Collaborative Research: the past, present, and future of boreal fire feedbacks

Introduction: Problem and Limits

The boreal forest is the world's largest terrestrial biome, encircling the northern hemisphere's arctic and sub-arctic regions. Underlain by vast regions of both continuous and discontinuous permafrost, the region stores immense amounts of carbon (Malhi et al. 1999, Tarnocai et al. 2009), comprising 30-50% of the world's forest C stocks (Pan et al. 2011) and 53% of US forest carbon stocks (Zhu and McGuire 2016). Boreal forests have exhibited resilience to high-severity wildfires for thousands of years (e.g., Hoecker et al. 2020), with species composition and carbon storage relatively stable over centuries to millennia (Johnstone et al. 2016). However, recent (Box et al. 2019) and predicted (Young et al. 2017) climate-driven increases in fire activity will potentially undermine this long-standing ecosystem resilience. Shorter intervals between fires, a consequence of increased fire activity, can eliminate forest cover (Buma et al. 2013, Hayes and Buma *in press*) and reduce ecosystem carbon stocks (Kelly et al. 2016). More fire activity also increases permafrost thaw by removing insulating vegetation cover, a positive feedback with climate warming (among other detrimental effects, like increased smoke). While short-interval fires in themselves are not novel, their increasing frequency and spatial extent is of concern, because they can drive rapid ecological change. We need to know whether they promote positive or negative feedbacks with future fire, and what key thresholds in climate and vegetation govern these feedbacks (Mitchell et al., *in prep*). We do not know the temporal legacy of short-interval fire on vegetation (beyond modeling studies) due to a lack of observational records. Finally, we do not know the ecological effects of short-interval fire in emerging boreal landscapes dominated by deciduous or shrub species.

Plan

Through three project components that integrate across time scales, we will quantify the effects of short-interval fires on the composition, structure, and flammability of boreal vegetation, focusing on key mechanisms of fire behavior and vegetation change to assess if short-interval fires function as a key tipping point or catalysts of broad-scale changes in arctic and boreal ecosystems. Specifically, we will (1) quantify spatial patterns and temporal legacies of short-interval fires on vegetation structure/composition using a combination of paleoecology and contemporary field surveys; (2) combine this information to quantify the impact of vegetation changes on fire behavior, including the rate of spread, fire intensity, and fire severity, utilizing cutting-edge fire behavior models; and (3) undertake an assessment of how short-interval fires will likely impact boreal vegetation under 21st-century climate projections, with a particular focus on positive- or negative feedbacks between climate-driven increases in fire likelihood and postfire vegetation.

Vision

Success for this project will directly address a key knowledge gap in understanding Arctic ecosystem change, in the past, present, and future. Specifically, we will explicitly identify *thresholds* - in climate, and vegetation - governing boreal forest resilience and fire behavior to a changing climate. We will further use this information to develop scenarios for future change, based on state-of-the-art fire modeling experiments informed by both paleo and modern records of climate and vegetation. Combined, this work will also allow us to identify past and anticipate future *feedbacks* between increasing fire activity and postfire vegetation in Arctic and boreal ecosystems. This work will be transformative for fire-climate modeling (given the long-term context and fire-vegetation feedbacks) and for on-the-ground management. We will also enable educators worldwide to share the science of fire and Arctic and boreal ecosystem change via a scientifically valid, attractive, and fun model for students and through science communication training for graduate students and researchers.

Core Questions

1. <u>Historical context and expectations</u>: How often have boreal ecosystems experienced short-intervals fires in the past, and what are the characteristic rates and pattern of postfire vegetation change? Do those patterns match with contemporary short-interval events?

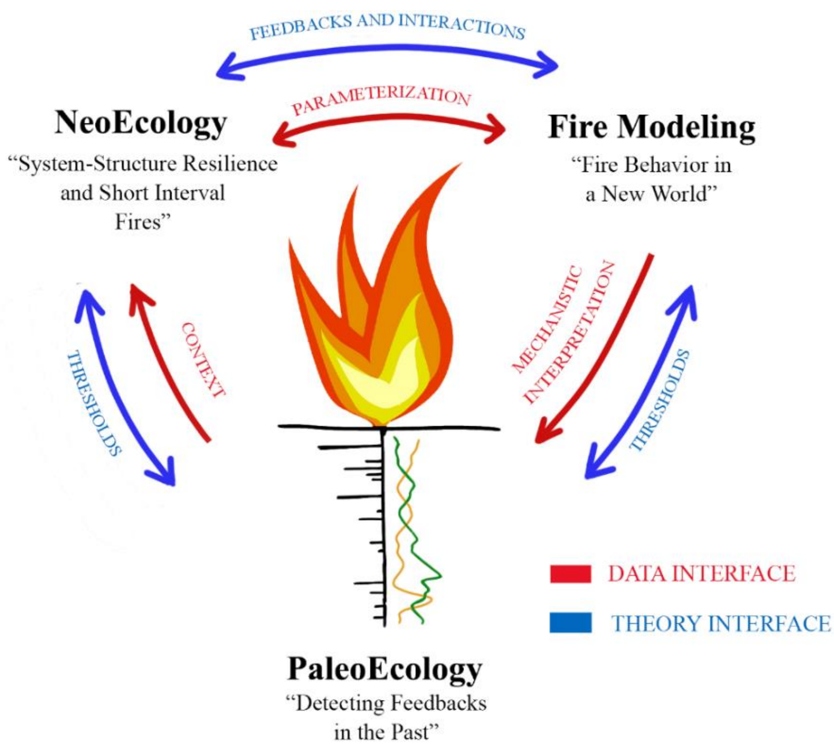


Figure 1. Our project links long-term paleo perspectives with contemporary observations and state-of-the-art fire behavioral modeling through data collection and theory.

Approach: Analyze paleoecological records of boreal fire activity across key periods of late Holocene environmental change; quantify the frequency of short-interval fires and patterns of postfire vegetation change and compare to evidence from contemporary field studies.

2. <u>Current conditions and structural effects</u>: How does the composition and structure of vegetation communities change after short-interval fires, how does this differ from longer intervals between fires, and what do short-term changes suggest about future vegetation trajectories and fire behavior?
Approach: Quantify vegetation characteristics in recently burned boreal landscapes in the present and past, focusing on composition and structure most relevant to fire ignition, spread, intensity, and severity.

3. <u>Fire behavior, now and in the future</u>: Are there identifiable thresholds in vegetation composition, vegetation structure, or fire weather and climate conditions, past which historical negative feedbacks between fire and vegetation change degrade; given future climate projections and scenarios of vegetation change, what is the likelihood of surpassing these thresholds in the 21st century?
Approach: High resolution fire-behavior modeling, with structural parameterization from field studies, and fire-weather and climate scenarios based on past, current, and projected climate conditions.

