior (Van Wagner, 1977). WMC was calculated by summing the fuel moisture of each fuel component multiplied by each

component's mass fraction, i.e.:

$$WMC (\%) = f_{10} * M_{10} + f_{lit} * M_{lit} + f_{sh} * M_{sh} + f_{fo} * M_{fo} + f_{gr} * M_{gr} + f_{uAs} * M_{uAs} \\ + f_{uCon} * M_{uCon}$$

where  $f$  is the mass fraction and  $M$  is moisture content of 10-h woody fuels ( $10$ ), litter ( $lit$ ), shrubs ( $sh$ ), forbs ( $fo$ ), grasses ( $gr$ ), aspen foliage < 6 m height ( $uAs$ ), and conifer foliage < 6 m height ( $uCon$ ).

Each component's mass fraction ( $f$ ) was calculated using this equation:

$$f_x = \frac{load_x}{total\ surface\ load}$$

where  $x$  is the fuel component and *total surface load* is the sum of all fine surface fuel components in that plot. The mass fraction of woody 10-h, litter, shrub, forb, and grass components was included for every plot, while the mass fraction of understory aspen and conifer foliage was only included for plots that had measurable understory tree vegetation.

Because we observed no difference in the moisture content of specific fuel components among stand types (see Results), we used the mean moisture content across all samples (i.e., across all stand types) for each sampling period as the input moisture value ( $M$ ) for each component. To investigate seasonal trends in WMC, we calculated a WMC value for every sampling date that moisture content data was collected.

### *Analysis*

Fuel load of individual surface fuel components, canopy bulk density (CBD), and weighted moisture content were the three primary responses evaluated. Statistical tests were conducted separately for the two study areas to analyze fuel load and weighted moisture content, while plots from both study areas were aggregated to analyze CBD.

Response variables that did not meet normality or constant variance assumptions were log-transformed prior to analysis. All statistical analyses were conducted using R statistical software (version 4.2.0, R Core Team, 2022).

To evaluate statistically significant differences in surface fuel load and CBD among the four stand types, one-way analysis of variance (ANOVA) was performed followed by post-hoc Tukey's Honestly Significant Difference tests (Tukey's HSD; alpha level of  $p < 0.05$ ). To analyze differences in weighted moisture content among stand types, two analysis methods were applied. First, ANOVA followed by post-hoc Tukey's HSD tests were conducted for each study area and for each of the six sampling dates separately. Second, as an overall analysis, a repeated measures ANOVA with a randomized block design was utilized with stand type as the predictor variable, sampling date as a blocking factor, and plot as a repeated measurement random effect (*lmer* function in the *lme4* package, Bates *et al.*, 2015). Post-hoc Tukey's HSD tests were used to discern which stand types had significant differences in mean of weighted moisture content (*glht* function in the *multcomp* package, Hothorn *et al.*, 2008).

## Results

### *Surface fuel load*

In general, fine dead fuel load (litter, woody 1-h, and woody 10-h) was lowest in pure, late development stands, followed by pure, early development, then mixed, early development and mixed, late development stands (Fig. 9). In the Tavaputs, average litter load was about five times higher in mixed, late development stands compared to the other three stand types; this difference was statistically significant ( $p < 0.001$ ). In the Bear

Rivers, average litter load was about six times higher in mixed, late development stands compared to mixed, early development stands ( $p = 0.004$ ) and about ten times higher compared to both pure aspen stand types ( $p < 0.001$ ). Woody 1-h fuel load was about two times higher in both development stages of mixed stands compared to pure stands in the Tavaputs and Bear Rivers. This difference was significant between pure, late development stands and mixed, late development ( $p = 0.006$ ) and mixed, early development ( $p = 0.03$ ) stands in the Tavaputs and between pure, early development stands and mixed, early development stands in the Bear Rivers ( $p = 0.04$ ). No significant differences in woody 10-h (Fig 9C), 100-h, or 1000-h (i.e., coarse woody fuels; Fig. D.2) were found among stand types.

Live surface fuel load (shrubs, forbs, and grasses) was generally lowest in mixed, late development stands, followed by mixed, early development, then both development stages of pure stands (Fig. 10). Load of forbs was particularly higher in the Bear Rivers compared to the Tavaputs; comparing the median values between similar stand types at the each of the study areas, the Bear Rivers had five to fourteen times the load of forbs compared to the Tavaputs. Forb load was significantly lower in mixed, late development stands compared to the other three stand types in the Tavaputs (about five times lower;  $p < 0.001$  between pure, early and late development types and  $p = 0.01$  between the mixed, early development type). Forb load was two to three times higher in pure stands (both development stage types) compared to mixed stands (both development stand types) in the Bear Rivers, but differences were not quite significant. Shrub load did not differ among stand types in the Tavaputs, though in the Bear Rivers, shrub load was about ten times higher in pure, late development stands compared to mixed, late development ( $p <$

0.001), fifteen times higher in pure, early development compared to mixed, late development ( $p < 0.001$ ), and six times higher in pure, early development compared to mixed, early development ( $p = 0.02$ ). Grass load was lowest in mixed, late development stands compared to the other three stand types in the Tavaputs, about two times lower compared to pure, early development stand ( $p = 0.03$ ) and seven times lower compared to pure, late development ( $p < 0.001$ ) and mixed, early development ( $p = 0.03$ ) stands. Grass load was about twenty times higher in pure, early development compared to mixed, late development stands in the Bear Rivers ( $p = 0.02$ ).

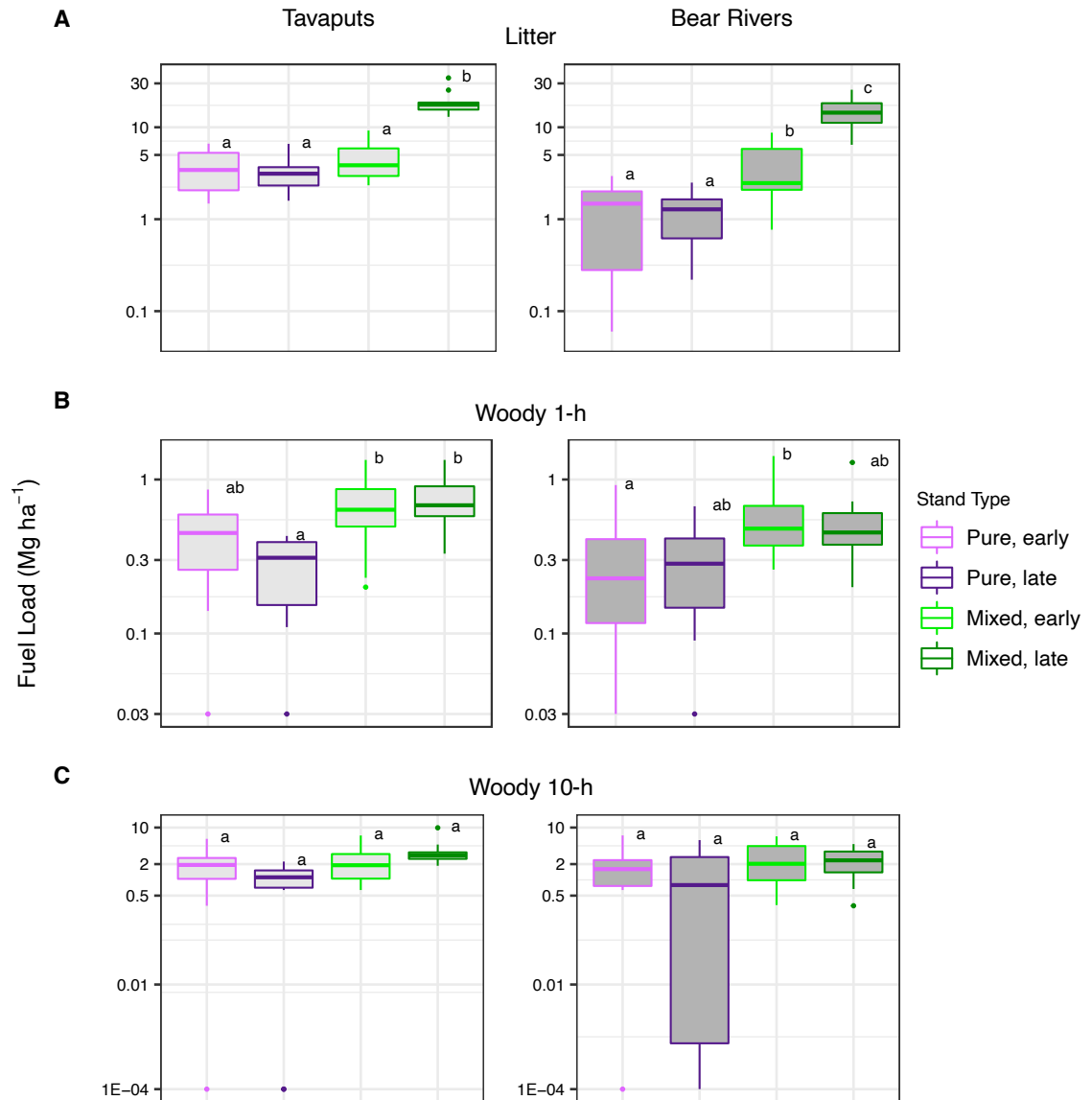


Figure 9: Fuel load of fine dead surface fuels (a) litter, (b) woody 1-h, (c) woody 10-h across aspen stand types in two study areas. Note that the y-axis is on a logged scale and that the scale varies by fuel component. Each boxplot represents ten plots. Different letters above boxplots indicates statistical significance ( $p < 0.05$ ) among group means.



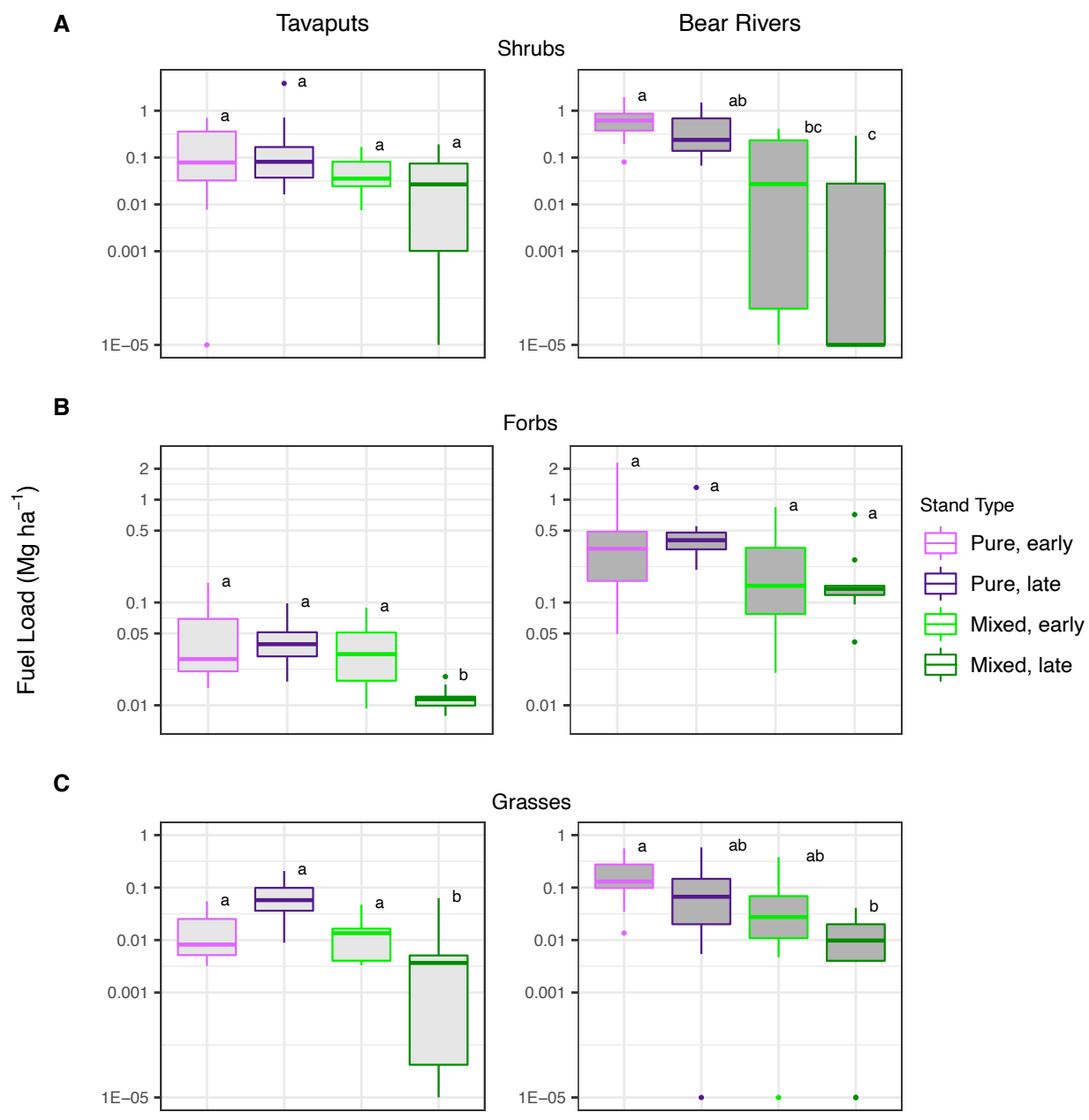


Figure 10: Fuel load of live surface fuels (a) shrubs, (b) forbs, (c) grasses across aspen stand types in two study areas. Note that the y-axis is on a logged scale and that the scale varies by fuel component. Each boxplot represents ten plots. Different letters above boxplots indicates statistical significance ( $p < 0.05$ ) among group means.

### Canopy bulk density

Canopy bulk density (CBD) was significantly higher ( $p < 0.001$ ) in both early and late development mixed aspen-conifer stands compared to pure aspen stands (Fig. 11). In general, CBD increased from pure, early development stands (mean of  $0.024 \text{ kg m}^{-3}$ ) to pure, late development stands (mean of  $0.052 \text{ kg m}^{-3}$ ) to mixed, early development stands (mean of  $0.122 \text{ kg m}^{-3}$ ) to mixed, late development stands (mean of  $0.138 \text{ kg m}^{-3}$ ).

