Forest Ecology and Management

Decadal impacts of wildfire fuel reduction treatments on ecosystem characteristics and fire behavior in Alaskan boreal forests

--Manuscript Draft--

Manuscript Number:	FORECO-D-23-00741R1
Article Type:	Full Length Article
Keywords:	climate change; disturbance; forest regeneration; permafrost; vegetation composition
Corresponding Author:	Michelle Mack UNITED STATES
First Author:	Melissa Anna Boyd, MSc
Order of Authors:	Melissa Anna Boyd, MSc
	Xanthe J. Walker
	Jennifer Barnes
	Gerardo Celis
	Scott J. Goetz
	Jill F. Johnstone
	Nicholas T. Link
	April M. Melvin
	Lisa Saperstein
	Edward A.G. Schuur
	Michelle C. Mack
Abstract:	Wildfire activity is increasing in boreal forests as climate warms and dries, increasing risks to rural and urban communities. In black spruce forests of Interior Alaska, fuel reduction treatments are used to create a defensible space for fire suppression and slow fire spread. These treatments introduce novel disturbance characteristics, making longer-term outcomes on ecosystem structure and wildfire risk reduction uncertain. We remeasured a network of sites where fuels were reduced through hand thinning or mechanical shearblading in Interior Alaska to assess how successional trajectories of tree dominance, understory composition, and permafrost change over ~20 years after treatment. We also assessed if these fuel reduction treatments reduce modeled surface rate of fire spread (ROS), flame length, and fireline intensity relative to an untreated black spruce stand, and if surface fire behavior changes over time. In thinned areas, soil organic layer (SOL) disturbance promoted tree seedling recruitment but did not change over time. In shearbladed sites, by contrast, both conifer and seedling density increased over time and broad-leaved deciduous seedlings were 20 times more abundant than spruce. Thaw depth increased over time in both treatments and was greatest in shearbladed sites with thin a SOL. Understory composition was not altered by thinning but in shearbladed treatments shifted from forbs and horsetail to tall deciduous shrubs and grasses over time. Modeled surface fire behavior was constant in shearbladed sites. This finding is inconsistent with expert opinion, highlighting the need for additional fuels-specific data to capture the changing vegetation structure. Treatment effectiveness at reducing modeled surface ROS, flame length, and fireline intensity depended on the fuel model used for an untreated black spruce stand, pointing to uncertainties about the efficacy of these treatments at mitigating surface fire behavior. Overall, we show that fuel reduction treatments can promote low flammability, deciduous-dominated successional trajectories, and that shearblading has strong effects on understory composition and permafrost degradation that persist for nearly two decades after disturbance. Such factors need to be considered to enhance the design, management, and predictions of fire behavior in these treatments.

Suggested Reviewers:	Stacy Drury stacy.a.drury@usda.gov Expertise in fire behavior modeling in Alaska
	Jennifer Beverly jen.beverly@ualberta.ca Fire behavior modeling expertise
	Anna Dabros anna.dabros@nrcan-rncan.gc.ca Boreal ecology expertise
	Quinn Barber quinn.barber@canada.ca Boreal ecology expertise
Response to Reviewers:	Editors and Reviewer comments: [our response in blue] The paper has properly addressed the comments provided by previous reviewers. Reviewer #1: Overall, the authors have presented interesting results from a study about a topic that is relevant for fire prevention. The manuscript is generally well-written, but it is very long. Keywords. I think that the first three words are included in the title. I would change these words to other keywords. These words are changed to: climate change; disturbance; forest regeneration; permafrost Line 89: some references are needed in this sentence Added Johnstone et al. 2010b Line 156, line 499 and line 557. What type of thinning was implemented (heavy, light)? Added “Thinning consists of stem reduction to a ~ 3 m spacing and pruning of ladder fuels to ~2 m height on the bole.” Line 170. I don´t understand this idea. If larch is also coniferous, why larch is not included in this group? Added “Larch is a deciduous conifer, but few were observed in our study sites (0.3% of all seedlings). Grouping them into conifers or removing them from analyses did not change our findings (results not shown). Hereafter, our reference to deciduous trees refers to broad-leaved deciduous trees.” We have also added the term “broad-leaved deciduous trees” to several key sections to clarify this difference. Line 181: How was measured the SOL? Added “In each quadrat, we cut a 10 x 10 cm block of organic soil with a bread knife, removed it to the mineral soil or permafrost interface, and measured total SOL depth from the surface of the soil, including moss, to mineral soil or permafrost surface.” Line 276: Why is used a wind speed of 8.5 km/h? Added “This wind speed was the summer average (May-September) from 1984-2018 for the Fairbanks International Airport (NOAA 2021). A wind adjustment factor for thinned sites was calculated based on site-specific canopy cover, a canopy height of 10 m, and a crown ratio of 0.5.” Table S10: What is NA in some plots? WAF should change based on the fuel treatment What about fuel moisture change after fuel treatments? I think that thinning could affect fuel moisture based on solar radiation Please see above. Line 364: the authors make an assertion that I believe is not supported by the data. It may be that the line numbers we are seeing are different and we are not identifying the right line. Line 364 says “In thinned and shearbladed sites SOL depth increased over time (0.84 ± 0.19 cm yr-1 in thinned and 0.33 ± 0.16 cm yr-1 in shearbladed;

Figure 4; Table S8).” These are results.

Line 433: some references are needed in this sentence
Added Melvin et al. 2018.

Line 438: some references are needed in this sentence
I must be off in line numbers, because this sentence describes our findings in this paper.

