*Fire spread in reburned boreal deciduous forests is limited by wind speed and fuel connectivity, not fuel availability*

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4Justin’s new affiliation (?)

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## Abstract

Fire frequency in the boreal forest has increased via longer burning seasons, dryer conditions, and higher temperatures. But fires have historically also self-regulated via fuel limitations, mediating the effects of changes in climate and fire weather. Post-fire landscapes are believed to produce negative feedbacks to future burning, via the lower flammability of regenerating, typically deciduous shrub-dominated landscapes compared to their intact, conifer counterparts. However, the strength of that self-regulation remains unclear in the context of changing fire weather and emerging novel forest communities and structures. One first step in evaluating potential future fire behavior in emerging deciduous landscapes is evaluating the abundance, composition, and structure of fuels across a landscape scale to understand how these unique fuel complexes influence the rate and sustainability of fire spread and fuel consumption. We quantified fuel composition, abundance, and structure in stands in Interior Alaska after 1, 2 or 3 fires in short-intervals, and then created virtual landscapes and simulated fire behavior using the Wildland-Urban Interface Fire Dynamics Simulator. After a single fire, extreme fire weather conditions allowed for sustained fire spread, suggesting that intense fire conditions can enable short-interval events. However, fires could not carry in thrice-burned landscapes, where regeneration was often dense but more clumped and thus overall less connected, separated by patches of bare soil. Fire traveled an average of 50 meters into thrice-burned landscapes before dying out, even under extreme fire weather conditions. This work suggests that the negative feedbacks observed today may continue, at least after repeated fire, due to a lack of fuel continuity. It also provides crucial insight into the mechanistic drivers of fire activity into the boreal under changing fire regimes and can inform future fire management efforts under drying conditions.

**Keywords**:

## Introduction

Warming temperatures and drier conditions can decrease the interval between fire events, leading to an increase in reburning in Interior Alaska (Buma et al. 2022). Historically, return intervals between fires were 100 to 300 years in Interior Alaska (Hoecker and Higuera 2019), enforcing a ‘legacy lock’ on forest composition that allowed conifers like black spruce (*Picea mariana*) to dominate (Johnstone et al. 2010). Reburns (two fires in an interval of 50 years or less in the boreal) and continued reburning (three or more fires in an interval of 150 years or less) drive stand-level transitions from conifer-dominated forests to deciduous shrublands and grasslands (Johnstone and Chapin 2010, Hayes and Buma 2021). Deciduous communities in the boreal are historically less flammable (less capable of igniting and carrying fire spread, Pausas et al. 2017), due to higher foliage moisture (Kelly et al. 2013). Thus, increased presence of deciduous species on the landscape may provide a negative feedback to future fire (Brubaker et al. 2009), enacting a process also referred to as ‘self-regulation’ (Parks et al. 2015, Hart et al. 2019). However, the strength, reliability and potential duration of negative feedbacks derived from an increased presence of deciduous species remains unclear, given that ongoing reburning is shifting community composition outside of historic norms. Here, we explore the strength of deciduous self-regulation by investigating the relationship between fuels and potential fire behavior in emerging reburned stands.

Fire in Alaska is determined by a combination of fire weather and climate, referred to here as top-down controls (Barrett et al. 2016, Walker et al. 2020), and species composition and stand structure, bottom-up controls (Chapin et al. 2006, Walker et al. 2019). Both directions of fire drivers are highly variable in space and time: Top-down drivers of fire include the day-to-day fluctuations in fuel moisture, the seasonal impact of fire weather and the long-term patterns of climate. In contrast, bottom-up drivers can include variability in both macro- and microtopography, fuel availability, fuel connectivity and underlying drainage. Depending on the scale of investigation, both top-down and bottom-up drivers are important drivers of fire; while fire weather in extreme seasons can drive increases in burning, over longer time scales, bottom-up drivers of fuel drive burning across boreal ecoregions (Walker et al. 2020).