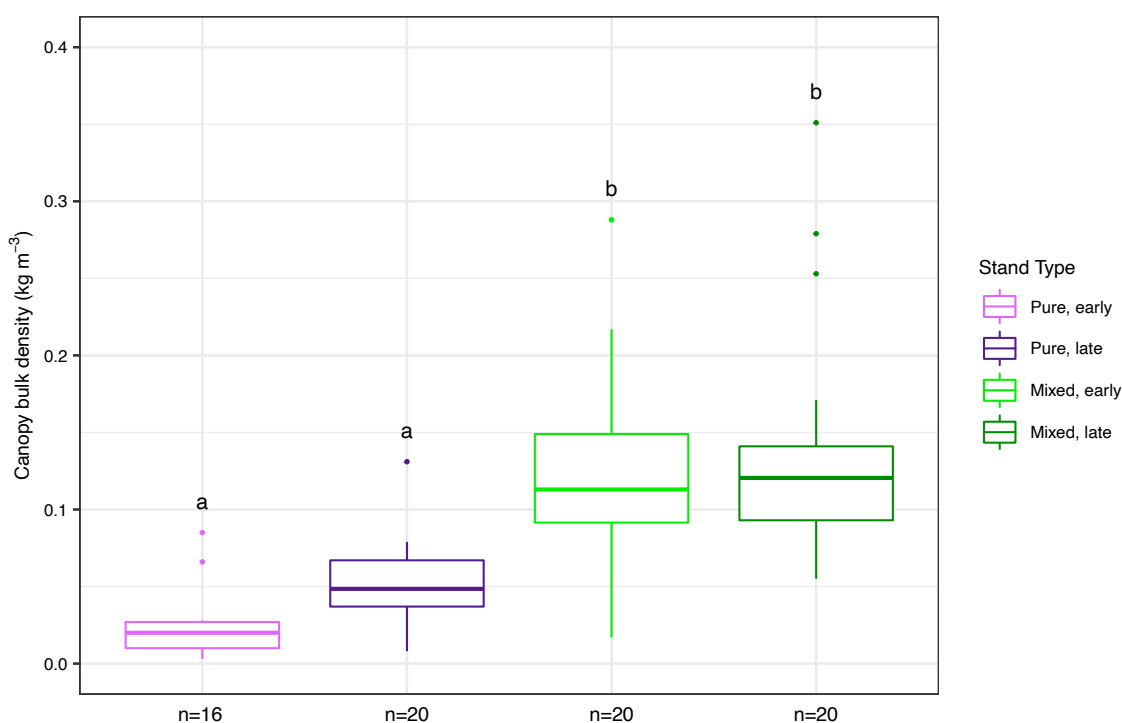


Figure 11: Canopy bulk density (CBD) of four aspen stand types across two study areas. CBD was only calculated for live trees  $>10 \text{ cm DBH}$ ; four stands in the pure, early development group did not have any trees  $>10 \text{ cm DBH}$ , so CBD was not calculated for those stands. Only foliage was considered in CBD calculations. Different letters above boxplots indicates statistical significance ( $p < 0.05$ ) among group means.

### Fuel and soil moisture

In general, moisture content of fuel components did not differ by stand type or study area (Fig. 12). Aspen, shrub, forb, and grass foliage had the highest moisture

content in late June and generally exhibited a decreasing trend through mid-September. On average, aspen foliage decreased from 198% to 144%, shrub foliage decreased from 253% to 152%, forb foliage decreased from 498% to 249%, and grass foliage decreased from 302% to 141% from late June to mid-September. Forb and grass moisture content was higher in the Bear Rivers than the Tavaputs study area in June through July, then moisture content was about the same between the study areas from August through mid-September. Conifer foliage moisture content remained relatively constant through the growing season at both study areas, around 120%.

Dead fuel moisture content remained relatively constant through the sampling period (Fig. 12 and Fig. D.3), with increases observed after precipitation events (Fig. D.4). Litter moisture content remained around 25% from late June through mid-August at both study areas and stayed constant through mid-September in the Bear Rivers, while litter moisture content increased to 111% by mid-September in the Tavaputs, after monsoonal precipitation events. In general, woody 10-h fuel moisture content was between 6% and 25%, 100-h fuel moisture content was between 5% and 40%, and 1000-h fuel moisture content was between 6% and 55%.

Soil moisture content did not vary among stand types and fluctuated throughout the season, increasing after precipitation and decreasing after periods of dryness (Fig. 13). In the Tavaputs, mean soil moisture content was lowest in mid-August (20%) and highest in mid-September (41%), while in the Bear Rivers, mean soil moisture content was lowest in mid-September (7%) and highest in mid-August (39%).

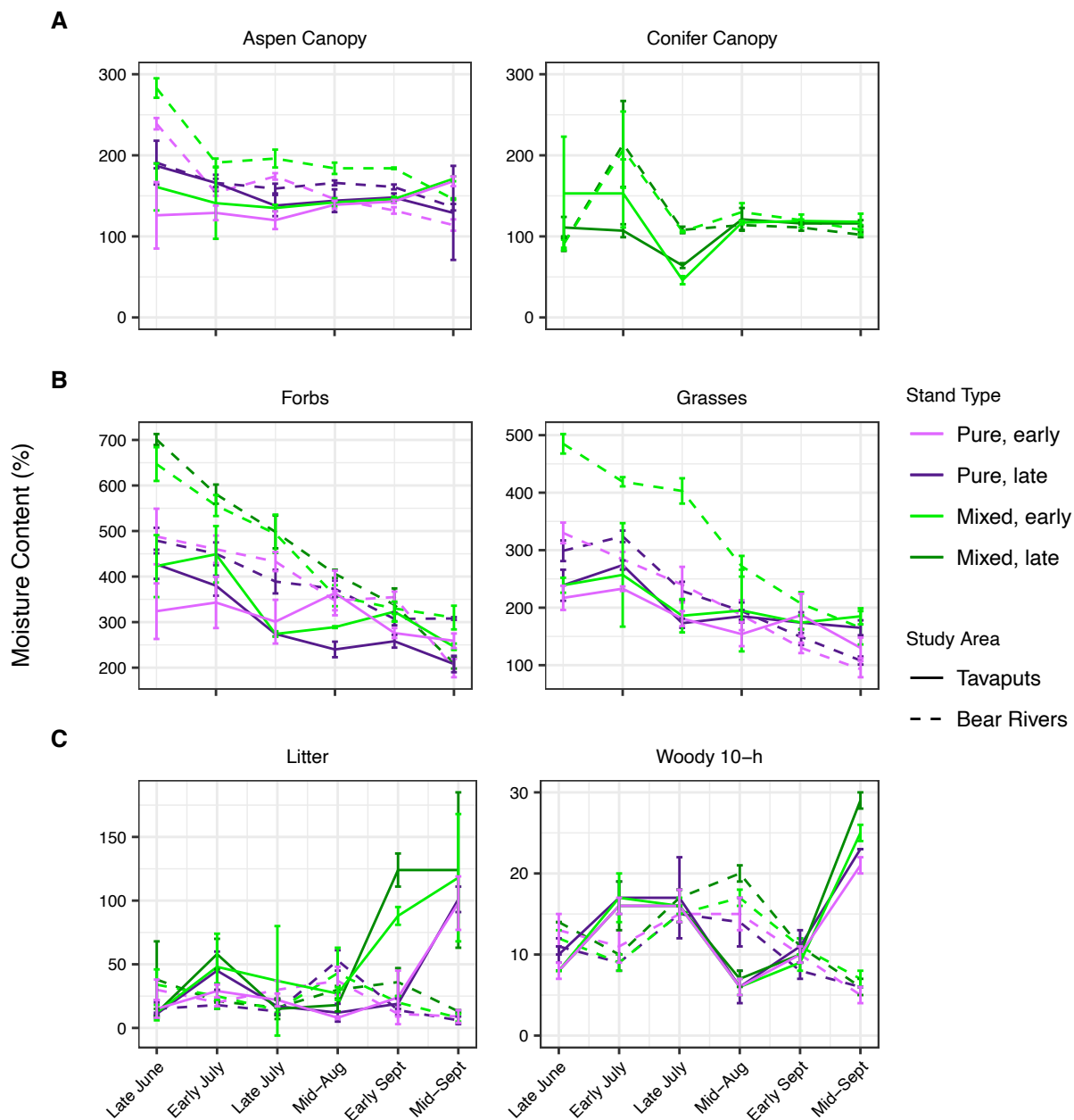


Figure 12: Moisture content trends of fuel components across aspen stand types in two study areas. Note that the y-axis scales vary by fuel component. Panel A depicts moisture content of aspen leaves and conifer needles in the canopy (> 2 m above surface). Tree foliage that was below 2 m height above the ground (i.e., were a part of the surface fuel bed) were also collected but are not shown here because they did not differ from the canopy foliage. Panel B depicts moisture content of forbs and grasses; shrubs were also collected and exhibited a similar decreasing trend. Panel C depicts moisture content of fine dead fuel (litter and woody 10-h); moisture content trends of coarse dead woody fuels are shown in Fig. D.3. See Fig. D.4 for precipitation trends at the two study areas.

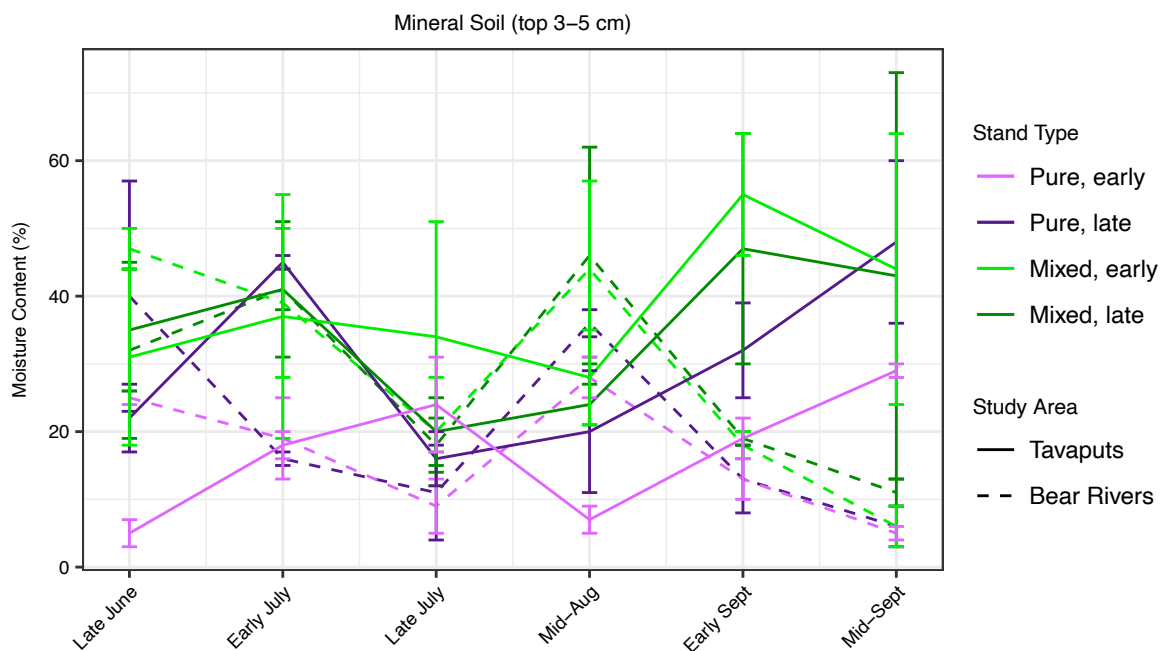


Figure 13: Soil moisture content trends across aspen stand types in two study areas.

### *Weighted moisture content*

Weighted moisture content (WMC) differed among the stand types, in which pure aspen stands had higher WMC than mixed aspen-conifer stands throughout the sampling period at both study areas (Fig. 14). In general, WMC was ordered at both study areas with the pure, late development stand types having the highest WMC followed by pure, early development, then mixed, early development, and finally mixed, late development. From the repeat measurements ANOVA for the Tavaputs, pure, late development aspen stands had significantly higher mean WMC compared to pure, early development ( $p = 0.01$ ), mixed, early development ( $p = 0.002$ ), and mixed, late development ( $p < 0.001$ ). For the repeat measurements ANOVA for the Bear Rivers, pairwise comparisons among all four stand types were significantly different ( $p < 0.001$ ) except between the two pure aspen stand types.

In the Tavaputs, mean WMC of pure, late development stands was around 12-19% higher than mixed, late development stands until mid-September, when mean WMC was only 5% higher than mixed, late development stands. No statistically significant differences among the stand types were detected using the separate ANOVA tests by sampling date in the Tavaputs, except on the mid-September date, when pure, late development stands had an average of 20% higher WMC than mixed, early development stands ( $p = 0.03$ ). In the Bear Rivers, the difference in mean WMC between pure, late development and mixed, late development stands decreased throughout the sampling period, with pure, late development stands having an average of 104% higher WMC in late June and an average of 48% higher WMC in mid-September compared to mixed, late development stands. Both development stages of pure aspen stands had very similar WMC in the Bear Rivers and were significantly higher in WMC than both of the mixed stand types throughout the sampling period ( $p < 0.001$ ). Significant differences were also detected between the early and late development mixed stands in early July ( $p = 0.01$ ), late July ( $p = 0.006$ ), and mid-August ( $p = 0.02$ ).

The two study areas also exhibited different trends in WMC across the sampling period. WMC generally increased from late June through mid-September in the Tavaputs and WMC decreased over the sampling period in the Bear Rivers, particularly in the pure aspen stand types. In pure, late development stands in the Tavaputs, WMC was ~31-60% from early June through mid-August, then steadily increased to ~104% by mid-September. In pure stands in the Bear Rivers, WMC was highest in late June (~152%) and decreased to ~65% by mid-September, while WMC remained steadier in mixed stands, decreasing from ~50% to ~20% from June through September. Variability in

WMC was very high within pure aspen stand types for both study areas, with lower variability within the mixed stand types.