Background

Wildfire is the dominant disturbance in boreal forests worldwide, primarily driven by broad-scale climatic forcing rather than ignition likelihood or other factors (Payette 1992, Macias Fauria and Johnson 2008). At broad spatial domains and over the last 6,000 years, this system generally appears resilient to wildfire activity, despite substantial climatic fluctuations, including the Medieval Climate Anomaly (MCA) and Little Ice Age (Mann et al. 2009, Kelly et al. 2013). The long-standing presence of fire in these systems means organisms have traits that provide resilience to fire (Kurkowski et al. 2008), such as serotinous cones (black spruce: *Picea mariana*) and the ability to regenerate vegetatively (e.g., aspen: *Populus tremuloides*). This resilience has resulted in relatively stable landscape composition over recent millennia (Johnstone et al. 2010; Hoecker et al. 2020).

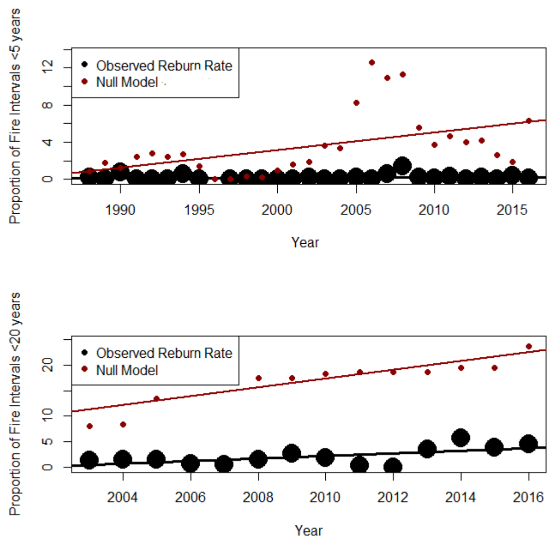


Figure 2. Proportion of short-interval fires across Alaska for two intervals (5 yr, top, 20 yr, bottom). Black dots: observed proportion of short-interval fires. Red dots: expected proportion of short-intervals fires under a null model assuming random spatial placement of fires on the landscape. Strong negative feedbacks are apparent at 5 yr, given little reburning as fire frequency increases (as shown by null model). Negative feedbacks persist but weaken by 20-yr. Methods from Buma et al. (2020).

But that resilience appears to be eroding. Fire activity in Alaskan boreal forests has reached levels unprecedented for at least 10,000 years (last three decades; Kelly et al. 2013). Increased fire activity results in increasingly shorter fire-free periods ("short-interval fires"), limiting ecosystem recovery and dramatically reducing resilience (e.g., Buma et al. 2013). "Short-interval" is defined differently in different systems but generally refers to fires occurring in the same location within a time period shorter than the typical recovery period (often with a focus on the recovery of seed banks or other resilience mechanisms). In boreal forests, a lack of conifer regeneration and a subsequent shift to deciduous dominance has been well documented after fire intervals < 50 years (e.g., Brown and Johnstone 2012, Hayes and Buma *in press*). This shift represents a major change in the species composition of boreal forest, with implications for habitat (Lemaître et al. 2012, Joly et al. 2012), carbon stocks and fluxes (Pastick et al. 2017), and permafrost sustainability (Trainor et al. 2009) among other factors. It is generally assumed that deciduous forests function as a "living firebreak," and thus act as a negative feedback to increasing fire activity (Johnstone et al. 2010). Historically deciduous forests were indeed less likely to burn, even in the early Holocene when climate was generally warmer than the 20th century (Higuera et al. 2009). But, as temperatures increase outside the range of Holocene variability, the persistence of this negative feedback is unclear.

There are several reasons to doubt that negative feedback will persist. First, eventually warming and drying will pass a threshold where even broadleaved boreal forests become flammable enough to readily support fire spread (Johnson 1992), especially in high wind conditions and low fuel moistures. This threshold needs to be quantified. Secondly, the negative feedback from reduced fuels and fuel connectivity is temporary, declining significantly by 20 years postfire (Fig. 2). Short-interval fires in early successional stands further reduce forest density (Fig. 2; Hayes and Buma *in press*), potentially increasing surface wind flow and solar radiation to support ground fire spread (Fig. 3). With more solar heating due to canopy loss, permafrost also declines dramatically (Hayes and Buma *unpublished data*), increasing soil drainage and reducing water availability for plants and increasing the fuel aridity – leading to more surface biomass available to burn. A positive feedback between fire and vegetation flammability can result; similar mechanisms have been documented elsewhere (e.g., Tepley et al. 2018, Kitzberger et al. 2016, Paritsis et al. 2015). Thus, while historically the boreal has enjoyed negative feedbacks against the positive pressure of climate change on fire frequency (e.g., Kelly et al. 2013, there is ample reason to believe that those negative feedbacks will weaken or even reverse.

INTELLECTUAL MERIT

Summary of Recent Findings

Increased fire frequency and increased proportion of short-interval fire: Fires are becoming more frequent, and the proportion of fires that occur in short time intervals ("short-interval fires") is also increasing (Fig. 1). The frequency of short-interval fires (here defined as < 50 years between events, based on general time to significant seed production) is lower than expectations based on chance alone, suggesting that negative feedbacks have indeed been constraining the fire occurrence (Fig. 2). But recent years have seen wildfires burning into and within areas that had burned in recent decades, suggesting that a warming climate may overwhelm vegetation-mediated negative feedbacks.

Community changes result from short-interval fires: When short-interval fires occur, conifers are rapidly lost due to depletion of seedbank and deciduous tree invasion. Continued burning opens the deciduous canopy further, creating a mosaic of open spaces and shrubby, coppice-like short tree/bushes (Eastern Canada: Hogg et al. 1995; Fig. 3). Topography and edaphic conditions moderate but do not completely mitigate this conversion (Duffy et al. 2007). The first empirical study of short-interval fires in deciduous forests suggests continued ecosystem conversion to more open, shrub-dominated (*Salix*) landscapes (Hayes and Buma *in press*).

Short-intervals fires and the paleo record: Short-interval fire are not a new phenomenon. For example, drawing on 27 previously published paleo-fire records from Alaska (summarized by Hoecker et al. 2020), we assessed the proportion of short-intervals fires over the past 4000 years to provide context to contemporary burning. Fire return intervals < 20 years accounted for approximately 4% of the 585 reconstructed fire events, broadly similar to rates observed over the period 1960-2019 (Higuera et al. *in prep*), and proportions varied among ecoregions and over time, reflecting differences in climate and vegetation. This work highlights the potential to utilize pollen and charcoal records to study short-interval fires over past periods of climate change and characterize rates and pattern of postfire vegetation change.