From a bottom-up perspective, changing forest characteristics should be able to alter fire behavior. But forests in boreal Interior Alaska have been remarkably stable in terms of structure and composition for thousands of years (Kelly et al. 2013). Paleoecological community types, on which the description of a negative feedback are based, are not analogous to modern emerging communities in Alaska: mid-Holocene boreal deciduous environments were dominated by birch (*Betula neoalaskana*) (Higuera et al. 2008; Kelly et al. 2013) while recent studies have found alder (*Alnus crispa*), aspen (*Populus tremuloides*), and even willow (*Salix* spp.) in dominant quantities in modern boreal forests after reburning (Johnstone et al. 2020, Hayes and Buma 2021). Early observations of regenerating deciduous landscapes in Interior Alaska demonstrate that stand structure changes distinctively across a 1-3 short-interval fire gradient: three burns result in a more open, clumped spatial distribution with increased presence of willow and aspen (Hayes and Buma 2021). The role of stand structure in shaping fuel distributions (Hély et al. 2000, Eckdahl et al. 2022) strengthens the argument that paleoecological studies are not a perfect analogue for fire environments of modern changing landscapes (Kelly et al. 2013).

The spatial distribution of fuels determines both local wind flow and the arrangement of combustible material, two factors that can meaningfully alter fire behavior (Parsons et al. 2017; Atchley et al. 2021). Although we know there are significant compositional changes associated with emerging high-frequency fire regimes (Hayes and Buma 2021), we don’t know how shifts in forest composition change the spatial distribution of fuels. More open landscapes may increase wind speeds at fire elevations, for example. Facing this knowledge gap, specific modern empirical data on the spatial distribution of fuel elements is required to both evaluate the presence significance of a deciduous any self-regulation feedback and to inform future management directions.

Structural changes are an example of bottom-up controls on fire behavior, but top-down climate forcing can increase fire extents as well. The fire seasons of 2004 and 2005 are direct examples of modern burning exceeding historic or paleoecologic analogs. Fires in the summer of 2004 burned 8-times the area of the 10-year state average (Turquety et al. 2007). During both 2004 and 2005, spruce and mature deciduous stands burned at similar frequencies (Kasischke et al. 2010). This fire pattern suggests that deciduous stands have the potential to burn as frequently as coniferous stands under modern extreme conditions. Extreme fire seasons (like the ones in 2004 and 2005) may become the norm via increasingly warm and dry summers (Balshi et al. 2009). In addition, landscape-level studies of recent reburning in Alaska found the effects of self-regulation are strongest within the first decade after fire but begin to decay within 10 to 20 years (Buma et al. 2022). The combined impact of novel community types, more open stand structures, and extreme climate-driven fire weather may enable fire to overcome previous self-regulation thresholds. Understanding the future characteristics of boreal fire regimes requires evaluating the combined role of shifts in community type, forest structure, and fire weather conditions and their potential cumulative impact on future fire behavior.

One challenge in understanding potential future fire behavior is the intrinsic novelty in emerging forest types: most of our tools for understanding and predicting fire behavior depend on rules and relationships determined by historic observations (i.e., standardized indices of fuel types, Stocks et al. 1989). Emerging forest types with structure and composition that differ from historic norms require models that can test changing fire weather simultaneously with shifts in fuel characteristics and stand structures.

Physics-based wildland fire behavior modeling can explore potential fire behavior even in systems with novel fuel characteristics (Hoffman et al. 2018). Modelers distinguish between landscape models (or formulaic models), which use empirically-derived, static metrics of spread rates and other components, and physics-based (or process-based) models which use and solve equations for the first-order physical processes underlying fire spread. Because physics-based models incorporate underlying processes explicitly instead of implicitly, users can study the role of factors like wind, fuel structure, fuel moisture, terrain, and others. Both landscape and physics-based models have limitations – simpler formulaic models cannot be justifiably applied to environmental conditions outside the ones where they were derived, and complex models can be prohibitively computationally expensive. Given adequate resources, physics-based fire behavior models can explore dynamics of fire outside of documented historic norms of fuel and fire weather conditions, where landscape models have been calibrated, (Mell et al. 2010, Linn et al. 2013).