Line 613. The fuel model selection is only based on one case, but fire behavior is strongly dependent on the fuel (line 612)
We have revised this to: “The Alaska Fuel model guide recommends TU3 for closed black spruce stands under moderate weather conditions but suggests that SH5 is more applicable in dry conditions (Alaska Fuel Model Guide Task Group 2018). Both SH5 (Drury 2019) and TU4 (Horschel 2007) have been used to predict black spruce fire behavior. Because our fire behavior analyses focused primarily on the comparison between treated and unmanaged stands, we compared treated stands to all three fuel types commonly used to model fire behavior in black spruce (e.g., Drury, 2019, Saperstein et al., 2014), holding moisture conditions and fire weather constant across categories.”

Line 617. After fuel treatment, I don´t think that fuel model will be constant because of the vegetation dynamics
We have revised this to: “In both thinned and shearbladed stands, fire behavior did not change over time. This makes sense in thinned stands because understory vegetation and assigned fuel types were constant. In shearbladed stands, however, we were surprised that changes in understory vegetation and assigned fuel types did not impact fire behavior over time. Specifically, because we observed a temporal change from forb and horsetail to a greater abundance of grasses, tall deciduous shrubs, litter, and woody debris, which should increase fire behavior.”

It is said that conifer seedling density increased over time, but this increase is very small. Was it significant (statistical analysis)?
Yes, this is significant as reported in the results section: “In shearbladed sites, deciduous tree seedling density did not change over time (Figure 2b; Table S6) but conifer tree seedling density significantly increased (~0.2 ± 0.06 stems m-2 yr-1; Figure 2c; Table S6).” Over a decade, this increase is substantially more than we see in self-replacing black spruce stands recovering from wildfire (Johnstone et al. 2020).

I think that the authors should disclose the limitations of their sampling methods and size of the sampling
The size of the sampling is disclosed in the methods section. We have added some sentences to the methods to emphasize the relatively large spatial scope that these sites cover here: “In the summer of 2018, we re-sampled 11 hand thinned and 14 shearbladed sites in Interior Alaska that were previously measured in 2012 or 2013 (Melvin et al. 2018), and one thinned site where tree seedling density was measured in 2011 (Figure 1; Table S1). When these sites were originally selected, they comprised all accessible fuel reduction treatments in Interior Alaska that were located on the road system. From north to south, the sites were spread across approximately 500 km of Interior forests.”

We also highlighted our small sample size but broad spatial scope in the conclusions to prevent extrapolation beyond the constraints of our study. “. In Interior Alaska, large-scale fuel treatments were initiated in the decade after the record 2004 wildfire season. Our study focused on decadal change and was thus limited to the relatively few spatially independent fuel treatments of this age: 12 thinned 14 shearbladed sites. Although our sample size was small, sites were spread out across approximately 500 km, covering a large range of Interior Alaska forest and distinct, statistically significant patterns emerged across these sites.”

Thank you for the opportunity to review this paper

We really appreciate your willingness to review, and your helpful comments!

ECOS^S Center for Ecosystem Science and Society at Northern Arizona University
PO Box 5620, Flagstaff, AZ 86011

August 4, 2023

María Elena Fernández
Editor, Forest Ecology and Management

Please find enclosed the revised manuscript "Decadal impacts of wildfire fuel-reduction treatments on ecosystem structure and fire behavior in Alaskan boreal forests" by Melissa A. Boyd, Xanthe J. Walker, April M. Melvin, Jennifer Barnes, Gerardo Celis, Scott M. Goetz, Jill F. Johnstone, Nicholas T. Link, Lisa Saperstein, Edward A.G. Schuur, and Michelle C. Mack. It has taken us longer than we originally anticipated to revise this manuscript due to job changes by Melissa Boyd, the first author. We are hopeful that you will still consider this resubmission.

We would like to thank the Editor and the reviewer for their feedback on our manuscript. We have carefully addressed all reviewer comments and provide line by line responses below.

Please address all correspondence concerning this manuscript to Michelle Mack (email: michelle.mack@nau.edu). We look forward to hearing from you.

Sincerely,

Michelle C. Mack

Michelle Mack

Editors and Reviewer comments:
[our response in blue]

The paper has properly addressed the comments provided by previous reviewers.

Reviewer #1:

Overall, the authors have presented interesting results from a study about a topic that is relevant for fire prevention. The manuscript is generally well-written, but it is very long. Keywords. I think that the first three words are included in the title. I would change these words to other keywords.
These words are changed to: climate change; disturbance; forest regeneration; permafrost

Line 89: some references are needed in this sentence
Added Johnstone et al. 2010b

Line 156, line 499 and line 557. What type of thinning was implemented (heavy, light)?
Added "Thinning consists of stem reduction to a ~ 3 m spacing and pruning of ladder fuels to ~2 m height on the bole."

Line 170. I don´t understand this idea. If larch is also coniferous, why larch is not included in this group?
Added "Larch is a deciduous conifer, but few were observed in our study sites (0.3% of all seedlings). Grouping them into conifers or removing them from analyses did not change our findings (results not shown). Hereafter, our reference to deciduous trees refers to broad-leaved deciduous trees." We have also added the term "broad-leaved deciduous trees" to several key sections to clarify this difference.

Line 181: How was measured the SOL?
Added "In each quadrat, we cut a 10 x 10 cm block of organic soil with a bread knife, removed it to the mineral soil or permafrost interface, and measured total SOL depth from the surface of the soil, including moss, to mineral soil or permafrost surface."

Line 276: Why is used a wind speed of 8.5 km/h?
Added "This wind speed was the summer average (May-September) from 1984-2018 for the Fairbanks International Airport (NOAA 2021). A wind adjustment factor for thinned sites was calculated based on site-specific canopy cover, a canopy height of 10 m, and a crown ratio of 0.5."