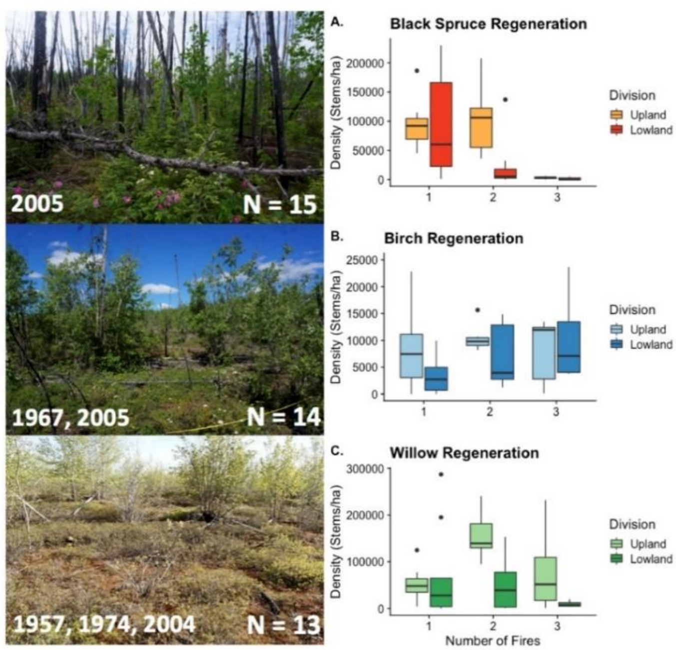


Figure 3. Vegetation communities after 1, 2, or 3 fires since 1950. All plots were mature black spruce prior to fires. A: Left: Pictures of previously surveyed plots. Right: Upland and lowland sites have similar trajectories but significant differences in conifer regeneration, especially in regards to more open growing birch vs. clumped willows. Hayes and Buma (*in press*).

Feedbacks and changing fire dynamics: The combination of abundant fine surface fuels (e.g., increasing grass coverage), low crown base heights, abundant lichen, and canopy fuels make black spruce forests one of the most flammable vegetation types in boreal ecosystems of North America. Short-interval fires alter forest structure (Fig. 2) and fuel-atmospheric interactions, which change fire behavior and severity (Mitchell et al., *in prep*). Changes in vegetation structure after short-interval fires can also increase surface fuel continuity and aridity, and lead to higher wind speeds due to lower tree densities.

Together, these findings suggest that structural changes associated with short-interval burning could fundamentally change fire-vegetation feedbacks, from current negative feedbacks to future positive feedbacks. Such changes would amplify the impacts of climate-induced increases in burning, and dramatically change the future trajectory of fire regimes in the boreal forest. Climatic conditions conducive to more frequent fire activity are only becoming more common; the question is *how* fire activity will increase, and specifically *how much* and *for how long?* Understanding these structural changes, fire-vegetation feedbacks, and interactions with climatic warming - in the past, present, and future - is critical for forecasting the future of the boreal forest biome and global carbon cycling.

HYPOTHESES

Our hypotheses test the general theoretical framework that ecosystem composition/structure, disturbance processes, and resilience mechanisms interact, and can drive both positive and negative feedbacks in relation to ecosystem stability.

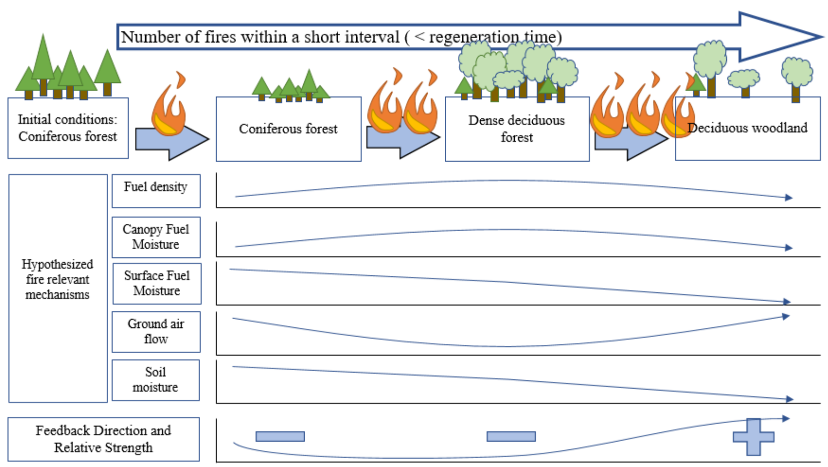


Figure 4. Hypothesized feedbacks among multiple fires, consequent shift in vegetation composition and structure, and impacts on fire behavior. We expect negative feedbacks between fire and vegetation after one short-interval fire. We further expected those feedbacks to diminish and potentially reverse after three fires in short succession, as forest density decreases.

H_1. Boreal forests were largely resilient to short-interval fires over the past c. 2500 years, with negative feedbacks between fire and postfire vegetation flammability persisting for decades, long enough to allow for forest composition to return to pre-fire states. During the warmest and driest periods of the late Holocene (e.g., the MCA), these negative feedbacks were weakened, and postfire vegetation recovery was either slowed or altered. *We propose to quantify the historical range of variability in postfire <u>recovery times</u> and postfire <u>vegetation trajectories</u> (including lack of recover, if present) in the paleorecord, and relate that to broad-scale climatic context, to expand our understanding of forest resilience to wildfire and inform expectations for the strength and duration of negative feedbacks on contemporary (H_2) and future landscapes (H_3).*

H_2. The rate of changing vegetation composition and structure associated with short-interval boreal fires is primarily controlled by topography and fire frequency, with resilience to fire ultimately limited by the fire-free interval between successive fires. Overall, systems become more deciduous and more structurally open with increasing fire. *We propose to quantify compositional and structural changes associated with short-interval fires. These analyses will provide a better understanding of the paleorecord (H_1) and the means to model fire behavior and fire-vegetation feedbacks under future climate scenarios (H_3).*

H_3. Structural, edaphic, and compositional shifts associated with more frequent short-interval burning will dampen negative fire-vegetation feedbacks. Key thresholds in (1) vegetation structure, (2) vegetation composition, and (3) fuel conditions will be associated with a shift to positive fire-vegetation feedbacks that will increase vegetation flammability and fire spread but decrease fire intensity in the future. *We propose identifying these thresholds in structure, composition, and fuels add context to our historical understanding (H_1) and identify ecosystems most vulnerable to a future loss of resilience as climate and vegetation cross key tipping points (H_2).*

