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

**Abstract: (AFE)**

Increased reburning drives shifts in forest communities from conifer to deciduous species in Interior Alaska, creating questions about future characteristics of boreal fire regimes. An increased presence of deciduous species after reburning has been considered negative self-regulating feedback to subsequent fire activity due to changes in fuel structure and moisture content, but changes in fire weather and community composition have brought up questions about the strength or longevity of that negative feedback. The potential strength or duration of self-regulation in Boreal stands is partly driven by the assembly of fuel on the landscape (or fuelscapes). To examine the initial impacts of short-interval reburning on fuelscapes, we quantified fuel composition, abundance, and fine-scale connectivity in stands in Interior Alaska after 1, 2 or 3 fires in short-intervals. Here we present estimates of fuelscapes that emerge after continued reburning. This work provides crucial insight into the mechanistic drivers of fire activity into the boreal under changing fire regimes and will inform future fire management efforts under drying conditions.

## Introduction

Continued reburning under shortening fire intervals in Interior Alaska drive stand-level transitions from conifer-dominated forests to deciduous shrublands and grasslands (Hayes and Buma 2021, Johnstone et al. 2010). Future characteristics of the boreal fire regime and of boreal forests themselves remain unclear under those circumstances. Increased presence of deciduous species may act as a negative feedback to future fire, as deciduous communities in the boreal are typically considered less flammable (CITE). However, the strength, reliability and potential duration of a deciduous negative feedback remain unclear given the context of ongoing reburning shifting community composition past historic norms.

Several lines of evidence point to a weakening or override of the hypothesized deciduous feedback. First, modern patterns of burning, when viewed in context to paleoecological records, suggest the deciduous feedback has been overridden: a synthesis of paleoecological records shows that present fire regimes may have surpassed past vegetation-induced limits (Kelly et al. 2013). Paleoecological community types are not analogous to modern emerging deciduous communities in Alaska: local lacustrine pollen records show mid-Holocene boreal deciduous environments were dominated by birch (Higuera et al. 2008) while recent studies have found alder, aspen, and even willow in dominant quantities in modern boreal forests after multiple reburns (Hayes and Buma 2021).

Secondly, preliminary observations of emerging deciduous landscapes (Hayes and Buma 2021) demonstrate 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 () strengthens the argument that paleoecological studies are not a perfect analogue for modern changing landscapes (i.e., ), 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 (find something recent). 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 can burn under 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 emerging deciduous stands will not be exempt from future fire activity and may burn in ways that diverge from past patterns. Novel community types in combination with present climate-driven fire weather extremes may enable burning to overcome previous feedbacks. Understanding the future characteristics of boreal fire regimes requires evaluating the strength of a potential negative feedback to burning driven by increasing presence of deciduous species under modern climatic and vegetation conditions.

Fuel abundance, connectivity and distribution shape the flammability of particular stands. Research on interactions between fires in other systems suggests that legacy effects of previous fires interact strongly with subsequent fires to shape future forest composition and structure (lots, Harris eat al. 2020, other compound disturbance papers). Specifically, previous fires alter the distribution and abundance of fuels (particularly CWD) within a stand, which through subsequent effects on soil, litter cover and shade may alter post-fire seedling establishment and survival (Harris et al. 2020). [right now does not tie in well with negative feedback framing, but feels important - either tie in better or move to discussion]

To examine the relationship between community type and fuel-scapes as driven by shortening fire intervals, we examined fine-scale fuel loads in reburned stands in Interior Alaska before modeling fire behavior in stands with differing numbers of short interval fires.

Position of trees / arrangement of trees around it influence whether the tree will burn or not (Linn et al. 2005)

This study has two objectives: 1) evaluate how the fuel-scape (fuel composition, density, and distribution) changes with increasing short-interval reburns while considering differences between upland and lowland contexts and 2) compare modeled fire rate of spread and biomass consumed to ground metrics collected in (1). To that effect, we ask 3 specific research questions: 1) how does the abundance of CWD change with continued reburning? 2) how does the connectivity of fuels change with continued reburning? 3) do the trends in fuel patterns identified in 1 and 2 lead to differing trends in modeled fire rate spread?

