**Title:** Short-interval reburning changes fuel structure and flammability of forests

This chapter examines dynamics and distributions of fuel loads in reburned stands in boreal Alaska to evaluate subsequent modeled changes in potential fire danger and initial fire behavior. This chapter is an extension of the dissertation, funded with a Graduate Innovation Award from the Joint Fire Science Program (ID 19-1-01-43).

## Introduction

Fire events at a local or landscape scale are fundamentally driven by three components: weather, fuel and local/landscape environmental controls (Whitlock et al. 2010). Changes in any single component can drive shifts in fire behavior or even fire regimes, depending on the scale. Changes in fuel in particular are directly related to subsequent changes in fire behavior across scales and regardless of system (Taylor and Fonda 1990, Schimmel and Grantsrom 1997, Hely et al. 2009). This relationship between fuel and fire behavior signifies that fuel serves as a link between vegetation type and combustion environment (Mitchell et al. 2009). Since the spatial distribution of fuel elements in a given stand shape both fire danger and initial surface fire behavior (Hely et al. 2009), shifts in community composition that alter the spatial distribution of fuels may influence subsequent fire behavior. Therefore, evaluating how ecological transitions alter the characteristics of fuel loads, connectivity and spatial distributions can provide insight into future landscape flammability and potential fire-vegetation feedbacks.

Ecological transition in the boreal from conifer to deciduous species (i.e., Hoy et al. 2016, Johnstone et al. 2010) has led to suggestions of a potential negative feedback to fire enabled through the increased presence of deciduous-dominated landscapes (Astrup et al. 2018).

The presence of less flammable deciduous species has been invoked as a landscape management solution to arctic and boreal warming, based on paleoecological evidence of declining fire activity found alongside increases in the presence of birch (Kelly et al. 2013, Brubaker et al. 2009). Evaluating the strength of a potential negative feedback to burning driven by increasing presence of deciduous species under modern climatic and vegetation conditions will provide crucial insight into the mechanistic drivers of fire activity into the boreal and will inform future fire management efforts under drying conditions.

Several lines of evidence point to a weakening or override of the hypothesized deciduous feedback. First, evidence of a negative feedback is primarily based on paleoecological records which may be an inadequate approach on its own: historical forest compositions are not analogous to modern conditions. According to local lacustrine pollen archives, past boreal environments were dominated by birch alone (Higuera et al. 2008) while recent studies have found alder, aspen, and even willow in dominant quantities in modern boreal forests (Hayes and Buma, *in review*). Furthermore, some have suggested that modern patterns of burning, when viewed in comparison to paleoecological records, demonstrate that the deciduous feedback has become overridden entirely. Kelly et al. 2013 in a synthesis of paleoecological sediment records suggest that the present fire regime may have surpassed the proposed vegetation-induced limits that constrained burning during the Medieval Climate Anomaly. Additionally, preliminary work (Hayes and Buma, *in press*) demonstrates that stand structure changes dramatically across a 1-3 short-interval fire gradient, with three burns resulting in more open, shrubby structure with increased presence of willow. The role of stand structure in shaping fuel distributions indicates that paleoecological studies are not a perfect analogue for modern change, and that specific modern empirical data on the spatial distribution of fuel elements is required to both evaluate the presence of a deciduous feedback and to inform future management directions.

Finally, the fire seasons of 2004 and 2005 are a tangible example of modern burning exceeding historic or paleoecologic analogs. Fires in the summer of 2004 burned more area within the season than any other year in Alaska’s 58-year historical fire record (Todd and Jewkes 2006). During those record-breaking seasons, fires burned spruce and deciduous stands at similar frequencies (Kasischke et al. 2010). This pattern of burning suggests that deciduous stands are perfectly capable of burning in modern extreme conditions. As extreme fire seasons (like the ones in 2004 and 2005) are expected to increase with increasing warm and dry summers (Balshi et al. 2009), it is possible that even emerging deciduous stands will not be exempt from future fire activity.

## Chapter Aims

### Study Objective

This study has three objectives: 1) evaluate how the distribution of fuel elements changes with increasing short-interval reburns, 2) examine differences in fuel distribution in an upland and lowland reburned environment and 3) assess how modeled fire behavior differs across reburn sequence and between topographic position. In contrast to previous studies that examine the distribution of fuel elements after a single fire event, here I assess fuel loads in boreal stands that have experienced between 1 to 3 short-interval sequential fires. These results provide fine-scale characterizations of variation in fuel loads and structures within reburned areas, contributing to our understanding of the strength of the proposed deciduous negative feedback.

### Research Questions

1. What is the spatial distribution of fuel elements in areas experiencing 1, 2 or 3 short interval fires?
2. How does the spatial distribution of fuel elements differ between uplands and lowlands in response to repeat burning?
3. What is the effect of short interval reburns on modeled fire danger and initial surface fire behavior?

### Hypotheses

* I hypothesize large fuels will decrease with increasing numbers of fire, and fine fuels will increase.
* I hypothesize that connectivity of fuels will increase in once- and twice-burned sites but decline in thrice-burned sites.
* I further hypothesize that modeled fire danger and initial surface fire behavior will be greatest in once and twice-burned stands via the hypothesized increase in fuel loads but will differ according to site type.

## Chapter Outline

### Methods

#### Study Design

To investigate the role of reburns in altering spatial distributions of fuel, we sampled loads and spatial patterns of fuels in two sites in Interior Alaska. Each site has experienced between 1-3 fires within >30-year intervals and between both locations, 42 plots were established randomly within burn perimeters. 8 additional plots were established in unburned remnants as a reference of inferred pre-fire conditions.