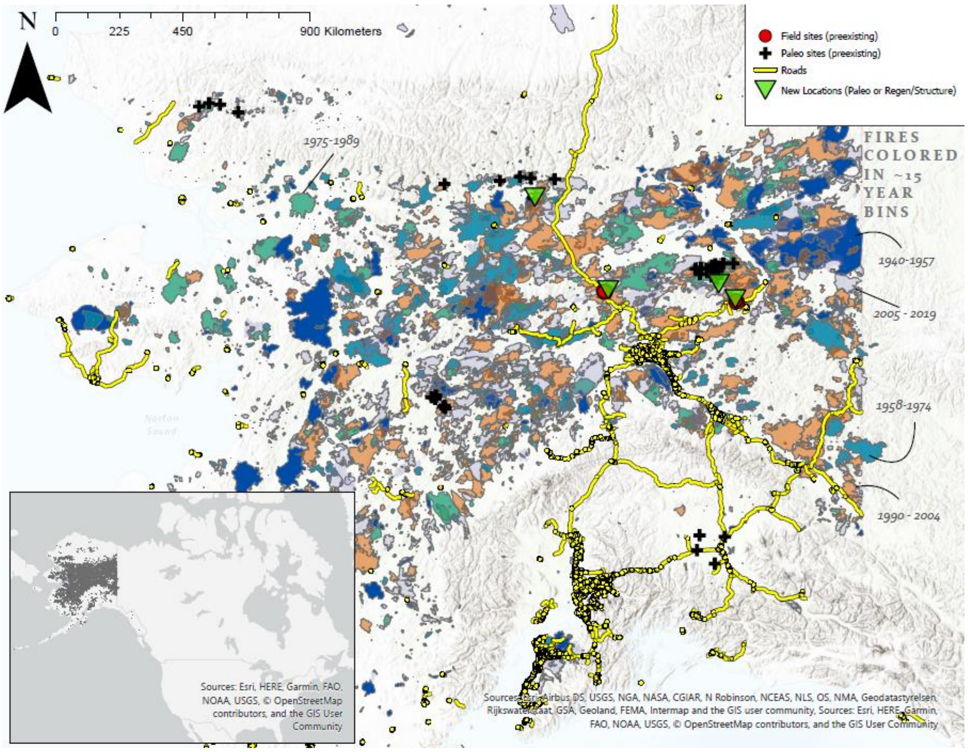


Figure 5. Map of fire history, pre-existing, and proposed field sites. Two new sites are for vegetation composition (regeneration) & structural data, co-located with existing paleo sites; two new sites are for new paleo work, co-located with existing regeneration data.

METHODS: Each hypothesis has its own line of investigation but depends on and integrates with the other hypotheses. The close interweaving of questions allows us to translate results across temporal and spatial scales, from past landscapes via paleo data, to contemporary forest stands via field measurements, and into the future via fire-scale fire modeling. We will leverage a network of established sites for both paleo- or neo-ecological questions, utilizing pre-existing data, supplementing with additional sites and measurements, and integrating activities across teams (Table 1).

H_1: To assess the resilience of boreal forest vegetation to past short-interval fires, we will develop six high-resolution fire and vegetation history records spanning the past 2500 years, including four new paleo fire and vegetation records, and two from among 20 existing lake-sediment records from across interior Alaska (Fig. 5). This approach includes two distinct components: (a) identifying short-interval fires in the paleo records and quantifying summary statistics over time (e.g., frequency, centennial- to millennial-scale mean fire return intervals); and (b) quantifying vegetation assemblages before and after these short-intervals fires. Each task calls upon well-developed methods for reconstructing fire and vegetation history, but also requires additional analyzes to understand the fidelity of the lake-sediment records for recording biophysical processes that are near the edge of detection. That is, we recognize that studying short-interval fires and the resulting vegetation changes is pushing the limits of what lake-sediment records can resolve, but we are confident that they contain relevant information that can inform our hypotheses (Fig. 6-7).

[a] Identifying short-interval fires from sediment-charcoal records: The strengths of lake-sediment charcoal records for reconstructing fire history are maximized in stand-replacing fire regimes like the boreal forest (Higuera et al. 2007). The limitations of lake-sediment records in these regions come from variability among fire events, including charcoal production, wind direction, and area burned around a lake. Despite these limitations, when summarized over time and pooled across space, statistics from estimated fire-return intervals or fire frequency from dozens of lakes are consistent with the known fire history from observational and tree-ring records spanning the past several decades to centuries (e.g., Higuera et al. 2009, Kelly et al. 2013).

Table 1. Proposed additional site locations. Leveraging pre-existing datasets, regeneration and paleo data need to be collected at two locations (multiple new plots and two sediment records within each broad location). Structure variables will be collected at each site. For definitions of regen vs. structural variables, both of which are collected as part of H_2, see Table 2.

Data Collection	Pre-existing Data	Lat./Long	Last Fire	Name
Regen/Structure	Paleo sites 25 km away	145.54°W 65.79°N	2004	Circle
Paleo/Structure	Regeneration on site	145.014°W 65.59°N	2004	Central
Paleo/Structure	Regeneration on site	149.05°W 65.71°N	2005	Dalton
Regen/Structure	Paleo sites 25 km away	-151.38°W 66.89°N	2004	Bettles

A recent analysis of 27 paleo records using these methods (Hoecker et al. 2020; Fig. 6) characterizes the historical range of variability and departures in fire activity in recent decades (Fig. 6A). As a proof-of-concept, we also quantified the frequency of individual fire return intervals less than 20, 40, and 60 years across all records and within four different ecoregions (Fig. 6A). Specific findings from over a dozen records from the Yukon Flats, one study region in the proposed work, are highlighted in Figure 6. We will use similar methods in the proposed research to quantify the historical range of variability in short-interval fires over the past 2500+ years, while adding on important work to validate the interpretation of short-interval fires in charcoal records, recognizing the coarser spatial precision of the paleo record relative to modern observations.

We will use records with a median sample resolution < 10-20 years, allowing us to identify FRIs of $\leq$ 20-40 yr, and we will interpret the source area of charcoal creating distinct charcoal peaks as c. 500-1000 m of a lake, as supported for Alaskan boreal forests (e.g., Higuera et al. 2007, 2009; Kelly et al. 2013). To further test and constrain these assumptions, we will compare sediment-charcoal records to observational fire-history records spanning the past 35-70 years (from MTBS and the Alaska Large Fire Database). This approach is broadly analogous to the way charcoal records are assessed for accuracy in general, and it will help further reveal the accuracy of sediment-charcoal records for detecting short-interval fires.