Table S10: What is NA in some plots? WAF should change based on the fuel treatment
What about fuel moisture change after fuel treatments? I think that thinning could affect fuel moisture based on solar radiation
Please see above.

Line 364: the authors make an assertion that I believe is not supported by the data.
It may be that the line numbers we are seeing are different and we are not identifying the right line. Line 364 says "In thinned and shearbladed sites SOL depth increased over time (0.84 ± 0.19 cm yr^{-1} in thinned and 0.33 ± 0.16 cm yr^{-1} in shearbladed; Figure 4; Table S8)." These are results.

Line 433: some references are needed in this sentence
Added Melvin et al. 2018.

Line 438: some references are needed in this sentence
I must be off in line numbers, because this sentence describes our findings in this paper.

Line 613. The fuel model selection is only based on one case, but fire behavior is strongly dependent on the fuel (line 612)
We have revised this to: "The Alaska Fuel model guide recommends TU3 for closed black spruce stands under moderate weather conditions but suggests that SH5 is more applicable in dry conditions (Alaska Fuel Model Guide Task Group 2018). Both SH5 (Drury 2019) and TU4 (Horschel 2007) have been used to predict black spruce fire behavior. Because our fire behavior analyses focused primarily on the comparison between treated and unmanaged stands, we compared treated stands to all three fuel types commonly used to model fire behavior in black spruce (e.g., Drury, 2019, Saperstein et al., 2014), holding moisture conditions and fire weather constant across categories."

Line 617. After fuel treatment, I don´t think that fuel model will be constant because of the vegetation dynamics
We have revised this to: "In both thinned and shearbladed stands, fire behavior did not change over time. This makes sense in thinned stands because understory vegetation and assigned fuel types were constant. In shearbladed stands, however, we were surprised that changes in understory vegetation and assigned fuel types did not impact fire behavior over time. Specifically, because we observed a temporal change from forb and horsetail to a greater abundance of grasses, tall deciduous shrubs, litter, and woody debris, which should increase fire behavior."

It is said that conifer seedling density increased over time, but this increase is very small. Was it significant (statistical analysis)?
Yes, this is significant as reported in the results section: "In shearbladed sites, deciduous tree seedling density did not change over time (Figure 2b; Table S6) but conifer tree seedling density significantly increased (~0.2 ± 0.06 stems m^{-2} yr^{-1}; Figure 2c; Table S6)." Over a decade, this increase is substantially more than we see in self-replacing black spruce stands recovering from wildfire (Johnstone et al. 2020).

I think that the authors should disclose the limitations of their sampling methods and size of the sampling

The size of the sampling is disclosed in the methods section. We have added some sentences to the methods to emphasize the relatively large spatial scope that these sites cover here: "In the summer of 2018, we re-sampled 11 hand thinned and 14 shearbladed sites in Interior Alaska that were previously measured in 2012 or 2013 (Melvin et al. 2018), and one thinned site where tree seedling density was measured in 2011 (Figure 1; Table S1). When these sites were originally selected, they comprised all accessible fuel reduction treatments in Interior Alaska that were located on the road system. From north to south, the sites were spread across approximately 500 km of Interior forests."

We also highlighted our small sample size but broad spatial scope in the conclusions to prevent extrapolation beyond the constraints of our study. ". In Interior Alaska, large-scale fuel treatments were initiated in the decade after the record 2004 wildfire season. Our study focused on decadal change and was thus limited to the relatively few spatially independent fuel treatments of this age: 12 thinned 14 shearbladed sites. Although our sample size was small, sites were spread out across approximately 500 km, covering a large range of Interior Alaska forest and distinct, statistically significant patterns emerged across these sites."

Thank you for the opportunity to review this paper

We really appreciate your willingness to review, and your helpful comments!

Highlights:

- Thinned and shearbladed treatments can promote tree recruitment
- Shearblading has greater long-term impacts on understory composition and thaw depth
- Fire behavior modeling did not capture temporal shifts in shearbladed understory
- Treatments did not consistently reduce fire behavior relative to an untreated stand

Title: Decadal impacts of wildfire fuel reduction treatments on ecosystem characteristics and fire behavior in Alaskan boreal forests

Authors: Melissa A. Boyd[a], Xanthe J. Walker[a], Jennifer Barnes [b], Gerardo Celis [c], Scott J. Goetz [d], Jill F. Johnstone [e, f], Nicholas T. Link[a], April M. Melvin [g], Lisa Saperstein [h], Edward A.G. Schuur [a], and Michelle C. Mack [a]

Addresses:

[a] Center for Ecosystem Science and Society and Department of Biological Sciences, Northern Arizona University, P.O. Box 5620, Flagstaff, Arizona 86011, USA; xanthe.walker@nau.edu, ted.schuur@nau.edu, michelle.mack@nau.edu

[b] National Park Service, Interior Region 11, 4175 Geist Rd., Fairbanks, Alaska 99709, USA; Jennifer_barnes@nps.gov

[c] Department of Anthropology, University of Arkansas, Old Main 330, Fayetteville, AR 72701, USA; gerardoc@uark.edu

[d] School of Informatics, Computing, and Cyber Systems, Northern Arizona University, P.O. Box 5620, Flagstaff, Arizona 86011, USA; scott.goetz@nau.edu

[e] YukonU Research Centre, Yukon University, 500 University Dr., Whitehorse, Yukon Y1A 5K4, Canada

[f] Institute of Arctic Biology, University of Alaska Fairbanks, 2140 Koyukuk Dr., Fairbanks, Alaska 99775, USA; jfjohnstone@alaska.edu