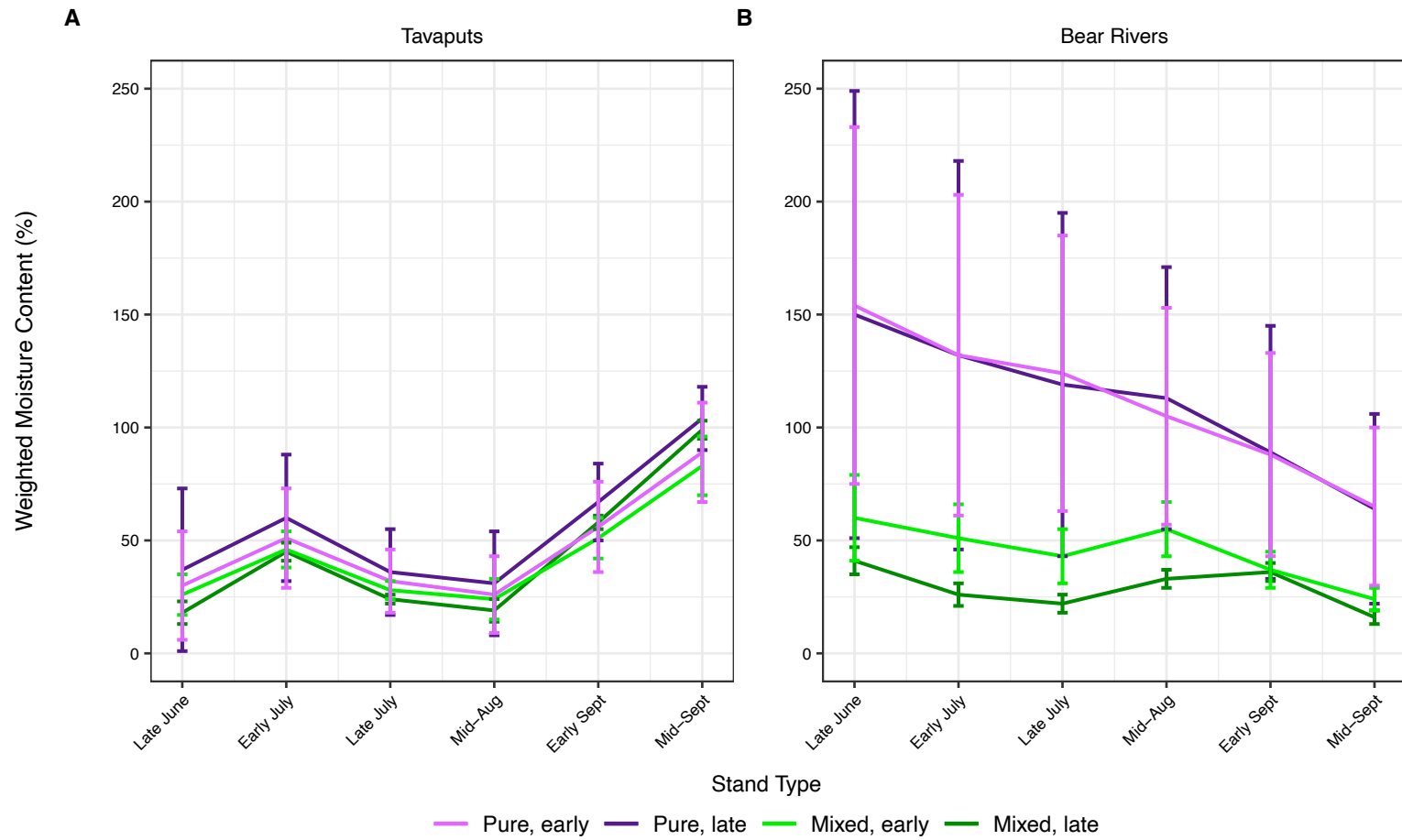


Figure 14: Weighted moisture content trends across aspen stand types in two study areas: Tavaputs (A) and Bear Rivers (B). Points and error bars on each sampling date are mean  $\pm$  standard deviation of 10 plots by stand type per study area.



## Discussion

The key driver of flammability in aspen forests—at least as it pertains to characteristics of the fuels themselves—appears to be the ratio of live to dead surface fuels, as the load of live and dead fuels (which differed in moisture content throughout the season) differed among aspen stand types. We described the overall flammability of aspen stands by determining each stand's weighted moisture content (i.e., a weighted moisture value that is based on the load of the fuel components present). In general, due to high load of live understory vegetation with high moisture and low load of fine dead fuel with low moisture, pure, late development aspen stands were the least flammable. By our metric of weighted moisture content, pure aspen stands were less flammable than mixed aspen-conifer stands from late June through mid-September, particularly at the Bear Rivers study area, but pure stands also exhibited very high variability and exhibited a greater seasonal decrease in weighted moisture content compared to mixed stands. Thus, while on *average*, pure aspen forests had fuel characteristics consistent with low flammability, under certain fuel type and seasonal conditions, pure aspen forests could also exhibit high flammability due largely to the herbaceous understory drying over the season.

Fuel characteristics in aspen stands differed along both gradients of species composition and development stage. Our findings of pure aspen stands having lower amounts of fine woody fuel, higher understory vegetation biomass (particularly grasses and forbs), and lower canopy bulk density compared to stands with greater conifer dominance aligns with other studies (i.e., Brown and Simmerman, 1986; Hély *et al.*, 2000; DeRose and Leffler, 2014). Mixed, late development stands—which were

characterized by co-dominant aspen and conifer overstory trees—had distinct fuel characteristics compared to both development stages of pure aspen and mixed, early development stands. Across both study areas, mixed, late development stands had surface fuel beds dominated by fine dead fuels (including litter and fine woody fuels) and low understory vegetation biomass. High litter and fine woody fuel accumulation in conifer-dominated stands is likely due to conifer trees contributing high amounts of fine fuels to the litter bed because of their high crown biomass (especially small branches and needles) and to slow litter decomposition (Brown, 1978; Prescott *et al.*, 2000; Jenkins *et al.*, 2003). Low understory vegetation biomass in the mixed, late development stands is likely due to less favorable understory conditions because of lower light penetration (due to higher leaf area index of conifer trees) compared to aspen-dominated stands (Lieffers and Stadt, 1994; Calder *et al.*, 2011) and lower organic matter and moisture content in soils that develop in conifer forests compared to aspen forests (Buck and St. Clair, 2012; Woldeselassie *et al.*, 2012).

We also measured moisture content of dead and live fuels to test the hypothesis that aspen promoted higher relative humidity in the understory—which would affect the moisture content of dead fuels—or promoted understory plant species that contained higher moisture content. In contrast to other studies that found differences in fuel moisture content among deciduous and coniferous forests (e.g., Pinto and Fernandes, 2014; Schunk *et al.*, 2017), we did not observe any differences in fuel moisture content among our aspen stand types along composition and development gradients. Additionally, we did not observe soil moisture content differences among pure aspen and mixed aspen-conifer stand types, which contrasts with findings from other studies (i.e.,

LaMalfa and Ryle, 2008). Moisture content of dead fuels was low throughout the sampling period at both study areas until September, when dead fuel moisture recovered after precipitation events. The observed decrease in moisture content of live foliage supports other studies that observed seasonal trends in fuel moisture content of plants as they senesce (i.e., Van Wagner, 1967; Loomis *et al.*, 1979; Brown *et al.*, 1989).

The different trends in weighted moisture content between the two study areas is likely due to differences in load of certain fuel components. In the Tavaputs, all four stand types had about two times greater litter load than stands in the Bear Rivers, and litter constituted a greater proportion of the total surface fuel bed for all stand types. This caused the weighted moisture content in the Tavaputs to be similar among stand types, and the seasonal trend of weighted moisture content followed precipitation patterns. The increasing trend of weighted moisture content from mid-August through mid-September in the Tavaputs (Fig. 14A) is likely due to a monsoon effect, as late summer and fall storms brought precipitation to the area (Fig. D.4A). In the Bear Rivers, there was less litter and much greater loads of forbs and grasses—particularly in the pure aspen stand types—compared to the Tavaputs. The high moisture of these live forbs and grasses likely drove the pattern of pure aspen stands having greater weighted moisture content than mixed aspen-conifer stands throughout the season. The overall decreasing trend of weighted moisture content through the season in the Bear Rivers is likely driven by forbs and grasses senescing and drying out over the season.

The differences of canopy fuel and surface fuel attributes among aspen stand types affects potential fire spread and behavior through canopies (crown fire) and on the ground (surface fire). Crown fires are driven by the characteristics of tree crowns,

including foliar moisture content and physical properties of branches and foliage such as size, distribution, and bulk density. In our study, pure aspen stands had lower canopy bulk density than stands mixed with conifer, and aspen foliage generally had higher moisture content than conifer foliage; these characteristics have been documented in other studies as well (i.e., Van Wagner, 1977; DeRose and Leffler, 2014). These properties of aspen tree canopies likely reduce the probability of crown fire spread in pure aspen forests and could explain why high-intensity crown fires have been observed to “drop to the ground” upon encountering a pure aspen forest. Surface fire spread in aspen forests, on the other hand, appears to be harder to predict. Pure stands with herbaceous understories had the lowest flammability, due to high moisture content in understory vegetation; however, surface fuel type and load was highly variable among stands within the pure aspen forest type. Additionally, stands with high loads of herbaceous understory are susceptible to seasonal patterns of drying, so fire behavior is more likely to increase as the growing season progresses (i.e., into fall) when vegetation is dry, or during dry and windy weather conditions.

Findings from this study have important implications for flammability within aspen forests. In particular, tree species composition and development stage in western aspen forests affect canopy and surface fuel characteristics, though evaluating the relative impact of development stage on fuels is unclear. Compared to mixed aspen-conifer forests, pure aspen forests during the peak of the growing season generally have fuel conditions that do not promote fire spread, but the probability of fire spread increases as the season progresses and herbaceous understory fuels and aspen foliage senesce and dry. Increasing drought and warming in western North America due to climate change will

likely increase the probability of aspen forests burning, though more research is needed to assess how climate change may affect fuel conditions and seasonality in aspen forests. Finally, given that managers are interested in propagating and maintaining aspen stands to be used as a fire risk reduction treatment, further investigation of specific stand characteristics (such as the specific percentage of conifers in the overstory) that lead to higher flammability in aspen forests is required.

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## CHAPTER 4

### CONCLUSIONS

This thesis demonstrates the complexity of flammability and potential fire occurrence, behavior, and severity in aspen forests. The literature review and survey revealed that pure aspen stands with herbaceous understories were more likely to experience reduced fire behavior, particularly during the growing season when foliage has high moisture. Similarly, results based on empirical data collection identified the ratio of live to dead surface fuels as the key driver of surface flammability in aspen forests, where pure aspen, late development stands exhibited low flammability due to high amounts of live herbaceous vegetation with high moisture and low amounts of fine dead fuel with low moisture. However, during seasons when understory vegetation is senesced or dry (i.e., spring or fall) and in dry, windy conditions, pure aspen forests can become flammable and can burn easily and intensely, as shown during particularly intense prescribed fire and wildfire events (e.g., Kiil and Grigel, 1969; Alexander and Sando, 1989; Quintilio *et al.*, 1991; Ember Research Services Ltd., 2003) and in modeling studies (Brown and Simmerman, 1986; Beales, 1998; Hély *et al.*, 2001).

A key part of the complexity of the aspen-fire relationship that was revealed through the literature review and survey was how an “aspen stand” is defined. Aspen inhabit a wide range of geographic, environmental, and climatic conditions, and can exist in both pure stands of variable density or with a variety of other overstory and understory species; because of this high variability in conditions, potential fire behavior is difficult to predict. While a coarse threshold of 50% aspen composition was generally used to define an aspen stand in studies reviewed, studies were unsystematic regarding the classification



of aspen forests based on specific percent composition of aspen vs. conifer trees. In our field campaign study, we observed higher flammability conditions (due to high amounts of dry, fine dead fuel) particularly in late development, mixed aspen-conifer stands that were characterized by < 45% aspen composition by basal area. To our knowledge, quantitative guidelines regarding aspen vs. conifer composition and other aspen site and stand characteristics that result in lower flammability or potential fire behavior has not yet been established. Thus, it would be particularly useful to prepare clear and prescriptive methods for managers who are interested in using aspen as a fire risk reduction method.

Another key aspect that makes the aspen-fire relationship complex is the type of fire (i.e., crown fire vs. surface fire) that is discussed. Crown fires are typically driven by the characteristics of tree crowns, including foliar moisture content and physical properties of branches and foliage such as size, distribution, and bulk density. Results from our field campaign showed that pure aspen stands have lower canopy bulk density than stands mixed with conifer, and aspen foliage had higher moisture content than conifer foliage; these characteristics have been documented in other studies as well (e.g., Van Wagner, 1977; DeRose and Leffler, 2014;). These properties of aspen tree canopies reduce the probability of crown fire spread in pure aspen forests and could explain why high-intensity crown fires have been observed to “drop to the ground” upon encountering a pure aspen forest. However, some high-intensity crown fires are driven more by steep topography and high wind rather than attributes of the fuels themselves (Bessie and Johnson, 1995; Weise and Biging, 1997); in these cases, the high foliar moisture content and low canopy bulk density of aspen forests likely have less of an effect on fire

behavior. Surface fire spread in aspen forests, on the other hand, appears to be harder to predict due to the high variability of types and amounts of surface fuels and their associated moisture content, as well as potential confounding factors such as topography, weather, and season. Thus, while pure aspen forests may be less flammable than conifer forests in terms of crown fire spread, the same may not be true in terms of surface fire spread when conditions are right.