[b] Quantifying vegetation change after short-interval fires from pollen assemblages: Pollen assemblages from lake-sediment records integrate a signal of vegetation from a larger source area than macroscopic charcoal, typically within 1-10s of km from a lake. A pollen assemblage thus inherently integrates spatial heterogeneity in vegetation over landscape scales (10-100 km^2; e.g., Sugita et al. 1997), and temporal heterogeneity over years to decades (i.e., the time represented in any single sample). The paleo record of postfire vegetation change will thus only detect changes large enough in space to affect the majority of the pollen source area (e.g., a widespread reduction in spruce pollen). Small-scale changes (e.g., < 10^1 km^2) would likely go undetected. Thus, while the precision in the pollen record is significantly lower

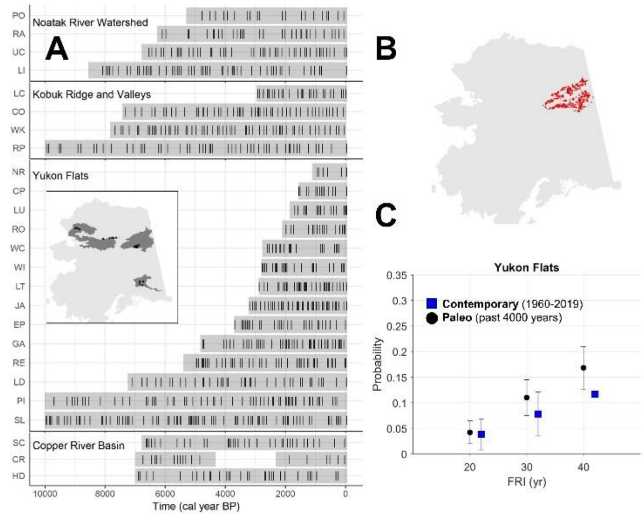


Figure 6. Fire history from sediment-charcoal records from four Alaskan ecoregions (A, from Hoecker et al. 2020). (B) Observed fire perimeters from 1960-2019 in the Yukon Flats, from the Alaska Large Fire database. (C) Proportion of "short-interval fire" defined by three fire return intervals (FRI) from the paleo (past 4000 years) and contemporary record (1960-2019).

than field measurements, it is well-suited for testing the overall resilience of boreal forest vegetation past variability in climate and fire activity (H_1).

We recently tested the ability of high-resolution pollen sampling to detect interpretable changes in postfire vegetation across a 3000-yr, high-resolution lake-sediment record from the Yukon Flats region of Alaska as a proof-of-concept for our approach. The charcoal record from Screaming Lynx Lake is based on contiguous samples that on average represent 10 yr (Kelly et al. 2013), and the pollen record is based on non-contiguous sampling, with an average of 45 yr between samples (Hu, unpublished data).

Intriguingly, the rate of change in pollen assemblages was highest after shorter-interval fires and decreased significantly with longer intervals (Fig. 7), suggesting distinct patterns of vegetation change with varying fire intervals.

We will develop six high-resolution pollen records spanning the past 2500+ years with an average sampling interval of c. 50 yr per sample, with higher-resolution around reconstructed fire events. In addition to the multivariate rate-of-change analyses noted in Figure 7, we will use taxa-specific patterns (e.g., black spruce) and relative proportions of conifer, deciduous, herbaceous, and grass pollen (e.g., spruce-aspen, spruce-grass, trees-grass pollen ratios) to characterize postfire vegetation change (as in Chileen et al. 2020; Crausbay et al. 2017). From across multiple fires from multiple lakes, we will characterize the average patterns and timing of postfire vegetation recovery or learn when and for how long postfire vegetation did not return to pre-fire conditions.

To inform fire-modeling efforts, we will use modern analog techniques to compare modern pollen samples (e.g., arboreal - non-arboreal pollen ratios) to the proportion of forest cover at varying radii from each lake. This will provide estimates of the percent forest cover, used to coarsely inform paleo scenarios for fire-behavior modeling. Our goal is not to replicate what occurred in the past; rather, most of the detailed inputs in the stand-scale fire behavior model will necessarily come from modern field-based measurements. Our goal is to develop modeling scenarios consistent with our best qualitative and quantitative interpretations of how past conditions differed from modern.

H_2: 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 H_3. At each site, measurements will be done at two scales: the plot scale via fieldwork, and landscape via drone-based remote sensing.

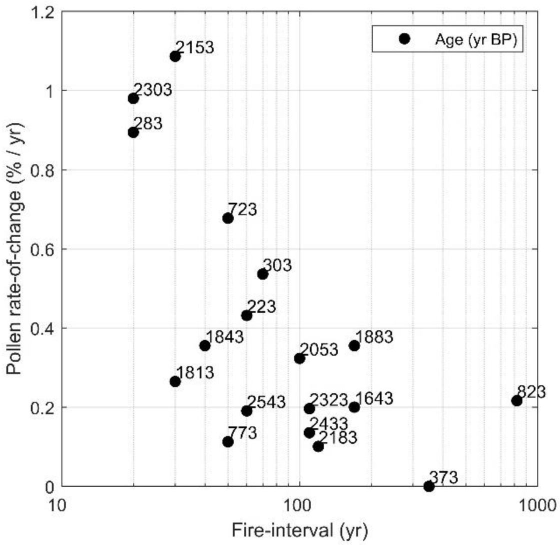


Figure 7. The rate-of-change in pollen assemblages over the past 3000 years was highest after short-intervals fires and decreased with longer fire intervals. "Rate-of-change" reflects a multivariate measure of seven pollen taxa and compares samples from the decade before to the decade after fires. Data are from a high-resolution pollen record in the Yukon Flats (Higuera et al. *in prep*).

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*).

Additional regeneration data will be measured at the two sites paired with pre-existing paleo data (doubling the pre-existing sample size, Table 1). At each new site, at least 5 transects with five plots each, spanning a gradient of slopes and aspects (key variables related to repeat fire effects; Hayes and Buma *in press*), will be sampled (n > 25 per site, providing sufficient statistical power based on preliminary work). Regeneration will be measured for the complete plot (species, diameter, height) for all individuals >10 cm tall; <10 cm individuals will be measured in smaller subplots. Ground cover will be assessed via random quadrat sampling (10x per plot, 1 m^2). Tree and groundcover allometrics have been specifically developed for the region (harvesting and drying in 2019; Hayes et al, *in prep*) will be used to calculate biomass. 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. Depth of active layer, an important proxy for seasonal drainage within a given topographic setting, will be assessed with a 2 m slide hammer coring apparatus used for this purpose by the Buma lab prior. 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). The effect size of number of fires in the historical record (0-3) and soil moisture on composition and biomass will be quantified via generalized mixed models, with site as a random effect, and topography, fire history, pre-fire composition, postfire weather, and active layer depth as fixed effects.

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 using Hawley et al. (2018) methodology. Biomass within that volume at three height strata will be measured (to align with the resolution of the fire model; see H_3 methods). 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 will allow us to generate realistic "fuel-scapes" that quantify fuel composition, density, and distribution to directly inform the H_3 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.

One limitation to our plot-level analysis is that it cannot capture fuel patterns larger than the plot itself (20 x 20 m). Repeat-burns create a complex mosaic of severities (Harris and Taylor 2017), and neither burn perimeters nor satellite data capture this mosaic well due to grain size limitations (Buma et al, unpublished data). Our modeling framework (H_3) will assess the significance of that pattern but requires field data for initial calibration. We will utilize drone-based remote sensing "structure from motion" (SFM) image analysis to scale up from the 400 m^2 plot area to approximately 25 km2 for broad-scale pattern analysis, and to parametrize patterns in the 36-ha modeling framework for H3.