One such model is the Wildland-Urban Interface Fire Dynamics Simulator (WFDS), a physics-based fire behavior model that represents individual ecosystem components and the interactions of combustion with the atmosphere. WFDS models vegetation composition and structure in three-dimensions, accounting for bulk density, surface area to volume ratio and fuel moisture. WFDS has a wide range of applicability (Mell et al. 2010), including exploring novel fire behavior across complex fuel structures like the Wildland-Urban-Interface (i.e., Mell et a. 2011), transitions between homogenous conifer forests to mixed conifer-deciduous forests (Ziegler e al. 2021) and fuel removal treatments (Ziegler et al. 2020).

The lack of important relevant information on emerging forests and their relationship with fire provides an ideal and timely opportunity to apply a physics-based model to questions related to fire behavior and fire self-regulation, topics of considerable importance for future boreal forest stability. These questions are of utmost importance to fire managers as well. Our objective was to evaluate how fuel composition, landscape-level fuel density, and distribution changes with increasing short-interval reburns in order to explore potential fire behavior across a gradient of fuel and weather conditions. In contrast to previous studies that examine the distribution and abundance of fuel elements after a single fire event, here we assess fuel characteristics 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 potential fire behavior may increase across both reburns and community type, given the difference in stand structure created by different dominating vegetation. Finally, we predict that extreme fire weather conditions (high winds and low fuel moisture) may produce novel potential fire behavior in reburned stands, potentially overwhelming bottom-up constraints (i.e., fuel connectivity or abundance) to burn stands that would not burn otherwise.

## 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 100 meters apart and a minimum of 50 meters from roads. 8 additional plots were established in unburned remnants as a reference of assumed pre-fire conditions.

### Field Sampling

To quantify fuel abundance in reburns, we measured dead down woody debris fuel loads (DWD, dead wood lying or standing below <45-degree angle) using two 28-m brown’s fuel transects (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 fine debris across subsets (1-hr = 2m, 10-hr = 5 m, 100-hr = 15m). Total fuel loading (tons/ha) was calculated by converting DWD field data into estimates of mass per area (grams per meter) following Brown (1974). We measured mass of understory fuels by harvesting randomly located 1 meter by 1-meter subplots, drying vegetation and then weighing. We measured surface fuel depth by recording height of the tallest vegetation connected continuously to the forest floor across 2-meter increments of the Brown’s transect line. To capture standing live and dead fuel abundance, we measured height and diameter at breast height (DBH 1.37 m) of standing live and dead trees at each plot in 200 m2 randomly selected subsections and scaled to produce estimates of tree density. We estimated total biomass of each species using a suite of local species-specific allometric equations (see Appendix: Table S1 for specifics, Binkley et al. 1984, Bond-Lamberty et al. 2002).

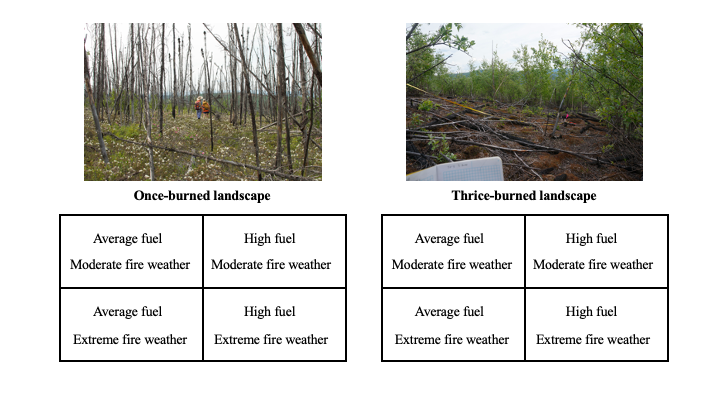
To capture the 3-dimensional pattern of fuels, we evaluated vertical and horizontal spatial patterns of fuels directly, using a modified 3-D sampling framework developed by Hawley et al. 2018. This framework allows for measurements of fuel biomass at scales and dimensions useful for characterizing heterogeneity in fuels within a stand. We randomly placed 10 3-D 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 within each frame). We also recorded the dominant ground cover as a visual estimate of percent 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 index, a metric of dispersion based on random-point-to-nearest-organism-distance, for each species across each plot (Hines and Hines 1979).

where = Eberhardt’s index of dispersion for point-to-organism distances, = the observed standard deviation of distances, and = the mean of point-to-organism distances. The expected value of in a random population is 1.27 – values below suggest a regular pattern, values above suggest clumping.