[g] The National Academies of Sciences, Engineering, and Medicine, Washington D.C., 20001, USA; amelvin@nas.edu

[h] United States Fish and Wildlife Service, Alaska Region, 1101 E. Tudor Rd., MS 223, Anchorage, Alaska 99503, USA; lisa_saperstein@fws.gov

[†] **Corresponding author:** Michelle C. Mack; michelle.mack@nau.edu

Abstract

Wildfire activity is increasing in boreal forests as climate warms and dries, increasing risks to rural and urban communities. In black spruce forests of Interior Alaska, fuel reduction treatments are used to create a defensible space for fire suppression and slow fire spread. These treatments introduce novel disturbance characteristics, making longer-term outcomes on ecosystem structure and wildfire risk reduction uncertain. We remeasured a network of sites where fuels were reduced through hand thinning or mechanical shearblading in Interior Alaska to assess how successional trajectories of tree dominance, understory composition, and permafrost change over ~20 years after treatment. We also assessed if these fuel reduction treatments reduce modeled surface rate of fire spread (ROS), flame length, and fireline intensity relative to an untreated black spruce stand, and if surface fire behavior changes over time. In thinned areas, soil organic layer (SOL) disturbance promoted tree seedling recruitment but did not change over time. In shearbladed sites, by contrast, both conifer and broad-leaved deciduous seedling density increased over time and deciduous seedlings were 20 times more abundant than spruce. Thaw depth increased over time in both treatments and was greatest in shearbladed sites with a thin SOL. Understory composition was not altered by thinning but in shearbladed treatments shifted from forbs and horsetail to tall deciduous shrubs and grasses over time. Modeled surface fire behavior was constant in shearbladed sites. This finding is inconsistent with expert opinion,

highlighting the need for additional fuels-specific data to capture the changing vegetation structure. Treatment effectiveness at reducing modeled surface ROS, flame length, and fireline intensity depended on the fuel model used for an untreated black spruce stand, pointing to uncertainties about the efficacy of these treatments at mitigating surface fire behavior. Overall, we show that fuel reduction treatments can promote low flammability, deciduous tree dominated successional trajectories, and that shearblading has strong effects on understory composition and permafrost degradation that persist for nearly two decades after disturbance. Such factors need to be considered to enhance the design, management, and predictions of fire behavior in these treatments.

Keywords: climate change; disturbance; forest regeneration; permafrost; vegetation composition

Introduction

Wildfire activity is increasing in North American boreal forests as the climate warms and dries (Balshi et al. 2009, Kasischke et al. 2010, Hoecker et al. 2020), posing a serious threat to human communities and infrastructure (Berman et al. 1999, Trainor et al. 2009). Over the last two decades, large fire years and increasing wildfire risk have prompted implementation of fuel reduction treatments in the wildland-urban interface of Interior Alaska. Through removal of crown and ground fuels, these treatments are designed to slow fire spread and reduce risks to firefighters (Ott and Jandt 2005, Saperstein et al. 2014, KPB 2018, Jandt et al. 2019). However, there is uncertainty in how the composition and structure of treated forests, and thus their fire behavior, change over time. Understanding how fuel treatment characteristics shift over decadal time scales is crucial for determining the maintenance schedule of older treatments and optimizing the construction of new treatments to promote long-term, cost-effective wildfire risk mitigation.

In Interior Alaska, black spruce (*Picea mariana*) forests dominate the landscape (Viereck et al. 1986) and pose the greatest wildfire threat to both rural and urban communities. The long-term impacts of wildfire disturbance on these forests are well studied and provide a framework for understanding how fuel treatment effects may play out over decadal timescales. Black spruce forests are highly flammable, have large ground and crown fuel loads, and experience high-intensity, stand-replacing fires (Hély et al. 2000) with a fire return interval of approximately 100 years in Interior Alaska (Johnstone et al. 2010a, Fire Effects Information System 2021). Historically, post-fire conditions have favored self-replacement successional trajectories. Seeds released from semi-serotinous black spruce cones recruit on partially combusted organic soils within the first few years after fire, establishing a single-aged cohort that dominates until the next fire (Johnstone et al. 2010a). Rapidly resprouting vascular understory species give way to mosses as stands age, promoting re-accumulation of a thick soil organic layer (SOL; Hart and Chen 2006, Johnstone et al. 2010a, Jean et al. 2017). While combustion of the insulating SOL deepens the active layer in permafrost-affected soils, re-accumulation of the SOL drives permafrost recovery (Shur and Jorgenson 2007, Viereck et al. 2008, Jafarov et al. 2013), with the active layer returning to its original depth 25-50 years after fire (Van Cleve and Viereck 1981).

Increased fire severity that burns deeply into the SOL disrupts historical post-fire recovery patterns of these forests and promotes alternative successional trajectories (Johnstone et al. 2010b). Deep burning and exposure of mineral soil favors recruitment of broad-leaved deciduous tree species, such as trembling aspen (*Populus tremuloides*) and Alaska paper birch (*Betula noealaskana;* Johnstone et al. 2020, Mack et al. 2021). Stands dominated by deciduous trees have little moss cover (Jean et al. 2017), shallow SOLs, and deeply thawed soils (Van Cleve et al. 1983, Melvin et al. 2015; Alexander and Mack 2016). The low flammability of deciduous forests (Cumming 2001) can reduce landscape fire activity (Hély et al. 2000, Johnstone et al. 2011, Girardin and Terrier 2015).