A Phantom 4 drone and open-source SFM photogrammetry software (Visual SFM 0.5.26, CMP-MVS) will be utilized, following the successes of Mlambo et al. (2017) settings structurally similar to the postfire boreal environment. Drone-based assessments of vegetation structure are a relatively recent methodology, but there are well-established methods to quantify fuels across areas too large to be evaluated on foot (e.g., Larrinaga and Brotons 2019). Drones can map fuel structures and types at extremely fine resolution (<50 cm; Tang and Shao 2015) depending on the height of flight; here we will aggregate to the 2-m resolution of the fire behavior model, calibrating the transfer model via the field measurements from the 2x2 m fuels plots, which will be marked with high-visibility tape and identifiable in the drone-captured images.

Using the SFM fuel heights and color-infrared photography, we will model fire severity (quantified as percent mortality), fuel mass, and height from the drone imagery using random forests (Breman 2001). This assessment of three-dimensional fuel structure and spatial heterogeneity will be a novel test of drone-based ability to collect fuels data at fine scales. Analysis of heterogeneity will be done via local Moran's I (LISA, Anselin 1995), and a comparison of the effects of topography vs burn frequency will be done statistically, as described above for regeneration. Although the team has not directly used drone data collection methods before, Buma has extensive experience with multiple remote sensing platforms including structural mapping with LiDAR and random forests and machine learning algorithms. Fuels maps will feed directly into H_3 for landscape-scale parameterization of vegetation.

H_3. To quantify the fire-vegetation feedbacks and identify key thresholds under different climate scenarios, we will combine vegetation composition and structure and composition information obtained from H1 and H_2 to inform a high-resolution, state-of-the-art fire behavior model. Specifically, we will use the HIGRAD/FIRTEC fire behavior model (Linn et al. 2002) to assess the significance of (1) vegetation composition and structure, and (2) weather and climatic conditions for creating negative or positive fire-fuel feedbacks hypothesized to lead to less or more frequent fires, respectively.

HIGRAD/FIRTEC is a physics-based fire behavior model that explicitly represents individual ecosystem components and both known and assumed combustion and atmospheric processes and interactions. HIGRAD/FIRETEC couples a large eddy simulation approach to solve for conservation of momentum, total mass, and energy with models for radiative and convective heat transfer, thermal degradation of vegetation, and gas-phase combustion to predict the spatial and temporal evolution of a wildfire. Vegetation composition and structure are represented in three-dimensions based on their bulk properties including the bulk density, surface area to volume ratio, and fuel moisture. This methodology, unlike most fire behavior modeling approaches, facilitates simulating fires in areas with complex fuels that are vertically and horizontally heterogeneous, and this methodology can capture the nonlinear interactions that occur among the fire, atmosphere and fuels complex. These simulations will allow us to explicitly account for the changes in vegetation composition and structure, altered windspeeds from changed structures, and changes in solar

Table 2. Field variables quantified (topographical variables not shown). Superscript R or S for plot variables indicates a Regeneration or Structure variable (see Table 1).

Plot scale (plot)	Landscape Scale (drone)
Stem density (per ha)^R	Stem density (validated w/plots)
Stem biomass (tons/ha)^R	Stem density (validated w/plots)
Tree species^R	Tree species (validated w/plots)
Woody debris (tons/ha)^R	NA
Woody debris distance to nearest tree (m)^S	Modeled based on field plots
Fine fuels (3D; mass)^S	Modeled based on field plots
Depth to active layer^S	NA
Fuel moisture^R	NA
NA	Patch size
NA	Stem heterogeneity
NA	Species heterogeneity

and wind-driven energy with the resulting shifts in fuel moisture and flammability. This model has been validated for high-latitude ecosystems by Marshall et. al. (2020) and Linn et. al. (2012).

[a] Model Overview and Analysis Plan: A total of 60 scenarios will be run (Fig. 1) to test the mechanisms and feedbacks hypothesized (Fig. 4): five climate scenarios (two paleo, one contemporary, two future), which directly impact mean fuel moisture and wind speed, and four fuels scenarios (0, 1, 2, 3 fires based on contemporary and/or paleo-informed vegetation), with three replications per combination (5 x 4 x 3 = 60 total runs). For each fire simulation we will assess fire behavior at both a global (domain-wide) and local (e.g., several square meters) scale. Global and local metrics will include the mean rate of spread, fuel consumption by class (e.g., overstory, shrub, herb) and fireline intensity (Table 3).

All simulations will be conducted in a three-dimensional domain with a 36-ha footprint (i.e., 800 x 450 x 600 m). The simulation domain will be divided into computational cells that are 2 m on horizontal sides and ~1.5 m in height near the ground. An initial wind simulation absent of fire will be completed for all scenarios following Marshall et al. (2020) to ensure steady state wind fields and to investigate how changes in vegetation structure affect wind flow. Following the wind-only simulation, the dynamic wind field is then used to initialize a fire simulation, where fires are ignited as a 350 m wide fire line 100 m from the upwind boundary of the simulated domain.

Model runs will be analyzed via two pathways, one for fine-grained metrics of fire behavior (within simulated fires) and one for fire-event scale (across simulated fires). At the fine-scale, marked point patterns will be used to analyze spatial correlations between local fuel structure (e.g., point-level biomass), weather (e.g., local wind speeds) and local fire behavior metrics (e.g., burn time), operating at the model-cell scale. Weighted regressions will accommodate the spatial dependence at the within-fire scale (Baddeley et al. 2016) and allow for varying local influence; effect sizes will be calculated for each predictor variable and presented in all results (not just significant effects). At the fire-event scale, we will analyze the relationship between vegetation structure and overall fire behavior (Table 3). To determine the effect sizes of the driving variables, we will use a bootstrapped random-assignment approach (Lahiri 2003) and a standard replicated block design experiment, with climate and burn histories as crossed treatments for both changes in mean and total variance (equivalent to landscape heterogeneity).

[b] Fuel Inputs: All trees and shrubs will be modeled using a parabolic profile similar to Linn et al. (2005), in which crown dimensions and locations will be derived from field data collected for H_2, and fuel mass will be calculated from regional allometrics (Hayes et al. *in prep*). Surface fuels, including grasses, litter, dead down woody debris, and moss/duff, will be modeled by developing spatial relationships between surface fuel mass and overstory composition and structure from the data collected for H_2. For contemporary model runs, observed point location patterning quantified under H_2 will be used to parameterize vegetation. We will fit a point process model (Cox) to the field- and drone-based data to develop fuel complexes in HIGRAD/FIRETEC that are representative of the observed tree and shrub spatial patterns. Future and paleo scenarios will use modifications of these contemporary vegetation parameters. Paleo-informed model runs will use pollen-inferred vegetation composition (e.g., proportion forested; proportion coniferous, deciduous, grass vegetation) to generically alter contemporary vegetation. For example, starting with the point patterns from H_2, the patterning will be thinned or new individuals added based on pollen-inferred proportions of forest cover, using a neutral spatial model based on patterns observed. Future scenarios will start with contemporary vegetation characteristics, anticipating an increased likelihood of future vegetation similar to that measured in sites with the most frequent fire activity.