Overall, aspen forests appear to promote lower flammability conditions compared to coniferous forests. Thus, aspen may facilitate diminishing or inhibiting fire—particularly crown fire—due to their canopy attributes and their promotion of live and generally high-moisture understory vegetation. However, aspen forests are certainly not “fireproof,” as flammability may greatly increase under certain seasonal, windy, or dry conditions, and uncertainty remains regarding the future of fire in aspen under a warming and drying climate.

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APPENDICES

## **Appendix A. Survey of Professionals with Expertise in Aspen-Fire Encounters**

### Aspen and Fire Survey

#### *Introduction*

Quaking aspen (*Populus tremuloides* Michx.) stands have long been described as “asbestos” or “fireproof” forests, as it is commonly reported that crown fires drop to the ground and fires spread only short distances in aspen stands. This is contrary to our knowledge, however, that many aspen types require high-intensity wildfire to regenerate. We are trying to quantify when and where aspen changes fire behavior and effects, and when and where it does not. In addition to searching the literature, we want to gather observations, reports, and photos from people who have watched fire burn in aspen stands. For this survey, we’re defining an “aspen stand” very broadly to include pure aspen stands, stands that have become overtopped by conifer, and any intermediate in between.

#### *Basic Questions*

Q1.1 Have you observed a fire in a forest where aspen was present? Select any that apply.

- Yes, a wildfire
- Yes, a prescribed burn
- No (if selected, proceed to Q8.1)

Q1.2 What organization/agency do you represent?

- US Forest Service
- Bureau of Land Management
- Other federal agency (please specify)

- State or county land management organization
- Non-profit organization (please specify)
- Fire Department (please specify)
- Other (please specify)

Q1.3 What is your position at this organization/agency?

- Firefighter
- Fire Ecologist
- Fuels Specialist
- Other (please specify)

Q2.1 How often have you seen fire interact with aspen?

- Often (5 or more times)
- A few times (2-4)
- Once
- I've never seen fire in aspen

### *Overview of Incident*

Q3.1 Think of the most recent time you've observed fire in aspen.

Q3.2 Was it a prescribed fire or a wildfire?

- Prescribed fire
- Wildfire

Q3.3 What was your role at the time of observation? (Burn boss? Firefighter? Pilot?

Resource advisor?) (Short answer)

Q3.4 Name of the incident? (Short answer)

Q3.5 Where was the incident (National Forest, nearest town, other landmarks, and/or state)? (Short answer)

Q3.6 What year? (Short answer)

Q3.7 What season did the fire burn in?

- Spring (proceed to Q3.8)
- Fall (proceed to Q3.9)
- Summer
- Winter

Q3.8 In spring, was it before or after leaf out?

- Before
- After

Q3.9 In fall, was it before or after the leaves had fallen?

- Before
- After

#### *Stand Characteristics*

Q4.1 Think of the most recent time you've observed fire in aspen.

Q4.2 How much conifer was mixed in with the aspen? Select one.

- No conifer (pure aspen)
- Aspen overstory with younger conifer in understory
- Co-dominant conifer and aspen overstory
- Predominantly conifer overstory, overtopped aspen
- Don't recall



Q4.3 What was the slope (generally)? Select one.

- Even or mild (0 to 20%)
- Moderate (20 - 40%)
- Steep (>40%)
- Don't recall

Q4.4 What was in the understory? Select any of the following.

- Small conifers
- Small aspen
- Grasses
- Shrubs
- Forbs
- Leaf or needle litter
- Down woody material
- Don't recall

Q4.5 What was the fuel loading like? Select one.

- Low
- Moderate
- Heavy
- Don't recall

Q4.6 What was the weather? Dry? Hot? Cool? Humid? Overcast? Low or high winds?

(Short answer)

Q5.1 What type of fire behavior did you observe in the aspen stand? Select any of the following.

- Surface
- Crown
- Torching
- Don't recall

Q5.2 Did you observe fire moving *into* a stand that contained aspen from a different forest type (e.g. from a conifer stand or grassland or shrubland)?

- Yes (Proceed to Q5.3)
- No
- Don't recall

Q5.3 What change (if any) in fire behavior did you observe from the fire moving into an aspen stand from a different forest type? Select one.

- No change in fire behavior
- Decreased intensity (e.g. went from a crown to a surface fire, fire slowed, fire spotted into aspen stand but didn't spread much, etc.). Please describe below.
- Increased intensity (e.g. went from a surface to a crown fire, torching occurred, etc.). Please describe below.
- Don't recall

Q5.4 What carried the fire? Select any.

- Leaf or needle litter
- Shrubs
- Grass/forbs
- Large logs
- Slash

- Other (please describe)
- Don't recall

*Next section displayed only if answered Q2.1 with "Often" or "A few times"*

Q6.1 You indicated that you've observed fire in aspen stands more than once. Think back on all of the instances that you've observed fire in aspen. Please provide a *rough* estimate of the percentage of fires that fall into each of the following categories.

- Percent stopped when hit an aspen stand:
- Percent decreased in intensity:
- Percent no change in fire behavior:
- Percent other or don't recall (please describe):
- Total:

Q6.2 Please provide any details, if possible. (Short answer)

Q7.1 Have you conducted a prescribed burn in aspen?

- Yes (proceed to Q7.2)
- No

Q7.2 Please describe: (Short answer)

1. The objectives for the prescribed burn (e.g. regenerate aspen),
2. If the prescribed burn was successful in meeting these objectives,
3. The fuel and weather conditions.

If you have conducted *multiple* prescribed burns in aspen, please summarize the fuel and weather conditions that were successful or not in meeting objectives.

Q8.1 Is it recommended practice for firefighters to identify aspen stands as safety zones?

- Yes
- No
- Unsure

Q8.2 Have you ever identified or used an aspen stand as a safety zone?

- Yes
- No
- Don't recall

Q8.3 Was it ever recommended practice for firefighters to identify aspen stands as safety zones?

- Yes (proceed to Q8.4)
- No
- Unsure

Q8.4 Why did this recommendation change? Select any.

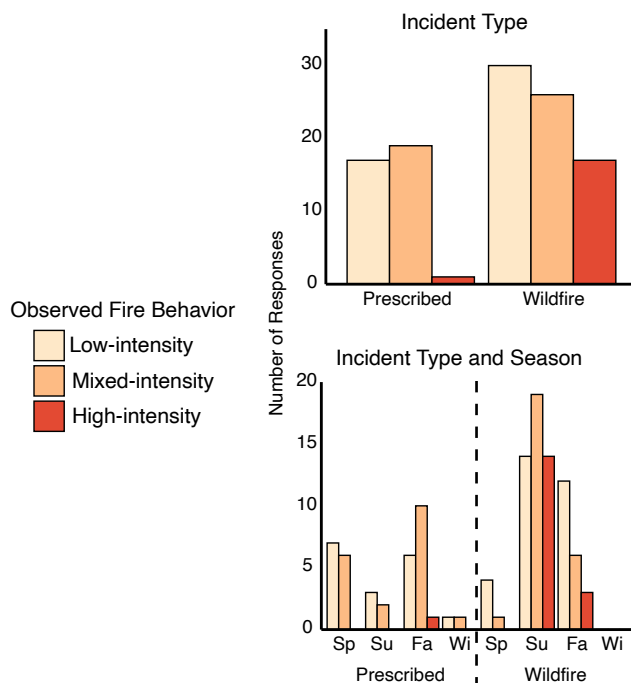
- Aspen is no longer considered "fireproof"
- Fire behavior has intensified
- Weather has created conditions that make aspen stands unreliable to use as safety zones
- Other (please specify)
- Unsure

Q9.1 We are seeking evidence for how aspen influences fire behavior. If you have read or written a report/article or have photos of aspen influencing fire behavior, please detail

here and/or send articles or photos to our emails (contact information is at end of survey). (Short answer)

Q9.2. If you would like to provide descriptions of other observations of fire behavior in aspen, please do so here or contact us (contact information is at end of survey). (Short answer)

## Appendix B. Survey Results: Observed Fire Behavior According to Incident Type and Season



Observed fire behavior related to incident type and interaction of incident type and season as reported by fire and land managers in response to a survey. Respondents had to select one option per category. Respondents could select multiple options of observed fire behavior (surface, torching, or crowning); respondents who selected only surface fire are grouped into the low-intensity category, those who selected torching and/or crowning in addition to surface fire are grouped into the mixed-intensity category, and those who selected torching and/or crowning only are grouped in the high-intensity category. A total of 110 respondents completed this section of the survey. Codes for the seasons for lower panel figure are: Sp = spring, Su = summer, Fa = fall, Wi = winter.

### Appendix C. Summary of Studies Reviewed

Authors	Year	Location <sup>a</sup>	Forest Type <sup>b</sup>	Fire Activity Discussed <sup>c</sup>	Factor Discussed <sup>d</sup>	Study Design	Key finding
Alexander and Sando	1989	Cent. MN and cent. WI	MAH (sugar maple, basswood)	Beh.	Wx	Measured rate of spread in six experimental fires to determine fire behavior in aspen stands	Wind was the key factor to get fire to spread in aspen stands with light fuel loading.
Alexander	2010	Canada (broadly)	PA	Occ. (Lik., Ar. Burn.) Beh.	Seas. Over. comp.	Reviewed literature related to surface fire potential in aspen stands in Canada	Proposed including "summer aspen" as an additional fuel type in the Fire Behavior Prediction System because seasonality is key for potential fire behavior in aspen stands. Conifer presence is also an important factor.
Alexander and Lanoville	2004	NT	PA	Beh.	Wx Over. comp.	Crowning experimental fire ignited in mixed-conifer stand spread to adjacent pure aspen stand	Fully leafed-out (in summer), pure aspen stand was an effective fuel break under moderately extreme weather conditions.
Bailey and Anderson	1980	Cent. AB	PA	Beh.	Wx.	Measured fire temperatures in a prescribed fire in grassland, shrubland, and aspen forest	Aspen forest was hard to burn because of moderate weather conditions, and fire temperatures were highly variable across the stand; higher temperatures were related to accumulated dry, fine woody fuel.
Baker	1925	Cent. UT	A-dom	Occ. (Lik., Freq.) Beh.	Graz.	Reviewed aspen ecology and documented fire evidence in aspen stands in Utah	Surface fires were historically (pre-European settlement) frequent (7-10 years) in aspen stands in central Utah. As of 1920, fires were virtually nonexistent in these stands. Grazing was "chiefly responsible for reducing the fire hazard" in these stands.

Bartos	2007	S. UT	Gen. Cover Type	Beh. Sev.	Over. comp.	Reviewed aspen ecology and management in southern Utah	Majority (60%) of aspen cover type in Utah was classified in the "drastically altered fire regime" category, due to increased conifer presence. This was expected to lead to increased fire intensity, severity, and substantial soil heating in these stand types.
Bartos and Mueggler	1981	W. WY	PA and MAC (subalpine fir)	Beh. Sev.	Over. comp.	Measured regeneration of aspen and early successional plants after a prescribed fire in 10 aspen clones	Fire intensities varied across sites due to different amounts of dry fuel on ground and slightly different moistures in duff and understory vegetation.
Bates et al.	2006	W. OR	MAC (western juniper)	Sev.	Seas.	Assessed effectiveness of using prescribed fire to restore aspen that was being invaded by western juniper	Higher severity fire with drier conditions (in fall compared to spring) allowed for higher post-fire aspen stem densities due to complete burning of litter layer
Baxter	2003	Cent. AB	PA and MAC (boreal)	Beh.	Wx Over. comp.	Reported conditions in harvested aspen stands that allowed for the House River Fire (2002) to spread	High-intensity, quickly spreading fire was primarily due to aspen slash combined with cured grass in the harvested area and low relative humidity at night.
Beales	1998	N. UT	A-dom	Beh.	Over. comp. Age Graz.	Measured fuel loads in 7 aspen stands of different ages (young: <70, old: >70); assessed relationships between fuel loads, stand characteristics, and site characteristics; modeled fire behavior (BEHAVE) under 2 weather conditions	Customized fuel models for each aspen type (young and old) were very different from the standardized fuel model typically used for these stand types. Young stands exhibited higher fire behavior (rate of spread, heat per area, intensity) in both weather scenarios of the fire behavior model compared to older stands, due to the less densely packed surface fuels.



Bessie and Johnson	1995	SW AB	C-dom (subalpine)	Beh.	Wx Over. comp.	Assessed the "weather vs. fuels" hypothesis in predicting fire behavior in boreal forests by modeling fire behavior using measured fuel loads and daily weather data	Weather was better predictor of potential fire behavior than fuels in subalpine forests; fire behavior did not vary much with stand age or species composition.
Beverly et al.	2009	Cent. AB	Gen. Cover Type	Occ. (Lik.)	Over. comp.	Investigated the spatial variation in fire susceptibility (number of times a location burned divided by total number of iterations) by modeling fire ignition and spread (Burn-P3 fire-landscape simulation model) in repeated simulations	Fire susceptibility was strongly associated with fuel composition and arrangement, topography, and ignition patterns. Deciduous forests (aspen) were associated with very low to low Fire Susceptibility Index values.
Bigler et al.	2005	NW CO	Gen. Cover Type	Occ. (Lik.) Sev.	Over. comp. Struc. Age	Investigated effects of two pre-fire disturbances (severe wildfire and spruce beetle outbreak), stand structure and vegetation composition, and topography on fire severity patterns in the Big Fish Lake wildfire (2002)	Aspen stands were 200 times more likely to not burn than spruce-fir stands; young stands were more likely to be in unburned category.
Bradley et al.	1992	UT	A-dom, MAC, C-dom (subalpine, montane)	Beh.	Seas. Over. comp. Graz.	Reviewed fire ecology and management of forest habitat types in Utah	There are many aspen community types in Utah, which affects the flammability of aspen: large down wood, small conifers, cured understory vegetation, windspeed, and dead fuel moisture play significant roles in fire spread in these stand types. Individual aspen stems are not resistant to fire, but the clone as a whole is.
Brown and DeByle	1987	SE ID and W. WY	PA	Sev.	Slope Asp.	Measured fire damage (bark charring and mortality) and aspen sucker regeneration after two prescribed burns and one wildfire	Recommended moderate- to high-intensity fire with flame lengths of at least 45 cm to meet objectives of regenerating aspen in a prescribed burn.