The primary fuel reduction treatments applied to black spruce forests in Alaska are manual thinning and shearblading. Thinning consists of stem reduction to a ~ 3 m spacing and pruning of ladder fuels to ~2 m height on the boles. Shearblading consists of mechanical removal of aboveground biomass with a sharp blade attached to a bulldozer. Although these treatments differ qualitatively from wildfires in disturbance characteristics, there are some impacts that are similar: removal of aboveground biomass that impacts seed sources and SOL disturbance that impacts seed beds. Similar to fire, loss of seed sources and exposure of mineral seed beds in fuel reduction treatments could promote a shift from high flammability black spruce to low flammability alternative deciduous successional trajectories. In thinned stands, impacts on stand regeneration through seedling recruitment, understory plant community composition, and SOL depth are minimal (Little et al. 2018, Melvin et al. 2018). Shearblading, by contrast, is more comparable to stand-replacing fire; it removes all aboveground tree biomass and may significantly disturb soils (Ott and Jandt 2005, Butler et al. 2013, Little et al. 2018). Shearblading is also more likely to expose mineral soil, resulting in high deciduous tree recruitment, establishment of early successional forbs and grasses, and large increases in soil thaw depth (Melvin et al. 2018).

To date, there is no published information on how ecosystem characteristics and fire behavior change over decadal timescales in treated forests of Interior Alaska. High deciduous tree recruitment and survival may shift treated areas towards deciduous-dominated forests that act as persistent living fuel breaks (Johnstone et al. 2011), yet dense thickets of deciduous trees or shrubs could impede firefighter access. Continued permafrost degradation in fuel treatments could modify hydrology and plant composition (Schuur and Mack 2018) and make these areas dangerous to access due to ground instability and collapsed trees (Osterkamp et al. 2000). Modeled fire behavior results show contrasting impacts of fuel treatments in Interior Alaska (DeFries 2003, Theisen 2003, Horschel 2007, Little et al. 2018), and empirical observations of wildfire behavior in fuel reduction treatments are limited (Butler et al., 2013). Research in other regions of the boreal biome also report conflicting impacts of fuel treatments on fire behavior (e.g., Mooney 2013, Beverly et al. 2020, Thompson et al. 2020). Knowing how potential fire behavior changes as treatments age will improve the design and maintenance schedule of fuel treatments that foster long-term wildfire risk mitigation.

To improve our understanding of how key ecosystem characteristics change over time after fuel reduction treatment, we remeasured a network of different aged thinned and shearbladed sites that were established ~20 years ago in Interior Alaska. We documented how successional trajectories of tree dominance, understory composition, and active layer depth changed over decadal timescales. We used these data to model surface ROS, flame length, and fireline intensity between treatment types and assessed if they were effective in reducing surface fire behavior relative to untreated black spruce stands. We also examined how surface fire behavior changed over time after treatment. Our results provide insight into fuel treatment impacts on temporal changes in ecosystem structure and thus how well the goals of reduced fire risk are likely to be met as these treatments age without further intervention.

Materials and Methods

Field Methods

In the summer of 2018, we re-sampled 11 hand thinned and 14 shearbladed sites in Interior Alaska that were previously measured in 2012 or 2013 (Melvin et al. 2018), and one thinned site where tree seedling density was measured in 2011 (Figure 1; Table S1). When these sites were originally selected, they comprised all accessible fuel reduction treatments in Interior Alaska that were located on the road system. From north to south, the sites were spread across approximately 500 km of Interior forests. In 2018, time after initiation of fuel reduction treatments ranged from 7 – 17 years. Each site was paired with an adjacent, unmanaged, black spruce-dominated stand to serve as a reference stand (see Melvin et al. 2018). See Table S2 for site level summaries of tree density, DBH, and basal area measured in 2012 or 2013. Overstory trees, vegetation, and ground cover were not re-measured in unmanaged sites as the slow pace of succession in these mature forests (Van Cleve et al. 1991, Hollingsworth 2004) indicates little potential for substantial vegetation change from 2012 or 2013 to 2018. Harvested biomass was burned on site in piles or windrows (see Table S1) in all treated areas except Chena Hot Springs Road North, Badger Road, Delta Junction, and Toghotthele. If harvested biomass was not burned on site, it was either removed from the site or piled and left at the site.

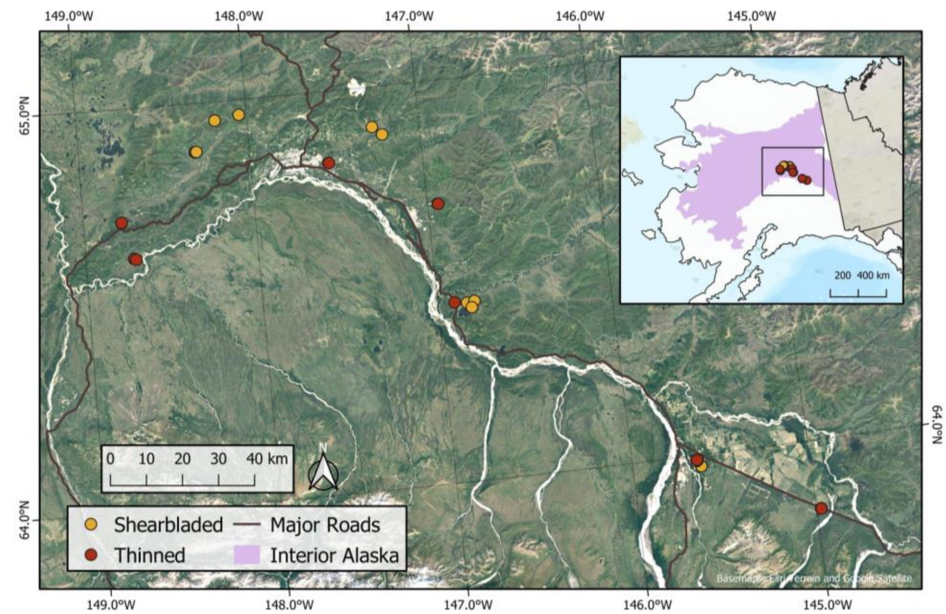


Figure 1. Map of sampled fuel treatments in Interior Alaska. See Table S1 for detailed information about the treatments sampled.