#### Field Sampling

Downed woody debris fuel loads (DWD, dead wood lying or standing below <45-degree angle) were measured using two 28-m transects (also referred to as brown’s lines, Brown 1974) radiating from the center of each 20m-by-20m plot. Transects were laid pointing northeast to northwest and southeast to southwest. Individual pieces of DWD were counted where they intercepted the transect line. Diameter, species, presence of charred material and decay class of 1000-hour fuels were measured across the full transect. DWD in the <3cm size class were counted according to fuel time lag categories (0-0.25 cm = 1-hour, 0.25-1 cm = 10-hour, 1-3 cm = 100-hour) and across the following subsets of transect (1-hr = 2m, 10-hr = 5 m, 100-hr = 15m).

Fine fuel loads were measured in the same two 28-m transects in each plot. Height of the tallest vegetation connected continuously to the forest floor was measured in centimeters acorss 2-meter increments of the transect line. [may shorten to just brown’s lines]

The two approaches above represent more traditional methods of evaluating fuel loads and arrangements in forest stands and while useful, do not fully capture the range of variability or spatial non-uniformity often found in surface fuelbeds (Hardy et al. 2008). To expand on those metrics, we also evaluated spatial patterns of fuels directly, using a 3D sampling framework developed by Hawley et al. 2018. The framework allows for measurements of fuel biomass at scales and dimensions useful for characterizing heterogeneity in fuels within a stand. The 3D fuels sampling framework uses a 3D rectangular sampling frame to collect fuel data at the scale of the entire frame (0.25 m3), the fuel stratum (0.025 m3) and the individual voxel (0.001 m3). We randomly placed ten 3D sampling frames within each plot, recording presence and absence of fuels within each strata. We destructively harvested representative samples of fuels to evaluate fuel moisture.

We will investigate forest resilience to contemporary short-interval fires (1-3 fires within ~50 years) at two scales (four sites [Table 1] and ~25 plots per site), spanning a gradient of soil moisture and recent fire histories. We will focus on (a) species regeneration patterns to link to postfire vegetation change inferred from H1 and (b) structural properties to link to fire behavior modeling in H3. At each site, measurements will be done at two scales: the plot scale via fieldwork, and landscape via drone-based remote sensing.

We will leverage existing regeneration data from two sites (Fig. 3) for efficiency, where only structural data remain to be collected. The two new sites have a pre-existing paleoecological record (Fig. 6), and we will collect regeneration and structural data nearby (Table 2). Determining precise plot points will be done with a combination of historical imagery and satellite remote sensing, following the methodology of Hayes and Buma (*in press*).

Postfire seasonal climate conditions, important for seedling survival, will be taken from regional climate-interpolation (via the Scenarios Network for Arctic Planning; SNAP) data products, spanning 5 years after each fire. Woody fuel moisture will be measured with a Delmhorst J-2000 (in field) and herbaceous material via harvest (wet weight, dry, reweigh; data already collected in prior projects).

Fine-scale spatial variability will be quantified in two ways. First, we will randomly place 10, 2x2x1 m sampling cubes within each plot and quantify fuel structure and biomass using Hawley et al. (2018) methodology. To calculate spatial dispersion of ground vs. standing fuel elements, we will measure the distance to nearest tree from each of the 10 sampling cubes. This spatial pattern data allows us to generate realistic “fuel-scapes” that quantify fuel composition, density, and distribution to directly inform the H3 model.

We anticipate fine-scale variability in fuel structure will be highest at sites that have burned twice, relative to sites that burned either once or three times in recent decades (Fig. 2). There is a small body of literature using similar techniques to measure fire refugia in flammable landscapes (at broader scales: Chapman et al. 2020); this project will extend that concept to short-interval fires, and link fuel characteristics to a high-resolution fire behavior model. Statistically, we will calculate and compare effect sizes of slope, aspect, and fire intervals on structural heterogeneity via generalized mixed modeling and boosted regression trees similar to the biomass and composition analysis.

#### Fire behavior modeling

To model fire behavior based on estimated fuels structures in reburns, we used the HIGRAD/FIRETEC system, a physics-based fire behavior that represents individual ecosystem components and combustion/atmospheric interactions explicitly. HIGRAD/FIRETEC specifically treats vegetation composition and structure in three-dimensions, accounting for bulk density, surface area to volume ratio and fuel moisture. By treating fuel beds as complex and homogenous (both vertically, and horizontally), HIGRAD/FIRETEC can simulate the effects of fine-scale shifts in fuels structure and composition on subsequent fire behavior.

Using this modeling framework, we modeled predicted fire danger. Fire danger here is defined as the summed stand-level characteristics (both chemical and physical) of fuel elements that favor flame propagation if ignition occurs (Hely et al. 2009). High fire danger would indicate a stand containing an abundance of fuel elements made up of either flammable products or products with the ability to sustain combustion (Hely et al. 2009). Estimating potential fire danger allows for direct insight into management of reburned stands and provides specific guidance for managers making decisions about resource allocations. Furthermore, I intend to translate predicted fire danger produced through the HIGRAD/FIRETEC system into the equivalent Canadian Forest Fire Danger Rating System (CFFDRS) ranking used by land managers and fire crews in Alaska. This will allow insights from this chapter to be shared widely with the Alaska fire science community, a network that includes fire scientists, policy makers and land managers.

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