Brown and DeByle	1989	SE ID	PA and MAC (> 35% subalpine fir)	Beh.Sev.	Wx Over. comp.	Measured regeneration of grasses, forbs, shrubs, and aspen suckers annually for four years in three prescribed fires in pure aspen and mixed aspen-conifer stands	Fine fuels and a shrub understory component were important to get a fire in an aspen stand to spread and produce high enough intensities/severities (moderate-severe) to kill overstory.
Brown and Simmerman	1986	SE ID and W. WY	PA and MAC (> 50% conifers; subalpine)	Beh.	Over. comp. Graz.	Measured fuel loads and live understory fuel moisture across aspen community types, modeled rate of spread and fire intensity (BEHAVE), created photo guides of aspen fuel types in southeastern Idaho and western Wyoming	Fire behavior varied substantially in different types of aspen forests. Aspen/low forb and mixed/forb are least flammable
Brown et al.	1989	W. WY	PA and MAC (subalpine fir)	Did not specify	Seas.	Measured weekly moisture content of common forbs, shrubs, and grasses in two aspen stands to assess seasonal changes in moisture content	Aspen flammability depends on condition (level of curing or moisture content trend over the season) of live understory plants, which varies over the season
Buck and St. Clair	2012	Cent. UT	A-dom (>75% aspen), MAC (50% aspen), C-dom (<25% aspen; subalpine)	Did not specify	Edap. char. Over. comp.	Assessed how overstory stand composition of aspen and mixed aspen-conifer stands correlated with soil properties (chemical, texture, moisture content, temperature, and respiration)	Aspen-dominant stands had higher soil nutrient concentrations and exhibited 30% higher soil moisture than conifer and mixed stands at the beginning of summer, though soil moistures reached the same levels by mid-summer.
Carlson et al.	2011	NE MN	MAC (boreal)	Sev.	Slope pos. Over. comp.	Investigated relationships between fire severity patterns, pre-fire composition, and site characteristics on two scales (local and landscape) after the Gabbro Lake Fire (1995)	Across the landscape, crown fire severity and canopy fuel consumed was lowest in aspen-birch patches, but all the forest types varied widely in fire severity. Fire severity increased as spruce-fir composition increased in aspen stands and on upper slopes.

Cavard et al.	2011	NW QC and NW ON	A-dom (89-95% aspen), MAC (27-69% aspen), C-dom (<4% aspen; boreal)	Did not specify	Edap. char. Over. comp.	Quantified soil nutrients, understory biomass, and annual growth rates at two sites along overstory species composition gradient from aspen-dominant to conifer-dominant	Increased tall shrub understory biomass was associated with increased overstory aspen; mixed aspen-conifer stands exhibited the lowest total understory biomass.
Chesterman and Stelfox	1995	NE AB	A-dom	Did not specify	Edap. char. Struc. Dens. Age	Measured microclimate attributes (wind speed, photosynthetically active radiation, air temperature, and ground temperature) in aspen-dominant stands of three age classes (young: 20-30, mature: 50-65, old: >120)	Microclimate differences between aspen stands of different ages was minimal. A few trends: snowpack was highest in old stands, young stands were colder at night and warmer during the day, old stands had lower soil temperatures in summer and mature stands had lower levels of photosynthetically active radiation and higher wind speeds.
Crouse	2005	N. AZ	Gen. Cover Type	Beh.	Wx	Modeled crown fire behavior (FlamMap) in three weather scenarios and two fuel moisture scenarios using field-verified remotely sensed cover type and fuel load data	With increasing wind speeds, the size of active crown fire patch increased in all forest types (including aspen), and aspen had greater area burned at active crown fire than bristlecone and spruce-fir forest types, and less area burned than mixed conifer and ponderosa.
Cumming	2001	NE AB	Gen. Cover Type	Occ. (Lik., Ar. Burn.)	Wx Over. comp.	Assessed the effect of forest cover type on fire occurrence and area burned in 48 lightning-ignited fires from 1980 to 1993 in northeast Alberta	Fire frequency in deciduous stands was low; at both local and regional scales, aspen stands were unlikely to burn, until they developed a substantial amount of white spruce in the overstory.

Dash et al.	2015	AK	Gen. Cover Type	Occ. (Lik., Freq., Ar. Burn.)	Wx Over. comp.	Assessed the effects of forest cover type and weather conditions on fire occurrence and area burned in all fires >0.4 km <sup>2</sup> from 2002-2014 in interior Alaskan boreal forest	Landcover type was more important in determining fire spread in Alaskan boreal systems when weather conditions were moderate (cool and wet). Under warm and dry conditions, landcover played less of a role and all forest types burned significantly more area (though conifer stands were preferentially burned during more extreme weather conditions).
de Groot et al.	2009	Canada (broadly)	A-dom; MAC; C-dom (boreal)	Beh. Sev.	Seas. Over. comp.	Correlated litter and duff fuel consumption data with components of the Canadian Forest Fire Weather Index System in 7 wildfires and 6 experimental fires across the Canadian boreal forest	The "leafless aspen" and "summer aspen" fuel types of the Fire Behavior Prediction system were quite different in litter and duff characteristics, which translated to different litter and duff consumption between these stands. "Leafless aspen" types had lower pre-burn litter and duff depth, and much lower pre-burn bulk density, fuel load, and fuel consumption compared to "summer aspen".
DeByle et al.	1987	Intermountain West, Southwest, and Rocky Mountain regions, U.S.	PA and A-dom (>50% aspen)	Occ. (Lik., Ar. Burn.) Beh.	Over. comp. Graz.	Estimated acreage of aspen burned in wildfires >100 acres between 1970 and 1982 across three U.S. Forest Service Regions through coarse computations of aspen acreage in each fire, field sampling of select fires, and interviews	Very low percentage of aspen types during this period were estimated to have burned annually. In a survey, a majority of fire managers described aspen as "asbestos type" and "firebreak" and commented on aspen's "relative nonflammability". The proportion of aspen in the stand was noted to make a large difference in flammability.

DeRose and Leffler	2014	N. UT	A-dom (75-100% aspen), MAC (35-75% aspen), C-dom (0-31% aspen; subalpine)	Beh.	Wx Over. comp.	Modeled crown fire behavior (Forest Vegetation Simulator-Fire and Fuels Extension) of aspen stands that ranged in canopy composition along three categories (low, medium, or high aspen dominance) under four weather scenarios (moderate, high, severe, and extreme)	Crown fire was less likely in stands with more overstory aspen composition, but only under moderate weather conditions; under extreme weather conditions, even more pure aspen stands had higher likelihood of crown fire.
Dickinson and Johnson	2003	Cent. SK	A-dom, MAC, C-dom (boreal)	Occ. (Lik., Ar. Burn.)	Wx Over. comp. Age	Tested differences in probability of carrying surface fire in aspen vs. conifer stands after measuring herbaceous and litter layer characteristics in 56 stands along gradients of moisture, nutrients, tree species composition, and time-since-fire	Aspen did not slow or stop fires during large-area-burned years (presumably more extreme weather years), and the probability of fire spread increased very rapidly in aspen-dominant stands in a short amount of time after the burn (i.e., younger stands were more likely to burn).
Drever et al.	2008	S. ON	MAH (sugar maple, yellow birch)	Occ. (Lik., Ar. Burn.)	Over. comp.	Tested factors (human, biophysical, climate, fire weather) that contribute to fire occurrence and area burned in deciduous-dominated forests	A greater percentage of overstory aspen composition was correlated with decreased fire occurrence and size.
Ember Research Services Ltd.	2003	Cent. AB	PA	Beh.	Wx Seas. Over. comp.	Measured stand attribute, understory species composition, and surface fuel load data in pure aspen stands that burned and did not burn in the Chisholm Fire (2001)	Aspen stands exhibited high-intensity fire behavior AND served as a fuel break in the wildfire. Down woody fuel accumulation and a fuelbed of continuous, cured grass, in addition to extreme weather conditions created conditions for aspen to burn rapidly and intensely.

Fechner and Barrows	1976	CO	A-dom	Occ. (Lik., Ar. Burn.)	Over. comp.	Summarized aspen ecology, compared fuel type models that represent aspen vs. conifer vs. grass, and analyzed relationships between forest cover type and fire occurrence and area burned in Colorado National Forests from 1960-1973	Flammability of aspen was expected to be less than half that of conifer species due to aspen stands having the lowest fire occurrence and ignitions in this study area and timeframe. Noted that aspen flammability varied widely due to site and stand conditions, seasonality, and amount of woody fuel in stand.
Fisher	1986	N. and S. NM	Did not specify	NA	Did not specify	Tested greenhouse, nursery, and site preparation techniques to optimize aspen seedling survival for the purpose of establishing aspen fuel breaks in recreation areas	Rationale for planting aspen seedlings as a fire management tool, particularly in mountain resort areas; noted that aspen is a good fuel break and could be important in "redirecting the course of wildfires".
Gordon	1976	S. MT	A-dom and MAC (Douglas-fir)	Beh.	Seas. Over. comp.	Forty-acre prescribed burn in spring of mature aspen-dominant stand and mixed aspen-conifer (Douglas-fir) stand to improve moose forage	Aspen-dominant stand burned well, even a "hot, running fire" at times. The "right" conditions (did not specify) are necessary for fire to spread in aspen stands.
Hély et al.	2000	W. QC	A-dom (>75% aspen), MAC (25-75% aspen), C-dom (<25% aspen; boreal)	Beh.	Wx Seas. Over. comp.	Modeled surface fire behavior (BEHAVE) using measured surface fuels in 48 stands that span a successional trajectory from deciduous to conifer species; assessed fire behavior differences between stand types in spring and summer and across a variety of weather conditions	Fire hazard increased along the successional pathway from deciduous to conifer in boreal forests. Increased fire hazard is not from an increase in total fuel load, but from conifer stands having significantly greater amounts of small diameter woody fuel.

Hély et al.	2001	W. QC	A-dom (>75% aspen), MAC (25-75% aspen), C-dom (<25% aspen; boreal)	Beh.	Wx Seas. Over. comp.	Tested differences in potential fire behavior outputs using the Canadian Fire Behavior Prediction System and BEHAVE of 48 stands that spanned a successional trajectory from deciduous to conifer; assessed fire behavior differences between stand types in spring and summer and across a variety of weather conditions	Under the Fire Behavior Prediction (FBP) System model, there were significant differences in potential fire behavior between stand types; deciduous stands always exhibited lower behavior than conifer stands. Season played a large role, in which simulations during the summer had lower fire behavior values than the spring. The FBP model appeared to be a better predictor of fire behavior in this forest type and region compared to BEHAVE.
Hinzman et al.	2003	Cent. AK	MAH (paper birch)	Beh.	Wx Over. comp.	Examined the relative roles of weather and fuel type on fire behavior in a prescribed burn (FROSTFIRE research project) in Alaska	Under fairly moderate weather conditions, mixed aspen-birch forest types did not burn in this prescribed burn.
Johnson	1975	MA, N. WI, S. MI	MAH (many spp.)	NA	Did not specify	Reviewed success of planting hardwood trees (including aspen) around conifer plantations to act as a fuel break	Rationale for regenerating aspen (and other hardwood species) in fuel breaks surrounding conifer plantations in high fire occurrence areas as a solution to reduce fire risk.
Johnstone et al.	2011	Cent. AK	Gen. Cover Type	Sev.	Wx Over. comp.	Modeled successional vegetation changes (from deciduous to black spruce-dominated) and fire severity in Alaskan boreal forest using a spatially explicit state-and-transition model (ALFRESCO) to assess future succession post-fire under future climate scenarios	The conversion of black spruce to deciduous forest after high severity fire in the model led to the conversion to a "less flammable forest type". However, weather is important; under a severe weather scenario, deciduous forest cover did not lessen fire severity or area burned.

Jones and DeByle	1985	Intermountain West, U.S.	A-dom, MAC, C-dom (subalpine)	Beh	Wx Seas.	Reviewed aspen ecology and management literature in the western U.S.	Season was key to assess the flammability of aspen stands; in the western U.S., fall is particularly prime for burning aspen because of loosely packed fallen leaves and dry conditions. An understory of dense conifers and shrubs, combined with dry fuel conditions, and fuel an intense fire in aspen.
Kay	1997	Western U.S.	PA	Occ. (Freq.)	Did not specify	Opinion article of aspen persistence in western U.S.	Argued that persistence of aspen and historically high frequency of fires in aspen stands in the western U.S. prior to European settlement was due to Indigenous fire use
Kiil	1970	E. AB	A-dom (76% aspen, 24% white spruce)	Beh. Sev.	Did not specify	Measured overstory, understory, and surface fuels attributes before and after a prescribed burn of ten 10-acre blocks of mature, mixed aspen-spruce stands; measured rate of spread, flame height, and depth of burn	Relatively low-intensity fire through these stands during the prescribed burn, though fire spread was continuous, overstory trees were charred, and most of the understory vegetation was consumed.
Kiil and Grigel	1969	Cent. AB	A-dom, MAC, C-dom (boreal)	Occ. (Lik.) Beh.	Wx Over. comp.	Reviewed the weather, fuels, and fire behavior during an extreme spring fire season in Alberta (1968)	Severe spring weather compounded by a multi-year drought created intense fire conditions; fires did not appear to distinguish between the forest types.
Krawchuk et al.	2006	Cent./E. AB	Gen. Cover Type	Occ. (Lik.)	Wx Over. comp.	Assessed relative contributions of weather and fuel type (7 common stand types) in fire initiation of lightning-started fires from 1983-1993 in Alberta	Spruce-dominated stands had more fire initiations from lightning strikes than aspen-dominated stands.