We used GPS coordinates to relocate and sample transects at each treated and adjacent unmanaged site measured in 2012 or 2013. There were two 20 m transects per treated or unmanaged area that were approximately 20 m apart. Three thinned areas required a different sampling design because they were smaller in area than the other sampling locations (Table S1). Each of these three areas consisted of two unmanaged 9 x 9 m plots that were paired with 9 x 9 m plots that had been either thinned to 2.4 x 2.4 m or 3 x 3 m tree spacing (see Ott and Jandt 2005). Within each 9 x 9 m plot we sampled two 7 m transects, 1 m from the plot edge, and 2 m apart in each of the two thinned and paired unmanaged plots. Within these areas, plots with different tree spacing were handled as individual sites. We also sampled transects at a thinned site where only tree seedling data was collected in 2011 (Table S1). We did not have transect coordinates for this site from 2011, and thus established two 20 m transects at the managed and paired unmanaged site.

To estimate the density of tree seedlings and trees (≤ 1.4 m in height), we placed five 1 x 1 m quadrats at random locations along each 20 m transect. In each quadrat all seedlings and trees were counted and identified as conifer (black spruce and white spruce (*Picea glauca*)) or broad-leaved deciduous (trembling aspen (*Populus tremuloides*), Alaska paper birch (*Betula neoalaskana*), and *Larix laricina* (larch)). Larch is a deciduous conifer, but few were observed in our study sites (0.3% of all seedlings). Grouping them into conifers or removing them from analyses did not change our findings (results not shown). Hereafter, our reference to deciduous trees refers to broad-leaved deciduous trees. We did not differentiate between deciduous tree suckers and seedlings, but the lack of deciduous trees in surrounding, unmanaged stands suggest that these were seedlings. Black spruce layers (asexual clones established from rooted branches) were included in regeneration measurements in 2012 and 2013, so in 2018 layers were counted in all quadrats but recorded separately from seedlings. To obtain a seedling count for 2012 and 2013 that did not include black spruce layers, we corrected for layers that were included in the 2012 and 2013 seedling counts using the ratio of seedlings to layers measured in 2018 at the transect level. We then standardized all seedling counts (excluding black spruce layers) by type (conifer and deciduous) to stems m^{-2} prior to statistical analysis.

In each quadrat, we cut a 10 x 10 cm block of organic soil with a bread knife, removed it to the mineral soil or permafrost interface, and measured total SOL depth from the surface of the soil, including moss, to mineral soil or permafrost surface. Adjacent to each soil sampling location, late summer thaw depth (an index of active layer depth) was measured using a 2 m steel probe, which was pushed into the ground until hitting ice. At thinned sites where the transects were 7 m, seedling density, SOL depth, and thaw depth were measured at two random locations along each transect. See Table S3 for site level summaries of SOL depth and thaw depth measured in 2018.

We used a point intercept method to measure plant and ground cover types in treated sites (Goodall 1952). A pin was dropped every 1 m along each transect and the number of hits were recorded for key plant genera (*Salix* spp., shrub *Betula* spp.) and plant functional types (horsetail, clubmoss, evergreen shrub, sedge, grass, forb, other deciduous shrub). At each point we also recorded ground cover, which included sphagnum moss, other moss, lichen, plant litter, liverwort, burned and unburned coarse woody debris (CWD), and burned and unburned organic soil. Prior to analysis, values were standardized by dividing the total number of hits for each plant and ground cover type by the number of sampling points along each transect.

Lastly, each treated site in every sampling year was assigned a fuel type as described in the Fuel Model Guide to Alaska Vegetation (henceforth 'Fuel Model Guide'; Alaska Fuel Model

Guide Task Group, 2018) using a combination of site photos, field observations, and measurements of understory composition from point-intercept data. These fuel types were then cross walked to a standard 40 fuel model (Scott and Burgan 2005) as described in the Fuel Model Guide. We typically assigned the default fuel model that best represented conditions in the treatments, although suggested alternates in the Fuel Model Guide were chosen when site-specific characteristics could affect fire behavior.

Statistical Methods

Our analyses were performed in R statistical software version 4.0.0 (R Development Core Team 2021) and included measurements taken in all sampling years (2011, 2012, 2013, and 2018). To infer change over time in tree seedling density, understory vegetation composition, SOL depth, and thaw depth, we combined repeated surveys (remeasurement of treated and unmanaged sites) and elements of a space-for-time substitution (i.e., where different-aged sites are used to represent change over time; Walker et al. 2010). We used a mixed modeling framework to account for repeated measures within a site (Zuur et al. 2009).

For most of our analyses we fit generalized linear mixed effects models (GLMMs) using the package ‘glmmTMB’ (Brooks et al. 2017) or linear mixed effects models (LMMs) using the package ‘nlme’ (Pinheiro et al. 2021). For these models we: (1) included the random intercept of site to account for spatial non-independence of repeated measurements within a site (Zuur et al. 2009), (2) tested for collinearity of covariates when there was more than one predictor using variance inflation factors (VIF < 5; Sheather 2009) in the ‘car’ package (Fox and Weisberg 2019), (3) determined the significance of fixed effects using maximum likelihood ratio tests comparing the full model to a reduced model and confirmed covariate importance with small sample corrected Akaike Information Criterion (AICc; Zuur et al. 2009). When interaction terms were significant, we performed post-hoc tests comparing factors or trends in the ‘emmeans’ package (Lenth et al. 2021) using a Bonferroni p-value adjustment for multiple comparisons (Haynes 2013). For GLMMs we determined the optimal model structure (Appendix 1) and examined residual diagnostics and verified model assumptions were met using the ‘DHARMa’ package (Hartig and Lohse 2021). For LMMs we visually inspected model residuals to verify that model assumptions were met and calculated optimal model coefficients using restricted maximum likelihood estimation (Zuur et al. 2009).