In contrast to previous studies that examine the distribution of fuel elements after a single fire event, here we assess fuelscapes in boreal stands that have experienced between 1 to 3 short-interval sequential fires. We hypothesize fuel connectivity and abundance will increase initially with additional fires but decrease after three short-interval fires as reburns continue to consume fuel. In addition, we expect fire behavior may differ across both reburns and community type, given the difference in stand structure created by different dominating vegetation.

## Methods

### Study Area

To investigate the role of reburns in altering spatial distributions of fuel, we sampled spatial patterns of fuel abundance and distribution in two locations 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 assumed 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. We recorded diameter, species, presence of charred material and decay class of 1000-hour fuels across the full transect and counted <3 cm debris across subsets (1-hr = 2m, 10-hr = 5 m, 100-hr = 15m). Total fuel loading (tons/ha) was calculated…

Fuel depth was measured by recording height of the tallest vegetation connected continuously to the forest floor across 2-meter increments of the Brown’s transect line. Fine fuel loading… (tons/ha)…

To expand on those metrics and capture the 3D patterns of fuels, we evaluated the spatial patterns of fuels directly, using a modified 3D sampling framework developed by Hawley et al. 2018. This framework allows for measurements of fuel biomass at scales and dimensions useful for characterizing heterogeneity in fuels within a stand. The 3D fuels sampling protocol uses a 3D rectangular sampling frame (2x2x1 meters large) 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 10 3D sampling frames within each plot, recording presence and absence of all fuel types (1/10/100/1000-hour fuels, forbs, shrubs, graminoids, feathermoss) within each voxel cell (n = 16). We also recorded the dominant ground cover within each sampling frame.

To calculate spatial dispersion of ground vs. standing fuel elements, we measured the distance to nearest tree of each species present on the plot from each of the 10 sampling cubes. We used the resulting measurements of a random point to each tree species to calculate Eberhardt’s statistic for each species across each plot (CITE).

We estimated total biomass of each species using a suite of allometric equations (copy over the specific ones from biomass draft).

### 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 a suite of fire behavior metrics, including wind velocity, fire intensity, fire consumption and fire velocity. These metrics are direct links to fire behavior properties that direct subsequent total area burned, fire severity, and fire management conditions.

### Data Analysis

We calculated and compared effect sizes of slope, aspect, and fire intervals on structural heterogeneity via generalized mixed modeling and boosted regression trees. …

## Results

### Fuel abundance

CWD differed across reburn history, site and size class (Fig. X). Fine fuels (1 and 10 hour fuels) were most abundant in once- and twice-burned plots in both the upland and lowland site, and decreased by a factor of X in thrice-burned plots, declining more in up vs low (?? - check which one / add factor).

**Figure X. Mass of fuel size classes across years since initial fire and between sites according to size classes.** [dots jittered to spread data]

**Chart, scatter chart

Description automatically generated**

### Fuel connectivity

[describe fuel connectivity trends]

**Figure X. Fine fuel heights across interval from first fire and between sites. Tallest height of vegetation measured in 28-m transect lines and averaged across line.** Dots represent outliers.

Chart, scatter chart

Description automatically generated

## Discussion

The presence of less-flammable deciduous species has been invoked as a landscape management solution to boreal warming, based on paleoecological evidence of declining fire activity found alongside increases in birch pollen presence (Kelly et al. 2013, Brubaker et al. 2009).

## Acknowledgements

This study was funded by support from the NSF Polar Services Office () and a Graduate Innovation Award from the Joint Fire Science Program (ID 19-1-01-43).

## References

Astrup, R., Bernier, P.Y., Genet, H., Lutz, D.A. and Bright, R.M., 2018. A sensible climate solution for the boreal forest. *Nature Climate Change*, *8*(1), pp.11-12.