### Fire behavior modeling

To model fire behavior based on estimated fuels structures in reburns, we used the Wildland-Urban Interface Fire Dynamics Simulator (WFDS), version 9977. We chose WFDS over other modeling approaches for two reasons. First, it operates off a first principle, fluid-dynamics-based physics framework, meaning it can capture emergent fire behavior associated with the interactions between vegetation structures and wind flow and the fire. Second, WFDS was developed with capacity to capture the complex fuel dynamics that occur in borders between dramatically different cover types (Hoffman et al. 2018; Mell et al. 2010; Castle et al. 2013), such as those occurring between mature black spruce forests and regenerating deciduous stands (Boby et al. 2010; Cahoon et al. 2022).



**Figure 1**. Modeling Scenarios. Simulated landscapes were built using observed forest composition and structure characteristics from once-burned and thrice-burned plots, using mean values and 90th quartile values to represent an average fuel load and an extreme fuel load.

Our simulation-based experimental design was fully factorial. This included (1) fuel setups with once- and thrice-burned fuels in the latter half of the fire simulations' domains (with unburned fuels in the front half). (2) Moderate or extreme fire weather. Moderate fire weathers had surface fuel moistures of 10%, open (10-m AGL) wind speeds of 4 m/s, and conifer/hardwood foliar moisture contents of 97%/109% respectively. Extreme fire weathers had surface fuel moistures of 10%, open (10-m AGL) wind speeds of 8 m/s, and conifer/hardwood foliar moisture contents of 77%/89%.

We generated random landscapes based on observed densities, surface fuels, and spatial dispersions of trees for once- and thrice-burned stands. To produce a representation of average fuel characteristics, we distributed the mean density of trees across each simulated landscape, and pulled from our distributions of composition, height and DBH to assign each tree a species, live/dead status, height, and volume. To produce an extreme representation of fuel, we distributed the 90th quartile density of trees across the same 800 by 300 m landscape pulled from the same distributions of composition, height and DBH to assign tree characteristics (code available online). In all scenarios, conifers are represented as cones and deciduous species are represented as cylinders. We used metrics of fuel moisture from the National Fuel Moisture Database (CITE), using the average (across 2011 - 2020) monthly August minimum of foliar moisture content. To capture the transition of fire from unburned to reburned stands, we started each modeled fire ignition in a simulated black spruce stand that were based on measurements of forest structure and composition in our unburned reference plots (Fig. 2).

Simulation domains spanned 560 m in the streamwise direction, 70 m in the spanwise direction and were 95 m tall. The once-or thrice burned fuels began 360 m from the inlet of the domain at a location labelled x = 0 and extended to the outlet of the domain 200 m down wind of the transition, x = 200 m. The upwind unburned forest fuels spanned from x = -360 to x = 0 m. Inlets (x = -360 m) had wind entering, following a typical wind profile power law function (u(z) = u(r) x (z/z(r))^(1/7) ) where u(r) was either 4 m/s or 8 m/s depending on our specific simulation case and z(r) was 10 m. Wind exited at x = 200 m.

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**Figure 2.** An example of a simulated WFDS landscape. X = 0 represents the transition zone between unburned and burned landscapes. The Z-axis represents the height of the modeling domain, determined by the 90th quartile of heights observed in the field. The Y-axis represents the width of the modeling domain and differed according to model scenario – high fuel scenarios produced too many trees to be tracked across the same space. Cones represent deciduous species, cylinders represent conifers.

We represented understory fuel loads using the combined mean values of understory vegetation weight and seedling weight per square meter. Based on observations of percent cover, we distributed two forms of surface fuels across each landscape: 1) a representative litter layer that included litter, lichen, fine fuels, and other organic materials, and 2) a litter, herb and shrub layer that included woody surface fuels.

To explore how characteristics of potential fire behavior differed across fuel / weather / burn scenarios, we tracked wind speed (meters per second), time of arrival (in seconds), rate of spread (meters per second) in each combustion simulation. Rate of spread was calculated in meters per second using loess smoothing of the time of arrival for each pixel from X = 0. Time of arrival represents the first time in seconds a loss of biomass is observed in each given pixel. These metrics are direct links to fire behavior properties that direct subsequent total area burned, fire severity, and fire management conditions. To explore how fire effects might differ in fuel / weather / burn scenarios, we estimated canopy and crown consumption in each scenario, measured as the percent of dry mass consumed between the start and end of the simulation.