As was done with the 2011, 2012, and 2013 data in Melvin et al. (2018), we compared the measured variables (i.e., seedling density, SOL depth, thaw depth etc.) between treated and unmanaged sites using the 2018 measurements. Our findings were similar with the measured variables differing between treatments and compared with the unmanaged sites (Appendix 2). Given the treatment differences, we built models separately for thinned and shearbladed treatments in the analyses that follow.

Tree seedlings

We used GLMMs to test whether tree seedling density (stem m^{-2}) changed over time in fuel reduction treatments and if it was influenced by SOL depth using seedling density (stem m^{-2}) as the response variable and fixed effects of years after treatment, seedling type (deciduous/conifer), their interaction, and SOL depth. For thinned sites, we used a type I negative binomial distribution and for shearbladed sites a type II negative binomial distribution. A single zero-inflation parameter was applied to all observations for both models (Appendix 1).

Understory vegetation composition and ground cover

We applied the Bray-Curtis dissimilarity index to understory vegetation and ground cover types, separately for thinned and shearbladed treatments, using the ‘metaNMDS’ function in the ‘vegan’ package (Oksanen et al. 2020). For thinned treatments, these indices were calculated from an initial matrix of 21 samples (one mean value per site in each sampling year) and the 10 vegetation and nine ground cover types described above. For shearbladed treatments, these indices were calculated from an initial matrix of 28 samples (one mean value per site in each sampling year) and the vegetation and ground cover types. We visually evaluated the dissimilarity indices using non-metric multidimensional scaling (NMDS) ordination. For both ordinations, the best NMDS solution was based on 20 random starts with 200 iterations and was well represented in two-dimensions (stress < 0.2; McCune and Grace 2002). To assess if years after treatment influenced the observed differences in plant composition and ground cover, we fit years after treatment as an environmental vector onto each ordination using the ‘envfit’ function in ‘vegan’ with site as a random effect (‘strata’; Oksanen et al. 2020).

SOL depth

To determine if SOL depth changed over time in fuel reduction treatments, we fit LMMs with SOL depth as the response variable and the fixed effect of years after treatment. For shearbladed sites, we square root transformed SOL depth to ensure normality and included a variance structure (varExp) to allow for differences in residual spread along years after treatment as revealed by diagnostic plots.

Thaw depth

To determine if soil thaw depth changed over time in fuel reduction treatments and if it was influenced by SOL depth, we fit LMMs with thaw depth difference (ΔTD; treated-unmanaged) as the response variable and the fixed effects of years after treatment and SOL depth. We determined ΔTD by calculating a mean thaw depth value for each adjacent unmanaged site and subtracting this from individual thaw depth measurements taken at the paired, treated site. We used ΔTD for this analysis to have a comparable measurement of thaw depth across sites as depths were measured in different years and times of year. Two shearbladed sites measured in 2018 (FTG1 and FTG2) were excluded from this analysis as thaw could not be measured due to high soil resistance.

Surface fire behavior

We evaluated potential surface fire behavior (ROS, flame length, and fireline intensity) at our study sites using the BehavePlus 6 (Andrews et al. 2005) fire modeling system (www. firelab.org/project/behaveplus). Model inputs included the Scott and Burgan (2005) fuel type, a slope steepness of zero, and a 20-ft wind speed of 8.85 km/hour. This wind speed was the summer average (May-September) from 1984-2018 for the Fairbanks International Airport (NOAA 2021). A wind adjustment factor for thinned sites was calculated based on site-specific canopy cover, a canopy height of 10 m, and a crown ratio of 0.5. Site-level canopy cover was calculated using measurements of tree diameter at breast height (DBH) and stand density measured in 2012 or 2013 (Melvin et al. 2018) and species-specific equations derived from Eastern US and Canada for crown diameter (Bechtold 2003). A canopy height of 10 m was included as black spruce height in Interior Alaska generally ranges from 9-11 m (Hegg 1967). One thinned site (NRTH2) was excluded from this analysis because we lacked tree inventory measurements. For shearbladed treatments, wind adjustment factors were based on the assigned fuel model.

Fire behavior modeling was performed under three fuel moisture scenarios to represent a range based on the Scott Compare Models spreadsheet (Pyrologix 2018): (1) below average ('dry'; 1 hour=3%, 10 hour=4%, 100 hour=5%, live herbaceous=30%, and live woody=60%), (2) average ('average'; 1 hour=6%, 10 hour=7%, 100 hour=8%, live herbaceous=60%, and live woody=90%), and (3) above average ('wet'; 1 hour=9%, 10 hour=10%, 100 hour=11%, live herbaceous=90%, and live woody=120%).

We chose to compare surface fire behavior in treated sites to a typical, untreated boreal black spruce stand as it is the most widespread forest type in Interior Alaska (Viereck et al. 1986) and the most likely forest type to be treated (e.g., Ott and Jandt, 2005). To model fire behavior in a typical black spruce forest, we used three commonly applied or recommended Scott and Burgan (2005) fuel types: SH5 (Shrub), TU3 (Timber-Understory), and TU4 (Horschel 2007; Alaska Fuel Model Guide Task Group 2018; Little et al. 2018; Drury 2019). A wind adjustment factor was calculated based on typical black spruce stand characteristics: a canopy cover of 60%, a canopy height of 10 m, and a crown ratio of 0.8 (Hegg 1967, Viereck et al. 1992, Little et al. 2018).