Table 3. Response variables (outputs) from the HIGRAD/FIRETEC fire behavior model. These metrics are directly linked to increased fire behavior properties that affect total area burned, fire severity, and the ability to suppress fires.

Metric	Unit	Example Justifications
Wind velocity and turbulence	m/s	a) Fire management planning: Minimum wind to sustain fire spread; rate of fire spread. b) Relevant to surface energy flux in absence of fire; relevant to long-term permafrost stability
Intensity	kW/m	a) Linked to fire severity b) Impacts fire suppression efforts
Consumption	g/m^2	a) Carbon emissions; fire severity
Velocity (spread)	m/min	a) Fire behavior; area burned b) Fire suppression efforts
Fraction burned	0-1	a) Tied to area burned by individual fire and over a fire season b) Important for management and for understanding negative fire-vegetation feedbacks
Duration	min	a) Impacts on soil closely tied to duration of burn; fire severity

[c] Weather/Climate Inputs: Paleoclimate scenarios will be developed to reflect the most extreme warm/dry and cool/wet conditions over the past 1200-2500 years. Our goal is conditions consistent with the best available paleoclimate information for the region, recognizing that the scale of even the most well-resolved paleoclimate data is coarser (in space and time) than the input data driving the model. We will use GCM simulations form the Paleoclimate Intercomparison Project Phase 3, or more recent (extending back 1200 years; Braconnot et al. 2012), benchmarked to best reflect existing paleoclimate records for our study area (e.g., Young et al. 2019; Results from Prior Support). With mean July temperature and total annual precipitation values (Young et al.), we will use a modern-analog approach to identify the most similar annual conditions from contemporary weather and climate datasets. From these, we will select 90-99th percentile daily values for weather, winds, and fuel moisture, as described next for contemporary climate scenarios.

Contemporary scenarios will reflect weather and fuel moisture conditions under extreme fire danger, when the most area is burned in Alaska, and under more moderate fire danger, to identify if and where thresholds exist. Weather inputs will be based on fire weather records reflecting 90-99th percentile conditions from RAWS stations and ICS 209 weather data during large fire events in the region (e.g., 2015, 2004, 2005). Fuel moisture inputs for these same conditions will come directly from the National Fuel Moisture Database (NFMD), which includes major tree species, grasses/forbs, and mosses (live and dead).

Scenarios reflecting future climate will be based on climate projections for 2050 and 2100 (SNAP). Winds will be based on projected daily quantiles, and fuel moisture will be derived from projected temperature and relative humidity based on contemporary relationship from the NFMD. Winds, temperature, and relative humidity in future projections are downscaled from CMIP5/RCP8.5 emissions pathway. From these, 90-99th percentile (future) conditions will be used.

[d] Advancing Model Development: HIGRAD/FIRETEC has been developed with an emphasis on predicting the spatial and temporal variability in the flaming combustion of fine fuels rather than smoldering combustion. Given the importance of smoldering combustion and duff consumption to boreal ecosystems, we will develop a process to link FIRETEC outputs (e.g., heat flux, duration of heating) to an existing physical one-dimensional model of duff and peat combustion (Huang et al. 2015). This will greatly aid ties between high-resolution fire models and ecological field studies, given the significance of duff consumption to boreal forest resilience to wildfire (e.g., Johnstone et al. 2012).

BROADER IMPACTS

Our project includes two main Broader Impacts components. First, we will create an on-line educational **fire modeling platform and associated pedagogical tools**, targeted at high school students worldwide. Second, we will focus on **science communication** through a two-day workshop and interactions with journalism students. Together, these components will help translate the research and our expertise to the broader educational world, while also advancing scientific training to improve science communication to journalists and the public.

Educational fire modeling tools will be developed in conjunction with the Concord Consortium (CC), a leading nonprofit organization dedicated to creating innovative education technology for STEM learning. CC has significant experience in developing online curriculum materials that include interactive dynamic computational models for middle- and high-school classrooms. “Systems thinking” has been long recognized as a unifying concept in the National Science Education Standards and as a crosscutting concept in K-12 science education. CC recently created the teaching-focused Wildfire Explorer (WFX) modeling environment, which visualizes single wildfire spread under various conditions and over a variety of static landscapes (Pallant 2020, Love 2020; learn.concord.org/geo-wildfire). WFX gives students the opportunity to experiment with multiple variables and use evidence from their exploration to develop scientific arguments. (Krajcik et al. 2000; Lehrer et al. 2007; Slotta 2004; Tinker 2003, 2004).

Currently, the WFX is a single fire, static environment with only fire perimeter simulated. For this proposal, CC will push WFX further, focusing on: (1) landscape resilience, (2) fire-vegetation feedbacks associated with short-interval fires, and (3) carbon storage, a critical ecosystem service of Arctic and boreal landscapes. For (1), the model will incorporate time-since-fire and fire size as a predictor of seed availability for potential regeneration of various vegetation types. Currently, the model only simulates a single event, at which point it must be reset. Multiple fires will allow both the simulation of a fire regime and resilience, because regeneration will be tied to existing vegetation, time-since-fire, and seed dispersal. For (2), previous fires will modify future fire spread. This effect will decay with time, temperature, moisture, and wind. For (3), additional vegetation types representing a wider variety of biomes will be added – specifically coniferous, mixed, and broadleaf boreal ecosystems. Each will have their own flammability (modified by climate) and carbon accumulation rates. Carbon will be tracked at the landscape level as the sum of all pixels given their composition and time-since-fire. Models will be parameterized by the team and CC using literature and field values.