WFDS can track a limited number of trees – due to limitations in computer resources, we tracked a smaller transect of trees in once-burned high fuel scenarios. Because of the relatively low number of replications (due to processing time), we chose to analyze the results in a primarily qualitative fashion.

## Results

### Fuel Abundance

Downed woody fuel abundance of all size classes increased with reburning but differed across specific reburn history and size class. Fine fuels (1- and 10-hour fuels) were most abundant in once- and twice-burned plots, increasing by an average factor of 3 after one fire, decreasing by a factor of 1.6 after two fires, and increasing by a factor of 2 after three. Large fuels (1,000-hour fuels) followed a similar trend, increasing by a factor of 8 after one fire, declining after the second, and reaching a maximum average of 4.29 tons per ha after three fires. Medium fuel size classes (100-hours) increased after one fire but didn’t change meaningfully between reburning (Fig. 3).

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**Figure 3.** Average mass fuel load by fuel size classes of dead down woody debris (Tons/Ha) across years since initial fire and between sites according to size classes. Dots represent outliers.

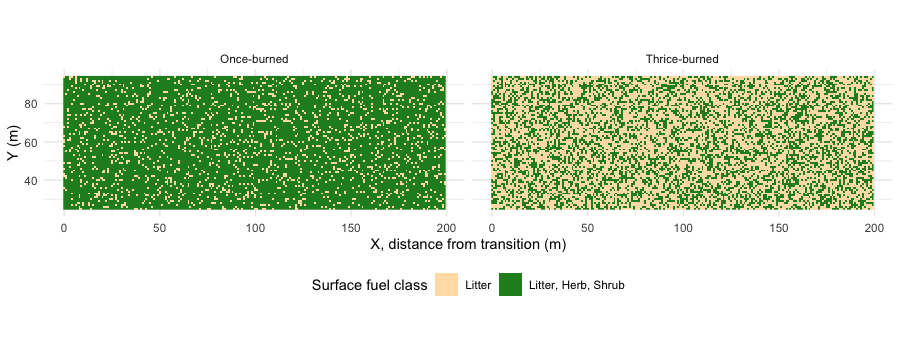
The density and mass of standing fuels (live and dead trees) differed between the once-burned and thrice-burned plots: once-burned plots contained greater numbers of dead trees, primarily spruce killed in the first fire. Those spruce were the largest in the dataset in terms of DBH, and thus contained the greatest mass. Tree height was greatest in once-burned stands, again due to the increased presence of dead spruce on the landscape (species height distributions presented in Appendix C: Fig. S1). Trees were less dense generally in thrice-burned plots. In both once- and thrice-burned scenarios, using the 90th quartile of tree density observations doubled the number of trees in the simulation and roughly doubled fuel load and density (Table 1).

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| --- | --- | --- | --- | --- | --- | --- |
| **Table 1**. Fuel abundance and density of trees (live/dead) within burns and scenarios. DBH is the average diameter of trees, measured in centimeters. Density is the number of trees per m2. SD stands for standard deviation. Fuel load is measured as kilograms per square meter. Fuel density is measured as kilograms per cubic meter. | | | | | | |
| Burn | Fuel  Scenario | Fuel Load (Kg/m2) | Fuel Density (Kg/m3) | Status | DBH (cm) | Density (trees/m2) |
| *1x* | Mean | 0.0166 | 0.00962 | Live | 0.714 (SD 0.465) | 0.758 |
| Dead | 3.22 (SD 2.69) | 0.756 |
| High | 0.0303 | 0.0175 | Live | 0.714 (SD 0.46) | 1.4 |
| Dead | 3.22 (SD 2.69) | 1.4 |
| *3x* | Mean | 0.0487 | 0.0127 | Live | 1.19 (SD 0.869) | 0.628 |
| Dead | 0.871 (SD 0.757) | 0.629 |
| High | 0.109 | 0.0286 | Live | 1.19 (SD 0.870) | 1.41 |
| Dead | 0.871 (SD 0.752) | 1.41 |