LaMalfa and Ryle	2008	N. UT	A-dom and C-dom (subalpine)	Did not specify	Edap. char. Over. comp.	Measured hydrologic variables (snow water equivalence, snow ablation, soil water content, snowpack sublimation, stand evapotranspiration) in adjacent aspen and conifer stands to estimate differences in potential annual water yield between stand types	Aspen-dominant stands accumulated more snowfall than conifer-dominant stands, which translated to higher soil water contents throughout the summer and greater annual water yield than conifer stands. However, the aspen stands had higher evapotranspiration rates during the summer.
Larsen	1997	N. AB	A-dom and C-dom (boreal)	Occ. (Lik., Freq.)	Edap. char. Over. comp.	Quantified differences in fire frequency intervals among aspen, jack pine, black spruce, and white spruce forest types using dendrochronology and fire records methods	Aspen burned more frequently than neighboring stands of white and black spruce but not jack pine; author attributed this to the aspen stands being farther away from water sources and thus having less soil moisture.
Leduc et al.	2007	QC	Gen. Cover Type	Sev.	Over. comp. Struc.	Analyzed influences of pre-fire forest composition and stand structure on post-fire forest cover attributes and fire severity	The non-burned fire severity metric was overrepresented in deciduous-dominated stands (aspen and white birch).
Lee et al.	1995	NE AB	A-dom	Did not specify	Dens. Age	Assessed differences in stand attributes, understory communities, surface fuels, and soil attributes between aspen stands of 3 different age classes (young: 20-30 years, mature: 50-65 years, old: > 120 years)	Old aspen stands were structurally distinct from young and mature stands because of low tree density, an increase in the amount of understory plants, the inclusion of a secondary canopy (birch and spruce), and an accumulation of surface woody fuel.
Lee et al.	1997	E. AB	A-dom	Did not specify	Age	Measured snag and down coarse woody debris attributes in aspen stands of 3 different age classes (young: 20-30 years, mature: 50-65 years, old: > 120 years)	Volume of coarse woody debris (>11 cm diameter) was greater in old aspen stands than mature or young.

Lieffers and Stadt	1994	Cent./W. AB	A-dom, MAC, C-dom (white spruce)	Did not specify	Over. Comp .Struc.	Measured cover and height growth of two common herbaceous plants, low shrubs, and white fir seedlings and measured light transmission in a range of stands from aspen-dominant to mixed aspen-conifer	The lowest light level transmission found in aspen-dominant stands was about 15%, which was sufficient for the understory vegetation to thrive. The open canopy structure of hardwood stands allow for the development of understory vegetation, which can allow fire to spread when cured.
Loomis and Roussopoulos	1978	NE MN	Did not specify	NA	Did not specify	Collected and oven-dried samples of aspen crowns (foliage, live and dead branches, and boles) to obtain allometric estimates of tree diameter related to crown weights of aspen in northeastern U.S.	Provided protocol and estimates for estimating crown weights of aspen trees based on diameter.
Loomis et al.	1979	NE MN	MAH (many spp.)	Did not specify	Seas.	Collected moisture contents of herbaceous plants in northern hardwood stands across the growing season, compared measured moisture content data to values used in the National Fire Danger Rating System	All herbaceous species exhibited slight decreases in fuel moisture across the season, and moisture content and rate of drying differed by species.
Loomis	1977	NE MN	A-dom, MAC, C-dom (jack pine)	Did not specify	Edap. char. Over. comp.	Measured weight, depth, and bulk density of forest floor layers (litter, fermentation, and humus) in jack pine and aspen stands in the summer	Found no significant differences in weight, depth, or bulk density for any forest floor layer (litter, fermentation, and humus) except bulk density of humus layer between jack pine and aspen stands.
Margolis and Farris	2014	N. CA	C-dom (>66% conifers; subalpine)	Beh. Sev.	Over. comp.	Measured post-fire aspen regeneration and fire severity after four prescribed burns in aspen stands from 1998-2008; noted fire behavior attributes during the fires	Fire behavior was creeping, low-intensity surface fire. Locally higher loads of coarse woody debris were observed to support higher flame lengths and longer residence times.

Norum	1983	Cent. AK	MAH (paper birch) and C-dom (black spruce)	Beh.	Slope pos. Over. comp. Struc.	Measured wind speeds in three fuel types (tussock, black spruce, and hardwood) that varied in structure, canopy cover, and topographic position to inform wind adjustment factors based on different fuel types	Aspen-birch stands had relatively high midflame windspeeds due to their open stand structure, which could support fire. Higher wind speeds were measured in aspen-birch stands in upper slope positions.
Otway et al.	2007a	Cent. AB	A-dom	Did not specify	Wx Slope Asp. Edap. char.	Sampled moisture content, bulk density, and inorganic matter component of duff layers in three aspen-dominant stands on different slopes and aspects, compared measured values to values in the Canadian Forest Fire Weather Index for aspen fuel types	The standards for the aspen fuel type under the Canadian Forest Fire Weather Index (FWI) did not accurately reflect duff moisture-holding capacities of aspen forests. Aspen duff was measured to be more moist than the FWI predicted. Duff depth and organic layer bulk density was higher compared to many conifer forest types.
Otway et al.	2007b	Cent. AB	A-dom	Beh.	Edap. char. Over. comp.	Ignited fires in duff and litter layers in aspen stands across a gradient of moisture and slope position to determine fire spread and duration in duff layers in Alberta aspen stands	Duff in this aspen stand had high bulk density, high inorganic content, and low depth, which made ground fire less probable.

Ouarmim et al.	2016	W. QC	MAH (paper birch) and C-dom (boreal)	Occ. (Lik.)	Wx Over. comp.	Measured canopy composition, structure, and surface fuel loads in 8 stands that were considered fire refuges, modeled fire behavior (BehavePlus and Canadian Fire Behavior Prediction System) under 4 weather conditions and different fuel moisture conditions, and assessed fire likelihood differences between stand types along a gradient from broadleaf to conifer using a spatially explicit fire probability model (FlamMap3)	Fuel moisture was the most important driver that maintained fire refugia. The likelihood of fire and stand fire hazard increased from broadleaf to mixed to conifer forest for nearly all scenarios and experiments.
Paragi et al.	2007	Cent. AK	MAC (boreal)	Sev.	Wx Slope Asp.	Measured aspen regeneration after three regeneration treatments (prescribed burn, shearblading, and felling)	Low relative humidity, slope of more than 10°, a south-facing aspect, and adjacency to open areas produced fire behavior in aspen stands that were high enough to ensure top-killing, which allowed for a vigorous sprouting response.
Perala	1974	N. MN	MAH (73% aspen, 27% basswood/paper birch/sugar maple)	Beh.	Wx Seas.	Measured aspen regeneration, aboveground mortality, and soil burn severity after prescribed burn in a previously harvested aspen stand; recommended suitable burning conditions to regenerate aspen	Recommended suitable burning conditions to regenerate aspen of a uniform distribution of cured, fine slash or herbaceous fuels (<7 cm) and "good" burning weather.

Philpot	1969	Intermountain West, U.S.	Did not specify	Beh.	Did not specify	Measured mineral content, extractive content (waxes, fats, oils, and terpenes) and high heat content of aspen leaves; conducted burning experiments to assess differences in rate of spread, flame length, and combustion in intact aspen leaves compared to aspen leaves that had been extracted with ether or acetone	Found a positive relationship between burning rate of aspen leaves and their extractive content (waxes, fats, oils, and terpenes). Postulated that there were seasonal trends in extractive contents in aspen leaves, but this had not yet been studied.
Podur and Martell	2009	NW ON	Gen. Cover Type	Occ. (Lik., Freq., Ar. Burn.)	Wx Over. comp.	Assessed relative importance of weather and fuel type (four conifer types, deciduous, slash, and grass) in determining area burned in large fire years in Ontario from 1996-2006	Found that weather was a more important driver of area burned, particularly for large fires in Ontario. Aspen burned at the same proportions as it was available on the landscape during large-fire-years.
Powell and Bork	2007	Cent. AB	PA	Did not specify	Edap. char. Struc. Dens.	Measured microclimate attributes (photosynthetically active radiation, air temperature, and relative humidity) and soil moisture in pure aspen stands that had three levels of canopy removal treatments and three root trenching treatments conducted in them	Aspen canopies moderated extreme air temperatures, there was no trend with relative humidity and aspen canopy, and soil moisture was highly variable throughout study site. At one site during a summer drought, aspen canopy cover did result in an increase in soil water.
Qian et al.	2003	N. BC	A-dom (>80% aspen) and C-dom (>80% black spruce)	Did not specify	Over. comp. Dens.	Examined understory species diversity and density in black spruce and aspen stands, assessed relationships between overstory stand composition and understory species density and environment variables	Aspen-dominant stands had higher understory vegetation density than black spruce-dominant stands.

Quintilio et al.	1991	Cent. AB	A-dom (99% aspen)	Beh.	Wx Seas. Over. comp.	Evaluate fire behavior in fourteen 0.15-ha area prescribed fires under a range of weather conditions in aspen-dominant stands	Under moderate weather conditions, fire spread and fire intensity was low. Noted that aspen can burn quickly and intensely under more extreme weather or when surface fuel loads are high.
Rogers et al.	2014	Western North America (broadly)	A-dom, MAC, C-dom (boreal, subalpine, montane)	Sev.	Edaph. char. Over. comp.	Proposed a conceptual model to classify aspen types based on environmental and ecological characteristics (tree associates, topography, stand size, annual precipitation, ecohydrology, rooting depth, regeneration type, and primary disturbance type)	Noted that fire frequency and severity depend on conifer presence and cover and soil moisture, in which greater conifer composition and lower soil moisture results in more frequent and/or severe fires. Pure (or stable) aspen noted to be generally less flammable, though the patch size of the stand and adjacent cover type is important; smaller patches may be subject to high-severity fire if they are adjacent to conifers.
Ryan	1976	CO	Gen. Cover Type	Occ. (Lik., Ar. Burn.)	Seas. Over. comp.	Developed model of potential fire hazard and risk by forest cover type and elevation in Colorado National Forests by assessing relationships between fire cause, forest cover at origin, aspect, and slope in fires in Colorado National Forests from 1960-1973 and estimating acreage of forest cover types using commercial timber acreage	The aspen forest type was found to have the lowest potential fire hazard and risk because of its low number of total fires, number of total acres burned, number of fires in large fire size classes, and number of ignitions. Author noted that fire potential in aspen stands was likely to be variable depending on stand and site conditions.
Samran et al.	1995	Cent. AB	A-dom (40-75% aspen)	Did not specify	Wx Slope Edap. char.	Assessed the relative contributions of precipitation and soil water to litter and duff moisture content	Precip. and soil water contributed to moisture of litter and duff layers; precip. most affected litter, soil water most affected duff. During study period, litter and duff layers did not have low enough moisture to burn (<30% moisture content).

Sando and Wick	1972	Lake States, U.S.	Did not specify	NA	Did not specify	Developed allometric equations for crown weights of common tree species (including aspen) in northeastern U.S.	Presented equations of aspen (and other species) crown weights based on stem diameter. Presented limited data on aspen because "hardwood fuels probably do not support fire spread except under very severe conditions".
Shinneman et al.	2013	Western U.S.	A-dom, MAC, C-dom (subalpine, montane)	Sev.	Over. comp.	Proposed a framework to classify aspen types based on different fire regimes	Different populations of aspen interact differently with fire; conifer presence is particularly important in determining how fire interacts with aspen stands.
Simard et al.	1983	N. MI	C-dom (boreal)	Beh.	Wx Over. comp.	Assessed fuel and weather conditions that allowed for a prescribed fire in jack pine slash to escape and grow into the Mack Lake Fire	Aspen stands burned during this escaped slash pile burn, with 100% mortality of overstory aspen that were adjacent to crowning jack pine.
Smith et al.	1993	Cent./N. CO	A-dom	Occ. (Ar. Burn.)Beh.	Edap. char. Over. comp.	Measured fire behavior attributes in 30 microplots in two prescribed burns in aspen stands with different understory compositions (herbaceous vs. common juniper)	Plots composed of common juniper shrub understory burned more intensely, released more heat, had higher flame lengths, and had deeper flaming zone depths than plots with herbaceous understory; there was no significant differences in for rate of spread or fire temperature between stands.
Tepley and Veblen	2015	SW CO	A-dom, MAC, C-dom (subalpine, montane)	Sev.	Over. comp.	Compared historic fire frequency and fire severity among four forest types (aspen, spruce-fir, dry mixed conifer, mesic mixed conifer) with different stand structure and stand age	Aspen acted as both a fuel break and burned in stand-replacing fires. Most (83%) of the aspen stands studied were multi-aged and thus thought to not exhibit high-severity fire, but rather frequency, low-severity fire. One young aspen stand that established post-fire appeared to act as a fuel break for a subsequent fire.

Terrier et al.	2013	QC	Gen. Cover Type	Occ. (Lik.)	Over. comp.	Predicted future fire occurrence in boreal forests under two tree dispersal scenarios using multivariate adaptive regression splines	Simulated that an increase in deciduous forest types was possible with a changing climate, and though fire occurrence also increased, the deciduous forest component may "significantly offset the impact of increased fire risk".
Thompson et al.	2017	N. AB and S. NT	A-dom, MAC, C-dom (jack pine)	Did not specify	Over. comp. Age	Measured surface and canopy fuels in 66 plots across a time-since-fire gradient and a moisture gradient (which correlated with major vegetation types)	There was no difference in total fuel loading between upland forest types, though all forest types exhibited a significant increase in total fuel loading over time. Increased total fuel loading over time was primarily due to an increase in canopy fuels.
Tucker and Jarvis	1967	SW MB	MAC (50% aspen, 50% whit spruce)	Sev.	Edap. char.	Measured fire severity (aboveground mortality and soil burn depth) in a prescribed burn in a previously harvested mixed aspen-white spruce stand with residual slash	Fire did not spread much beyond the slash-covered areas; only about 35% of each 1.5-acre plot burned.
Van Wagner	1977	E. ON	Did not specify	Beh.	Wx Over. comp.	Presented mathematical theory of how a crown fire initiates and spreads in conifer forests from experimental fires in common conifer forest types in Canada	Wind was noted to be a key factor in the initiation and spread of crown fire; noted that "aspen stands do not crown," likely because their foliar moisture contents are higher than conifer foliage.
Van Wagner	1967	E. ON	MAC (boreal)	Did not specify	Seas.	Sampled moisture content in leaves of 7 common tree species in eastern Canada across three growing seasons	Aspen flushed in spring with high moisture content (~250%), then moisture content fell rapidly and leveled off to ~140% by early July. Moisture content remained high (128-145%) even during leaf abscission in the fall.