Balshi, M.S., McGUIRE, A.D., Duffy, P., Flannigan, M., Walsh, J. and Melillo, J., 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biology, 15(3), pp.578-600.

Brown, J.K., 1974. Handbook for inventorying downed woody material. *Gen. Tech. Rep. INT-16. Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.*, *16*.

Brubaker, L.B., Higuera, P.E., Rupp, T.S., Olson, M.A., Anderson, P.M. and Hu, F.S., 2009. Linking sediment‐charcoal records and ecological modeling to understand causes of fire‐regime change in boreal forests. *Ecology*, *90*(7), pp.1788-1801.

Hardy, C., Heilman, W., Weise, D., Goodrick, S. and Ottmar, R., 2008. Final Report: Fire behavior advancement plan; a plan for addressing physical fire processes within the core fire science portfolio. *Joint Fire Science Program*.

Harris, Lucas B., Stacy A. Drury, and Alan H. Taylor. 2020. “Strong Legacy Effects of Prior Burn Severity on Forest Resilience to a High-Severity Fire.” Ecosystems , September. https://doi.org/10.1007/s10021-020-00548-x.

Hawley, C.M., Loudermilk, E.L., Rowell, E.M. and Pokswinski, S., 2018. A novel approach to fuel biomass sampling for 3D fuel characterization. *MethodsX*, *5*, pp.1597-1604.

Hély, C., Bergeron, Y. and Flannigan, M.D., 2000. Effects of stand composition on fire hazard in mixed‐wood Canadian boreal forest. *Journal of Vegetation Science*, *11*(6), pp.813-824.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Brown, T.A., Kennedy, A.T. and Hu, F.S., 2008. Frequent fires in ancient shrub tundra: implications of paleorecords for arctic environmental change. *PloS one*, *3*(3).

Hoy, E.E., Turetsky, M.R. and Kasischke, E.S., 2016. More frequent burning increases vulnerability of Alaskan boreal black spruce forests. *Environmental Research Letters*, *11*(9), p.095001.

Johnstone, J.F., Hollingsworth, T.N., Chapin, F.S. and Mack, M.C., 2010. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. Global Change Biology, 16(4), pp.1281-1295.

Kasischke, E.S., Verbyla, D.L., Rupp, T.S., McGuire, A.D., Murphy, K.A., Jandt, R., Barnes, J.L., Hoy, E.E., Duffy, P.A., Calef, M. and Turetsky, M.R., 2010. Alaska’s changing fire regime—implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research*, *40*(7), pp.1313-1324.

Kelly, R., Chipman, M.L., Higuera, P.E., Stefanova, I., Brubaker, L.B. and Hu, F.S., 2013. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. Proceedings of the National Academy of Sciences, 110(32), pp.13055-13060.

Koo, E., Linn, R.R., Pagni, P.J. and Edminster, C.B., 2012. Modelling firebrand transport in wildfires using HIGRAD/FIRETEC. *International journal of wildland fire*, *21*(4), pp.396-417.

Schimmel, J. and Granström, A., 1997. Fuel succession and fire behavior in the Swedish boreal forest. *Canadian Journal of Forest Research*, *27*(8), pp.1207-1216.

Taylor, K.L. and Fonda, R.W., 1990. Woody fuel structure and fire in subalpine fir forests, Olympic National Park, Washington. *Canadian Journal of Forest Research*, *20*(2), pp.193-199.

Todd, S.K. and Jewkes, H.A., 2006. Wildland fire in Alaska: a history of organized fire suppression and management in the last frontier.

Whitlock, C., Higuera, P.E., McWethy, D.B. and Briles, C.E., 2010. Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. *The Open Ecology Journal*, *3*(1).

Appendix

**Figure X. Differences in fuel moisture between sites and across treatments. Normalized weight loss is measured as the water weight lost after drying (wet weight – dry weight), divided by the initial wet weight in grams.**

Chart, box and whisker chart

Description automatically generatedChart, scatter chart

Description automatically generated