### Fuel Structure

Surface fuels were less connected in thrice-burned plots compared to once-burned (Fig. 4). Once-burned plots had greater cover of surface fuels and greater fuel loads than thrice-burned stands (Table 2). Thrice-burned plots had high amounts of patches of litter alone without surface fuels (Fig. 4)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 2.** Characteristics of surface fuel and ground cover between once-burned and thrice-burned plots. | | | | | | | |
| Burn | Fuel Type | % Cover | Height (m) | Moisture (kg) | Moisture (%) | Bulk Density (kg/m3) | Load (kg/m2) |
| 1 | Litter | 13.9% | 0.04 | 0.0255 | 20 | 2 | 0.02 |
| Litter, Herbs, Shrubs | 86.2% | 0.243 | 38 | 3.64 | 0.0668 |
| 3 | Litter | 61.1% | 0.04 | 0.0155 | 20 | 2 | 0.02 |
| Litter, herbs, shrubs | 38.9% | 0.243 | 65 | 10.2 | 0.0238 |



**Figure 4.** Surface fuels across once- and thrice-burned simulated landscapes. X = 0 indicates the beginning of the transition zone. Surface fuels are split into two classes: 1) litter only, shown in tan, where leaves, lichen, moss, and organic material is present but not understory vegetation, and 2) litter, herbs, and shrubs, shown in green, where herbs and woody shrubs are present on top of existing litter layer.

Trees of all species displayed a non-random spatial distribution (Fig. 5). While Eberhardt’s index for all species was above the 1.27 random pattern threshold, the spatial dispersion of species differed between once-burned and thrice-burned plots. Variability among species was greatest within once- and thrice-burned plots. Eberhardt’s index values for aspen in particular show the greatest change across burn history, increasing from 1.37 to 1.71 to 2.69 after three fires, indicating a more clumped spatial pattern.

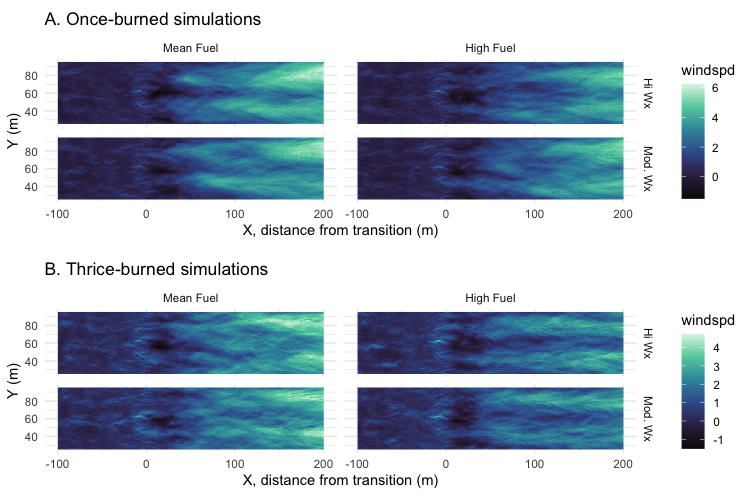
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**Figure 5.** Eberhardt’s index (a metric of dispersion based on random-point-to-nearest-organism distances) across reburn history. The expected value in a random population is 1.27 – values below suggest a regular pattern, values above suggest clumping.

### Modeled Fire Behavior

Wind in all simulations display turbulence after the transition point (x = 0) between mature and reburned landscapes. In all scenarios, wind speed was relatively stable across the mature forest landscape (x = -100 to 0), and then dropped down to speeds of 0 to 2 meters per second in the first 40 meters of reburned forest, occasionally reversing in direction back towards mature forest (represented by negative wind speeds in Fig. 6). After 50 meters of reburned forest, wind speeds in all scenarios begin to increase, initially rapidly (shown by the steeper slopes in average wind speed in Fig. 8), and then more slowly towards the end of the domain (x = 200). Wind speeds were slightly larger in mean fuel scenarios than high fuel scenarios, regardless of burn history. The primary difference between burn scenarios is the slightly faster wind speeds present towards the edge of the once-burned simulated landscape (x = 100 to 200, wind speeds reach 6 m/s, Fig. 6A) compared to the thrice-burned landscape (same region, wind speeds reach 4 m/s, Fig. 6B).