Wang	2002	SE MB	MAC (boreal)	Sev.	Over. comp.	Compared pre-fire species composition and fire severity in mixed aspen-conifer stands in the Black River fire (1999)	Severely burned areas had significantly higher pre-fire conifer basal area and significantly lower deciduous basal area compared to scorched and lightly burned. Patchiness of burn severity was related to differences in species composition.
Weber	1990	E. ON	A-dom	Beh. Sev.	Seas.	Measured aspen regeneration for three years in aspen-dominant stands with different treatment applications (clearcut and prescribed burn) in spring and fall; measured biomass consumption on plots that were burned	Summer prescribed burn in aspen stands had more extreme weather (less fuel moisture), which led to greater consumption and intensity than prescribed burn in the spring.
Wehmas	2018	Cent. AK	C-dom (boreal)	Occ. (Lik., Freq., Ar Burn.)	Wx Over. comp.	Calculated fire occurrence in broadleaf and conifer forest types in Large Fire Years (> 1 million ha total area burned) and Normal Fire Years (< 1 million ha total area burned) in Alaska fires from 2001-2015	Aspen-birch patches in boreal Alaska forest were more flammable than previously thought, even under "normal fire years" (<1 million acres burned across the state); concluded that the flammability of broadleaf stands would likely increase with a warming, drying climate in the region.
Whitman et al.	2018	N. AB and S. NT	Gen. Cover Type	Sev.		Assessed burn severity patterns in different forest cover types in 6 lightning-ignited wildfires and compared field measurements of burn severity to remotely sensed burn severity data	Fire severity was most variable in the upland mixedwood vegetation community type; authors attributed this variation to the different proportions of conifer and deciduous species. Open stands with high basal areas had lower burn severities.

Woods et al.	1982	NW CO	PA	Did not specify	Dens.	Measured understory vegetation load in 20 aspen stands with different stand density	Aspen stands with <10 m <sup>2</sup> /ha basal area had consistently nearly two times the amount of understory herbaceous biomass compared to aspen stands with >10 m <sup>2</sup> /ha.
Ziegler et al.	2020	E. CA and W. NV	MAC (49% aspen; subalpine)	Beh.	Over. comp. Struc.	Modeled fire behavior of three treatments with light, medium, and heavy conifer removal in mixed aspen-conifer stands with 3 wind speed scenarios using a physics-based model (Wildland Urban Interface Fire Dynamics Simulator)	Heavier conifer removal in mixed aspen-conifer stands led to higher likelihood of fire spread and higher rate of spread because of more within-stand wind speed, though crown fire activity decreased. Noted that would need to remove a lot of conifers in such stands to make a difference in aspen regeneration and fire behavior.

a - U.S. state and Canadian province names are shortened to two-letter abbreviations for display purposes

b - PA = pure aspen, A-dom = aspen-dominant, C-dom = conifer-dominant, MAH = mixed aspen-hardwood, MAC = mixed aspen-conifer. Percent composition and other tree species are listed in mixed and conifer-dominant stands when information was available. For stands that were mixed with multiple species of conifer, three classifications are used: boreal, subalpine, and montane. Boreal species include: black spruce, white spruce, jack pine, lodgepole pine, white pine (*Pinus strobus* L.), red pine (*Pinus resinosa* Ait.), and balsam fir. Subalpine species include: subalpine fir, Engelmann spruce, lodgepole pine, white fir (*Abies concolor* Gord. and Glend. Lindl. ex Hildebr.), Douglas-fir, Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) and red fir (*Abies magnifica* A. Murr.).

c - Occ. = fire occurrence (specified by likelihood (Lik.), area burned (Ar. Burn.), or frequency (freq.)), Beh. = fire behavior, Sev. = fire severity.

d - Wx = weather, Asp. = aspect, Slope pos. = slope position, Edap. char. = edaphic characteristics, Seas. = season, Over. comp. = overstory composition, Struc. = stand structure, Dens. = stand density, Graz. = grazing. See Fig. 1 for factors.

### Appendix D. Supplementary Tables and Figures for Chapter 3

Table D.1: Stand characteristics, fuel load, and canopy attributes of aspen stand types in two study areas.

	Pure, early development		Pure, late development		Mixed, early development		Mixed, late development	
	Tavaputs	Bear Rivers	Tavaputs	Bear Rivers	Tavaputs	Bear Rivers	Tavaputs	Bear Rivers
<i>Stand Characteristics</i>								
Basal area, live trees (m <sup>2</sup> ha <sup>-1</sup> )								
Overstory aspen	8.2 (2.5-33.5)	6.5 (1.7-10.7)	33.8 (18.1-48.6)	23.9 (5.2-34.7)	39.3 (15.0-66.4)	24.1 (9.5-41.0)	9.3 (0-17.9)	8.7 (0-16.3)
Overstory conifer	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	3.6 (0-17.9)	10.7 (0-24.0)	21.6 (17.1-36.5)	32.6 (15.3-47.6)
Understory aspen	14.3 (0.6-29.1)	5.1 (0.8-11.0)	0.6 (0-2.2)	1.4 (0.6-3.5)	0.9 (0-8.6)	1.4 (0-4.5)	0.02 (0-1.8)	0.2 (0-2.3)
Understory conifer	0 (0-0.5)	0 (0-0)	0 (0-0.4)	0 (0-0)	1.0 (0-12.3)	0.5 (0-6.4)	2.0 (0.5-4.1)	0 (0-2.4)
Basal area, dead trees (m <sup>2</sup> ha <sup>-1</sup> )								
Overstory aspen	0 (0-4.6)	2.5 (0-7.4)	2.5 (0-54.9)	1.7 (0-9.5)	3.9 (0-13.8)	1.8 (0-6.6)	0.5 (0-11.7)	3.6 (0-11.0)
Overstory conifer	0 (0-0)	0 (0-0)	0 (0-1.1)	0 (0-0)	0 (0-2.7)	0 (0-17.9)	5.6 (0-18.9)	8.4 (0-19.1)
Quadratic mean diameter (cm)	6.8 (1.4-8.9)	7.2 (3.5-10.3)	22.2 (9.3-47.8)	12.4 (6.8-16.7)	16.0 (10.1-32.1)	11.2 (8.7-17.2)	13.7 (6.4-19.8)	18.9 (9.4-36.6)
Relative Stand Density Index	0.10 (0-0.65)	0.11 (0-0.19)	0.51 (0.23-0.73)	0.38 (0.08-0.47)	0.71 (0.38-1.0)	0.51 (0.24-0.79)	0.54 (0.22-0.93)	0.48 (0.35-0.78)
Height of dominant trees (m)	8.5 (3.7-12.5)	7.9 (7-11.3)	16.0 (12.8-28)	17.1 (12.8-25.3)	16.0 (11.9-23.8)	21.0 (12.2-27.1)	18.3 (10.1-23.2)	27.0 (17.4-31.7)
Percent composition of aspen	100 (99-100)	100 (100-100)	100 (98-100)	100 (100-100)	93 (60-100)	70 (30-94)	29 (0-45)	24 (0-40)

*Fuel Load*

Litter	3.52 (1.48-6.63)	1.5 (0.06-2.95)	3.13 (1.59-6.6)	1.3 (0.22-2.5)	3.86 (2.34-9.21)	2.47 (0.77-8.72)	17.6 (12.99-34.41)	14.46 (6.45-25.6)
Woody 1-h	0.45 (0.03-0.86)	0.23 (0.03-0.92)	0.32 (0.03-0.43)	0.29 (0.03-0.67)	0.65 (0.2-1.34)	0.48 (0.26-1.42)	0.68 (0.33-1.34)	0.46 (0.2-1.29)
Woody 10-h	1.93 (0-6.08)	1.61 (0-7.07)	1.13 (0-2.24)	0.81 (0-5.76)	1.94 (0.64-7.05)	2.25 (0.33-6.77)	2.94 (1.86-9.9)	2.41 (0.32-4.83)
Woody 100-h	4.66 (0-22.79)	5.37 (0-14.74)	3.34 (0-14.62)	4.02 (0-6.8)	8.03 (2.67-22.62)	7.35 (2.69-15.98)	5.88 (3.84-15.65)	6.86 (0-16.03)
Woody 1000-h	4.76 (0-23.12)	6.6 (2.05-28.11)	10.95 (5.36-33.71)	12.49 (5.75-18.68)	5.75 (2.96-28.83)	10.23 (0-26.01)	10.56 (2.13-26.03)	11.32 (7.24-20.33)
Shrub	0.09 (0-0.7)	0.62 (0.08-1.94)	0.08 (0.02-3.83)	0.25 (0.07-1.49)	0.04 (0.008-0.17)	0.03 (0-0.41)	0.03 (0-0.19)	0 (0-0.29)
Forb	0.03 (0.01-0.16)	0.33 (0.05-2.28)	0.04 (0.02-0.1)	0.4 (0.21-1.31)	0.03 (0.009-0.09)	0.15 (0.02-0.84)	0.01 (0.008-0.02)	0.14 (0.04-0.72)
Grass	0.008 (0.003-0.05)	0.13 (0.01-0.56)	0.06 (0.008-0.21)	0.07 (0-0.58)	0.01 (0.003-0.05)	0.03 (0-0.38)	0.004 (0-0.06)	0.01 (0-0.04)

*Canopy Attributes*

Canopy bulk density (kg m <sup>-3</sup> )	0.027 (0.005-0.085)	0.014 (0.003-0.027)	0.067 (0.028-0.131)	0.040 (0.008-0.067)	0.119 (0.054-0.288)	0.101 (0.017-0.171)	0.140 (0.055-0.351)	0.110 (0.069-0.139)
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Note: Values are median (range). Overstory trees were >10 cm DBH, and understory trees were <10 cm DBH and at least 1.37 m tall (had a measurable DBH). Four stands in the pure, early development group (three in the Tavaputs, one in the Bear Rivers) did not have any trees >10 cm DBH, so overstory calculations were not conducted for those stands. The primary conifer species was subalpine fir, which constituted 98% of live overstory trees tallied in the Tavaputs (other species included Douglas-fir and Englemann spruce) and 82% of live overstory trees tallied in the Bear Rivers (other species included Douglas-fir, Englemann spruce, and lodgepole pine). Quadratic mean diameter and percent aspen composition includes all live trees > DBH that were measured. Relative Stand Density Index (SDI) was computed for live overstory trees, in relation to a max SDI value of 1380 (max SDI for quaking aspen in metric units). Fuel load values are in Mg ha<sup>-1</sup>. Canopy bulk density was calculated for live trees >10 cm DBH using crown foliage mass only; foliage mass was calculated for individual trees using equations in Jenkins *et al.*, 2003 for aspen and in Brown, 1978 for conifer species.



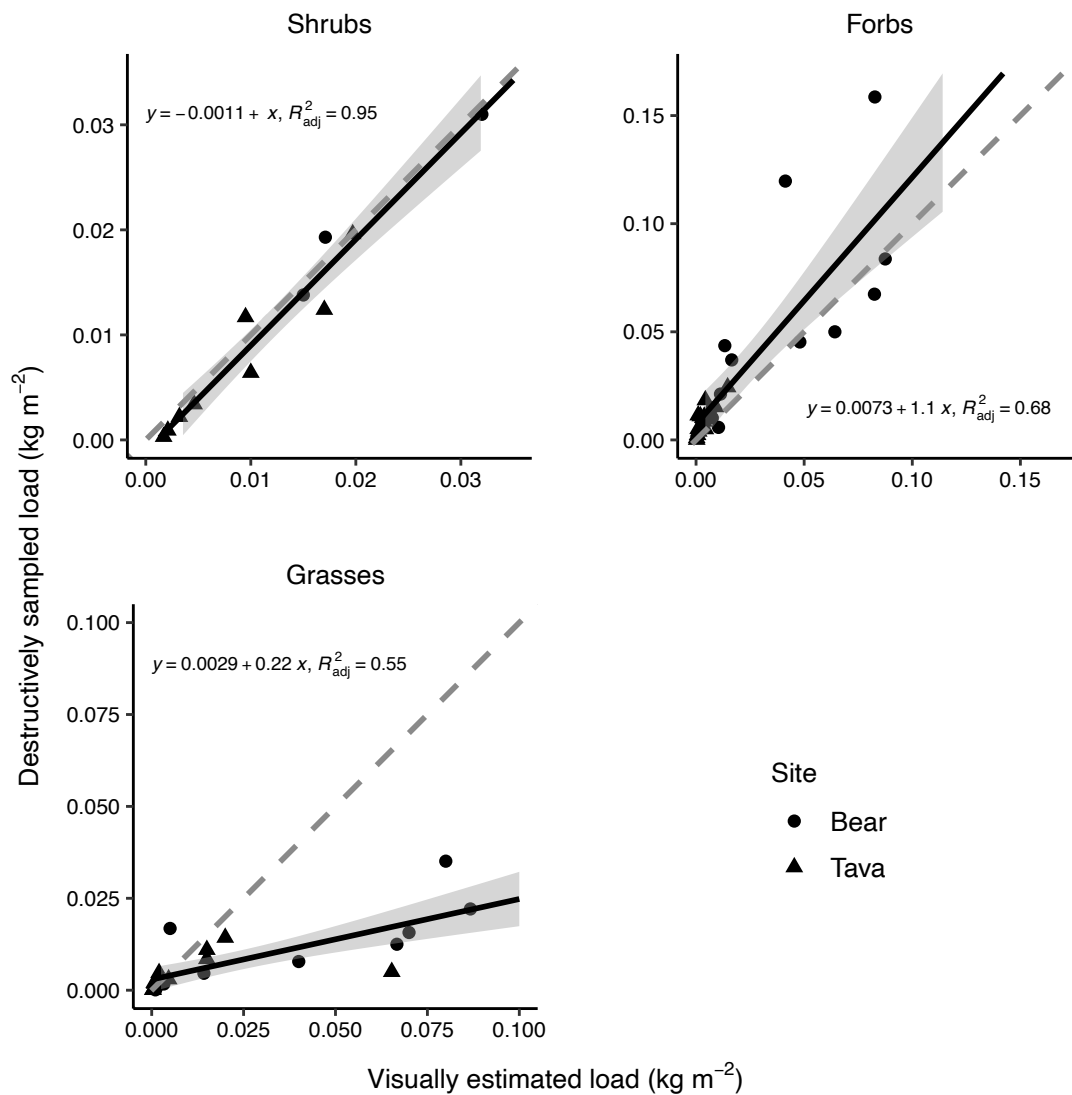


Figure D.1: Regression plots of destructively sampled load vs. visually estimated load for shrubs, forbs, and grasses at two study areas. Eleven shrub, 25 forb, and 22 grass samples were collected and are depicted here. Dashed gray lines represent the 1:1 line and gray bands around the black regression lines represent the 95% confidence intervals.

