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

**Abstract: [ v early draft]**

Increased reburning is driving shifts from conifer to deciduous dominated forests in Interior Alaska, driving questions about future characteristics of boreal fire regimes. Increased presence of deciduous species has been considered a negative feedback to subsequent fire activity, but changes in fire weather and community composition have brought up questions about the strength or longevity of that negative feedback. Here we directly test the deciduous-flammability feedback by examining the effects of reburning on fuel arrangement and abundance and using those fuel patterns to simulate subsequent shifts in fire behavior. Our results suggest … This work provides crucial insight into the mechanistic drivers of fire activity into the boreal and will inform future fire management efforts under drying conditions.

## Introduction

Shortening fire intervals in Interior Alaska are driving stand-level transitions from conifer-dominated forests to deciduous shrublands and grasslands (Hayes and Buma 2021). Fire-driven community shifts in dominant tree species in the boreal (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).

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 become overridden: Kelly et al. 2013 in a synthesis of paleoecological records suggest that the present fire regime may have surpassed the proposed vegetation-induced limits. One potential mechanism for driving burning pattrns past any previous deciduous feedback is shifting community types: paleoecological community types may not be analogous to modern emerging deciduous communities in Alaska. According to local lacustrine pollen records, past boreal 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, particularly 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 (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. 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.

[lit review of modern landscape-scale flammability/cover type analyses]

To examine the relationship between community type and flammability as driven by shortening fire intervals, we examined fine-scale fuel loads in reburned stands in Interior Alaska before modeling fire behavior in reburned stands. 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) connect landscape-scale trends in flammability with fine-scale measurements of fuel loads and patterns in reburned stands. In contrast to previous studies that examine the distribution of fuel elements after a single fire event, here we assess fuel loads 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 Design

To investigate the role of reburns in altering spatial distributions of fuel, we sampled spatial patterns of fuel abundance and distribution 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 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).

We used aforementioned browns’ lines to measure fine fuel loads in each plot by recording height of the tallest vegetation connected continuously to the forest floor in centimeters across 2-meter increments of the transect line.

The two approaches above represent more traditional methods of evaluating fuel loads and arrangements in forest stands and while meaningful, 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. 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 protoccol 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 within each voxel cell (n = 25). We destructively harvested representative samples of all fuels from each strata and dried and weighed each sample to evaluate fuel moisture. To calculate spatial dispersion of ground vs. standing fuel elements, we measured the distance to nearest tree from each of the 10 sampling cubes.

#### 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.

**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 as reflected by coarse-woody debris counts differed across reburn history, site and size class (Fig. X).

**Figure X. Counts of coarse-woody debris across reburn and between sites according to size classes.** Dots represent outliers. **[need to add steese unburned data]**

**Chart, box and whisker chart

Description automatically generated**

**Figure X. Fine fuel loads across reburn history and between sites. Loads evaluated as the tallest height of connected vegetation across the plot.** Dots represent outliers.

Chart, box and whisker 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*.

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).