**Figure 6.** Wind speed across scenario landscapes (in meters per seconds). X = -100 to 0 is the mature unburned simulated landscape, X = 0 is the start of the transition point, and X = 0 to 200 is the reburned simulated landscape. A) Wind speed across all scenarios of once-burned simulated landscapes. B) Wind speed across all scenarios of thrice-burned simulated landscapes.

Out of the 8 total scenarios, only one scenario (once-burned, mean fuel and extreme weather) experienced fire spread across the majority of the domain. In all other scenarios, fire burned into the reburned landscape, and halted within 50 to 75 meters beyond the transition point x = 0. Both once-burned and thrice-burned scenarios burned in WFDS, but fire behavior differed greatly between reburn histories. In both the once-burned and thrice-burned landscape, bare patches of ground seemed to prevent fire spread, demonstrated in both the high fuel + extreme weather scenarios, in which the fire forked in two directions due to the presence of a bare patch (Fig. 7A, Fig. 7B).

Graphical user interface

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**Figure 7**. Time of arrival of fire, measured as the first measurable loss of biomass within a given pixel, shown in two dimensions. X of 0 at the bottom left indicates the start of the burned fuels and the beginning of the transition between mature and burned landscapes. Contours represent 10 second intervals. A) Once-burned landscape. B) Thrice-burned landscape.

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**Figure 8**. Wind speed (in meters per second) averaged across the y-axis of landscape scenarios. “Hi Wx” stands for the extreme weather conditions and “Mod. Wx” for the moderate scenario of fire weather conditions. A) Windspeed across all scenarios of once-burned simulated landscapes. B) Windspeed across all scenarios of thrice-burned simulated landscapes.

Within each scenario, trends in the rate of spread of the fire initially followed trends in wind speed – as wind speed dropped after the transition point at x = 0 (Fig. 8), rate of spread declines in all scenarios (Fig. 9). As wind speed begins to pick back up with increasing distance from the transition point, rate of spread does as well. However, across all scenarios, rate of spread and wind diverge eventually. While wind speed continued to pick up with distance from the transition point in all scenarios, only the once-burned, mean fuel and extreme fire weather scenario continued to burn past 50-75 meters beyond the transition point.

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**Figure 9**. Rate of fire spread, in meters per second, across 200 meters of X beginning with the transition from simulated mature to reburned landscapes for each fuel / weather / burn scenario.

### Modeled Fire Effects

Canopy consumption was greatest in the once-burned, mean fuel and extreme weather scenario (Fig. 10), again the only scenario to burn past 75 meters beyond the transition point (x = 0). All other scenarios display high canopy consumption (< 75%) within the first 25 meters of combustion, before dropping to 0% by the first 40 meters of the reburned domain (Fig. 11).

Graphical user interface

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**Figure 10.** Two-dimensional consumption of canopy between 1-time and three-time burns and across median and high fuel scenarios. X of 0 at the bottom left indicates the start of the burned fuels and the beginning of the transition between mature and burned landscapes. High fuel scenarios are thinner strips due to constrictions on the number of trees that can be tracked in WFDS (the modeling domain stayed the consistent, however).

Average crown consumption is close to zero percent within 30 – 40 meters past the transition zone in all thrice-burned landscapes (Fig. 11).

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**Figure 11**. Crown consumption across 1-time and 3-time burns and median and high fuel scenarios. Circles represent the difference between starting crown mass and ending crown mass larger circles indicate a larger difference. Blue line represents the average.

## Discussion

Fuel abundance increased across reburn-history, particularly the fine and large fuels. The connectivity of both surface and canopy fuels declined across reburned landscapes: thrice-burned trees displayed the most clumped spatial pattern and most understory space in thrice-burned landscapes was bare litter.