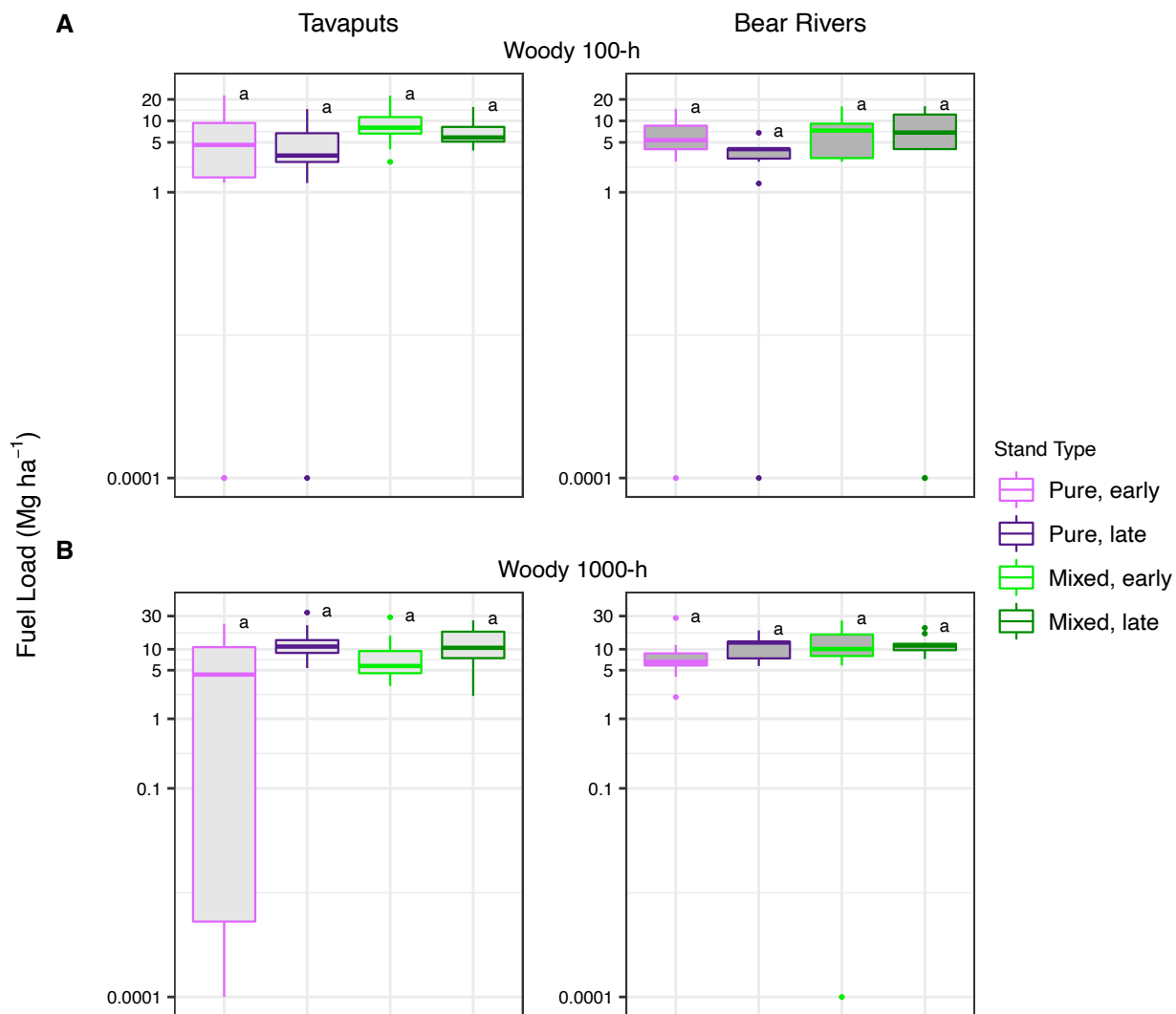


Figure D.2: Fuel load of coarse dead woody surface fuels (a) woody 100-h, (b) woody 1000-h across aspen stand types in two study areas. Note that the y-axis is on logged scale and that the scale varies by fuel component. Each boxplot represents ten plots. Different letters above boxplots indicates statistical significance ( $p < 0.05$ ) among group means.

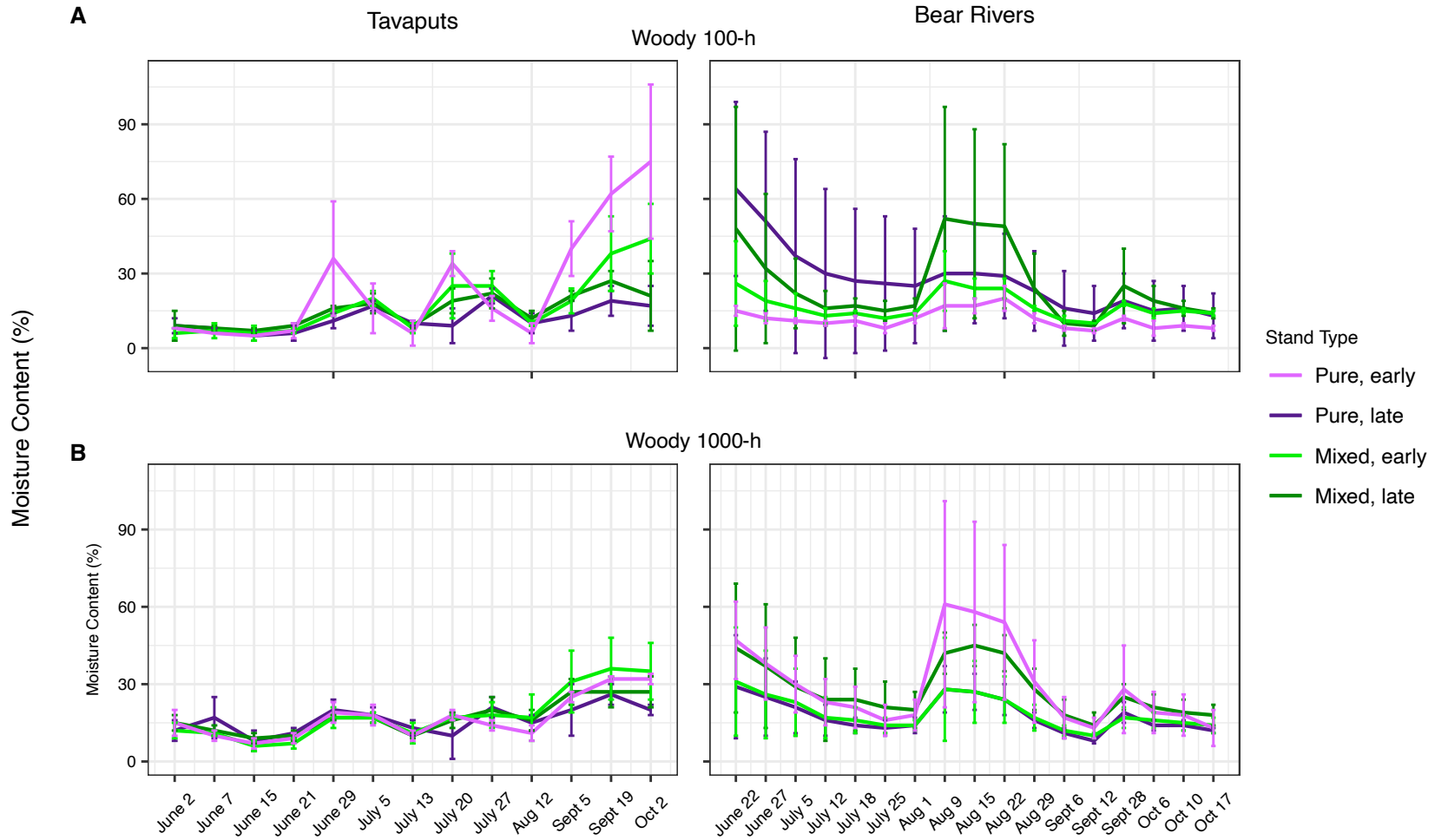


Figure D.3: Moisture content trends of coarse dead woody surface fuels across aspen stand types in two study areas. Woody 100-h fuels are 2.5 to 7.6 cm in diameter and 1000-h fuel are greater than 7.6 cm in diameter. Note that the y-axis scales vary by fuel component.



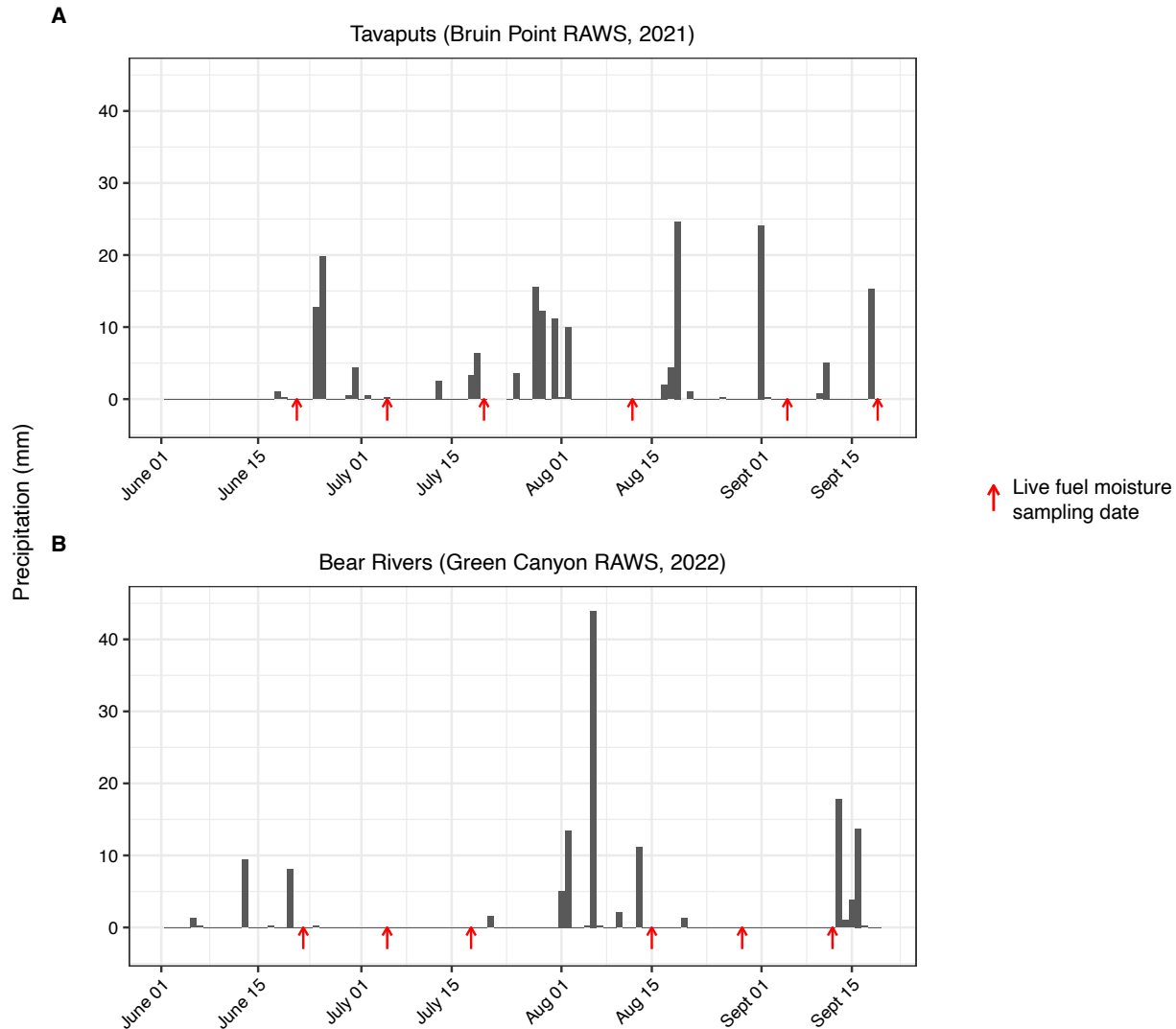


Figure D.4: Daily precipitation amounts during the growing season near two study areas: Tavaputs (A) and Bear Rivers (B). Data was downloaded from the nearest Remote Automatic Weather Station (RAWS; from Western Regional Climate Center) to fuel moisture sampling sites in each study area. Red arrows indicate the days on which live fuel moisture and soil moisture sampling occurred. The nearest station to the Tavaputs was the Bruin Point RAWS ( $39^{\circ} 36' 35''$  N,  $110^{\circ} 17' 40''$  W at 3109 m elevation) and the nearest station to the Bear Rivers was the Green Canyon RAWS ( $41^{\circ} 46' 10''$  N,  $111^{\circ} 46' 00''$  W at 1596 m elevation).