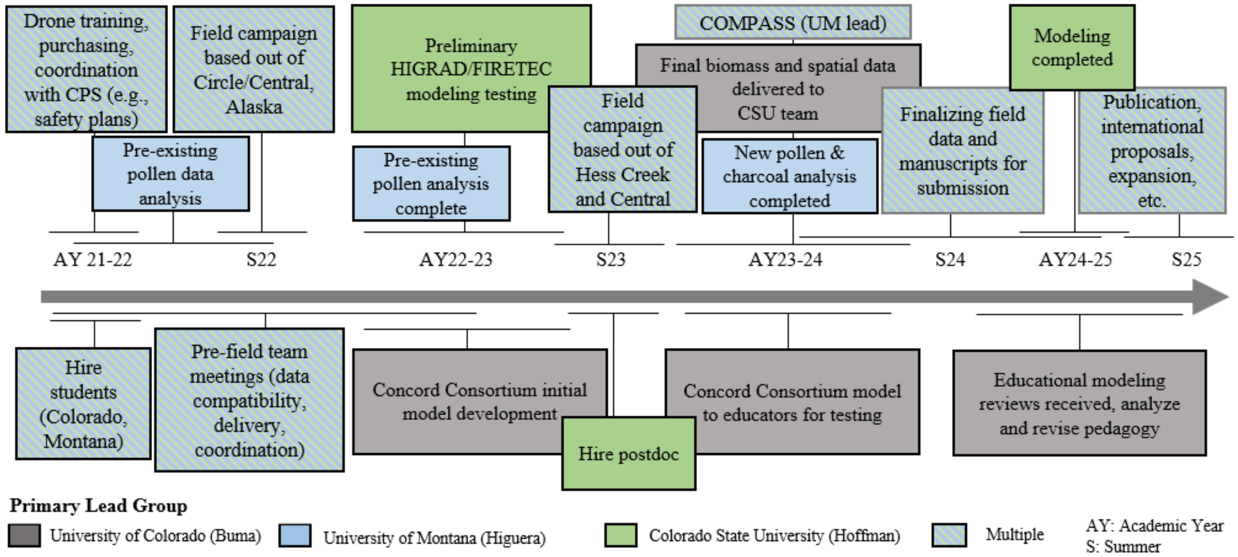
The materials will be disseminated widely to Earth and environmental science teachers across the country through CC's networks in Year 2-3. Success of the educational tools will be directly assessed: CC will collect feedback on the materials from the teachers and students in participating classrooms and report back to the larger team. The feedback will take the form of before and/or after questions like "What do you know about wildfires in the boreal?" "How is carbon impacted by increasing fire frequency?" or "Was this methodology valuable in teaching you ecological study design?" The team will coordinate with the University IRB team as applicable. PIs Higuera and Hoffman also teach 200-level introductory fire management classes annually and will integrate this leaning tool into classes and assessments.

Science communication on wildfires, fire ecology, and fire behavior is increasingly critical to society, given each passing record-setting fire season. The 2020 fire season in the western lower 48 states is the most recent example, punctuating a decades-long increase in area burned, well correlated with climate change and coming with increasingly devastating human impacts (Buma and Schultz 2020, Higuera and Abatzoglou 2020). To improve science communication and better integrate it into graduate training, the COMPASS program will provide a two-day training open to both grant participants and the larger university community (total of 20 participants). The COMPASS training involves hands-on practice with journalists and policy makers, workshopping, and active feedback, and PI Higuera participated in two previous, fire-specific COMPASS trainings in Montana (see budget and COMPASS quote). Targeted skills include communicating uncertainty, pitching stories to and communicating with journalists, communicating broadly via social media, and communicating to policy makers. In addition to the COMPASS training, PI Buma leads the Rocky Mountain Hub of the National Geographic Explorers and regularly communicates research finding through that platform and PI Higuera regularly hosts one journalism graduate student from the University of Montana's Environmental Science and Natural Resource Journalism program, through the programs "Story Lab" course. Each spring a journalism student "embeds" with the lab, participating in lab meetings, asking different prompts of lab members, and in some cases covering ongoing lab events. These activities will be broadened to include the entire project team, during regularly planed team meetings, exposing journalism students to the scope of this project and team members to the world of journalism in greater depth.

TEAM AND GROUP MANAGEMENT, TIMELINE:

Our team is highly qualified for the proposed work: Buma and Higuera have decades of experience in fire ecology and experience leading teams in remote areas of Alaska, including prior NSF-funded projects in the boreal forest, as does Sr. Personnel Chipman. Hoffman is the co-director of the Western Forest Fire Research Center at CSU and is an expert in computational fluid dynamics fire behavior modeling. Senior personnel Linn developed the FIRTEC model and is a senior scientist at Los Alamos National Lab and the associate director for fire science on the WIFIRE project (NSF 1331615 and NSF 2040676). Pallant is a senior research scientist at Concord Consortium. Sr. Personnel Hayes is experienced boreal fire researcher (current graduate student in the Buma lab) and will have a strong leadership role in the field component.

The project will be led by Buma, who will also lead the vegetation/drone/spatial analysis, with Higuera leading the paleoecological components, Hoffman leading the modeling components, and Pallant leading the educational components. We will assess progress towards our goals via monthly team meetings and in-person meetings at conferences and respective institutions. Finally, publications, presentations, and proposals (especially by the graduate students) will also be considered signs of project success. Fieldwork will be facilitated by CPS (see quote). We are acutely aware of the general lack of diversity for the current leadership team, as Pallant and Hayes are the only women, and will explicitly focus on under-represented groups for the graduate student positions and seek collaborations on subprojects with diverse PIs.



RESULTS OF PRIOR NSF SUPPORT

Buma: NSF ANS #1737706: Regional impacts of increasing fire frequency on carbon dynamics and species composition in the boreal forest (2018-2020). PI: Lucash, Co-PI: Buma. *Intellectual Merit:* New publications from this ongoing project include Buma et al. 2020, which quantifies timelines in negative fire feedbacks associated with reburning at the Western US scale (Buma et al. 2020) and Hayes and Buma (in press), the first evaluation of ongoing reburning in boreal forests. Multiple other papers are in preparation or in review (COVID delayed final fieldwork a year). *Broader Impacts*: 1 PhD student (Hayes), three undergraduates (two women, one male minority). Several 360 videos of our project and have filmed pedagogical videos for middle school students with ScienceLIVE, which is being finalized for release.

Higuera: NSF EF #1241846: Collaborative research and NEON: PalEON: PaleoEcolgocial Observatory Network to Assess Terrestrial Ecosystem Models (2013-2018). PI: Jason Mclachaln PI, Higuera collaborative PI for Alaskan component. *Intellectual Merit*: Newly published (Hoecker and Higuera 2019) and meta-analysis of previously published lake-sediment records (Hoecker et al. 2020) highlight unprecedented nature of recent fire frequencies and importance of fire-vegetation feedbacks in controlling past fire regimes. Applied statistical models of fire regimes in Alaska (NFS-ARC-1023669, Young et al. 2017) to past 1200 years through a model-paleodata comparison, highlighting sensitivity of threshold-governed processes to variability in climate in the past and future (Young et al. 2019). Helped develop Bayesian approach to paleofire reconstructions, to compare to existing approaches (Itter et al. 2017). *Products* include four published manuscripts and 1 MS thesis. *Broader Impacts*: 1 MS student, one undergraduate student, and three female postgraduate research assistants.

Pallant: NSF #1812362: GeoHazard: Modeling Natural Hazards and Assessing Risks (2018-2022). PI: Pallant. *Intellectual Merit*: This project contributes to the field's understanding of how to support students' analysis of dynamic models and real-world data in order to improve their conceptual understanding of complex Earth systems associated with natural hazards. *Broader Impacts.* As of today, 103 teachers and roughly 3400 students have participated in pilot testing of the modules. The materials will be released to a wide audience for free through The National Geographic Society and Concord Consortium Websites. Products include two publications and teaching models for wildfire (WFX) and hurricanes.

Hoffman: No NSF funding to report, though Hoffman has led successful projects funded by DOD and other federal institutions (see Current and Pending Support).