Once-burned landscapes displayed greater rate of spread and consumption than thrice-burned landscapes: fire rarely made it past 50 meters beyond the transition point in thrice-burned simulations, even under high fuel and extreme weather conditions. It appears bottom-up controls may overcome top-down controls in the thrice-burned landscapes, at least in the model and under the conditions tested. This finding is consistent with the results of other models applied in Interior Alaska: processed-based models like the University of Virginia Forest Model Enhanced (UVAFME) found that declines in fuel abundance led to lower fire severity and intensity in stands with greater deciduous presence (Foster et al. 2022). One element that remains unclear is the relative importance of fuel abundance vs fuel connectivity – untangling the roles of each individual bottom-up control is critical to anticipating future fuel characteristics. Fuel abundance in deciduous stands could increase via increases in general vegetation productivity driven by increasing atmospheric CO2 concentrations (Rahmstorf et al. 2007, Beck et al. 2011), whereas fuel connectivity may increase with stand age.

Transition zones, differences in modeled fire behavior between two types of fuels (i.e., unburned vs burned or structure vs wildland), are observable in a variety of ecosystem types. WFDS simulations from red pine and other forest types in the western US display transition zones from 6 to 300 meters. Transition zones between burned and unburned forests in the Interior have not been simulated using a combustion model prior to this, but have been documented by fire managers across the state. Here, our transition zone was 50-75 meters, given that we did not observe a consistent rate of spread in the majority of scenarios more than 75 meters from the . However, WFDS does not model embers – as wind picked up further into the reburned forest, it could be possible that embers could travel beyond the transition zone, expanding the area burned within reburned landscapes.

Several key limitations exist both in this study and with physic-based models more generally. Potentially key dynamics of fire behavior in boreal forests are not represented fully in WFDS: WFDS does not include soil organic layers, which are an important source of smoldering fires in the boreal. The lack of simulated embers may underestimate fire spread and combustion. WFDS track fire velocity and combustion until the fire line reaches the end of the domain, which may underestimate total combustion if fires continue to spread and smolder behind the leading line. In addition, WFDS models potential fire behavior – none of the fire behaviors or effects modeled in this study should be interpreted as prescriptive, and the presence of fires in simulated reburned stands does not imply definitively whether reburned stands will burn again in short-intervals in real-world scenarios. One way to test how well WFDS represents boreal fire behavior would be to compare landscapes burned and reburned in WFDS to characteristics of stand composition, structure and mass observed empirically in reburned stands in Alaska. However, given the emerging nature of continued short-interval reburning, there are still relatively few documented sites of twice- and thrice-burned landscapes in the Interior. Additional empirical observations of repeat reburning will help inform our understanding of potential future fire behavior in reburned stands (and thus the strength and/or duration of a negative deciduous feedback).

Another element that could complicate future fire behavior in the boreal is drought: moisture stress from increasing temperatures and drier conditions . Foster et al. (2022) predicted stronger bottom-up controls and thus negative feedbacks on fire intensity and severity under drought conditions brought on by climate change.

Our simulated reburned landscapes were based on observed characteristics of 15-year-old regenerating stands. Landscape analysis of the frequency of reburning suggests that self-regulating feedbacks persist in the first 20 years after fires (Buma et al. 2022), well in line with our findings. Our observation that once-burned landscapes with average fuel abundance burned under extreme weather conditions suggests that self-regulating feedbacks may be overcome by top-down controls in stands only hit by one fire, which would allow for continued reburning, but that a threshold may exist in fuel abundance or connectivity that prevents fire spread in thrice-burned landscapes.

Several studies (Astrup et al. 2018) have invoked the presence of less-flammable deciduous species as a landscape management solution to boreal warming, based on paleoecological evidence of declining fire activity found alongside increases in birch pollen presence (Brubaker et al. 2009, Kelly et al. 2013). Our finding that simulated fire spread did not occur in thrice-burned landscapes, even under extreme conditions, suggests that bottom-up controls outweigh top-down controls at least in the initial decades of post-fire regeneration.

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## Appendix

### Tree Height

Our observations of tree heights informed the upward space of the model. Given the age of reburned stands (15 years on average), tree height was much shorter in reburned plots compared to mature stands, which contained birch and black spruce individuals reaching a maximum height of 17 meters (Fig. S1). Based on those observations, we set the domain of the modeled landscape to a maximum height of 20 meters.

**Chart, box and whisker chart

Description automatically generated**

**Figure S1.** Heights in meters of tree species across reburn history. Dots represent outliers.