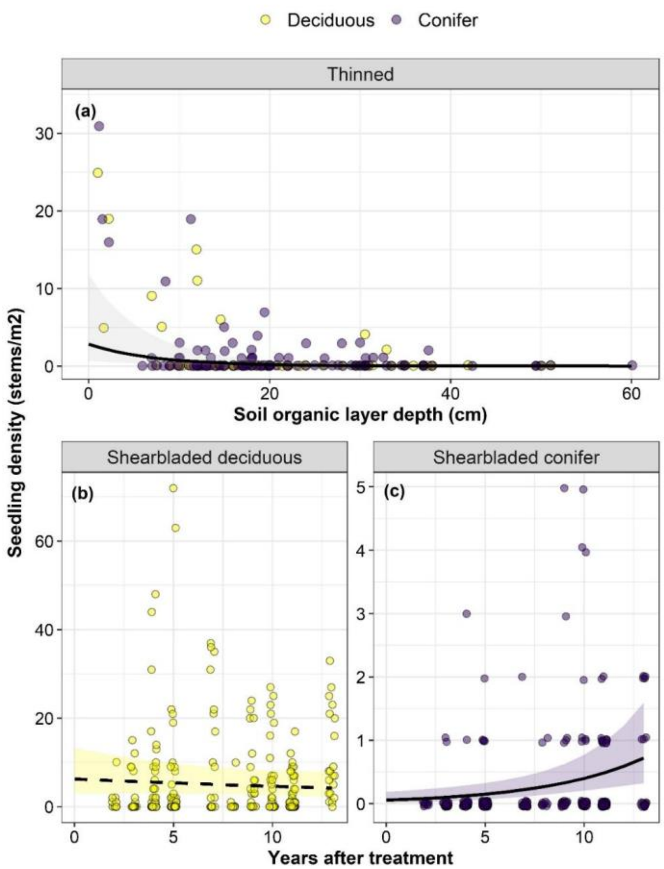
To compare surface fire behavior between treated sites, we fit LMMs separately for each fuel moisture category, with surface ROS, flame length, or fireline intensity as the response variable and the fixed effect of treatment (thinned and shearbladed). We could not statistically compare surface fire behavior between the treated sites and an untreated black spruce forest, so we visually compared the mean and variability of all fire behavior characteristics. To assess if surface fire behavior increased over time, we fit LMMs, separately for each moisture category and treatment (thinned and shearbladed), with ROS, flame length, or fireline intensity as the response variable and the fixed effect of years after treatment. We modeled flame length at average moisture as a function of years after treatment in thinned areas with a simple linear regression.

Results

Tree seedlings

In thinned sites, conifer and deciduous tree seedling densities did not change over time but were negatively associated with SOL depth, and deciduous seedlings were prevalent at SOL depths < 10 cm (Figure 2a; Table S4). Conifer tree seedlings were about three times more abundant than deciduous tree seedlings (Table S5). In shearbladed sites, deciduous tree seedling density did not change over time (Figure 2b; Table S6) but conifer tree seedling density significantly increased (~0.2 ± 0.06 stems m^{-2} yr^{-1}; Figure 2c; Table S6). However, deciduous tree seedling density was nearly 20 times greater than conifer tree seedling density in shearbladed treatments (Figure 2a; Table S6). SOL depth had no effect on seedling density in shearbladed sites (Table S4), likely because in this treatment the SOL was generally shallow in all sampling years (Melvin et al., 2018; Appendix 2). Compared with paired unmanaged sites, the density of conifer and deciduous seedlings in shearbladed sites in 2018 was significantly greater (~78 and 6.5 times greater, respectively; Appendix 2). While only conifer seedling density was significantly higher in thinned than unmanaged sites in 2018 (~6.5 times greater), deciduous seedlings were also more prevalent in thinned areas (~4 times greater; Appendix 2).

Figure 2. Results of generalized linear mixed models (GLMMs) depicting response of broad-leaved deciduous (yellow points) and conifer (purple points) tree seedling density to variation in (a) soil organic layer (SOL) depth in thinned sites and years after treatment for (b) deciduous and (c) conifer seedling density in shearbladed sites. Note that values on the y-axis differ among panels. Shading indicates the 95% confidence interval, each point is a seedling density measurement along a transect, and significant relationships are represented by solid lines. See Table S4 for model results and Table S4 for estimated marginal means of linear trends between



seedling density and years after treatment in shearbladed sites. Note that the y-axis differs across panels.

Commented [WK1]: Have this twice here.

Understory vegetation composition and ground cover

In thinned sites, the multivariate composition of understory plant and ground cover types did not change over time (Table S7). Understory composition in thinned sites in 2018 was analogous to that in unmanaged areas (Appendix 2). In shearbladed sites, the multivariate composition of understory plant and ground cover types shifted over time (Table S7), from a high abundance of forbs, horsetail, and a ground cover of burned organic soil and mineral soil in young sites to grasses, *Salix* spp., *Betula* spp., and a ground cover of litter and CWD in older sites (Figure 3). Understory composition differed between shearbladed sites in 2018 and unmanaged areas, with grasses, *Salix* spp., *Betula* spp., and litter dominating shearbladed sites and evergreen shrubs, lichen, and moss dominating unmanaged sites. This was influenced by SOL depth, such that differences in plant and ground cover types were associated with shallow SOLs in shearbladed sites and deep SOLs in unmanaged sites (Appendix 2).

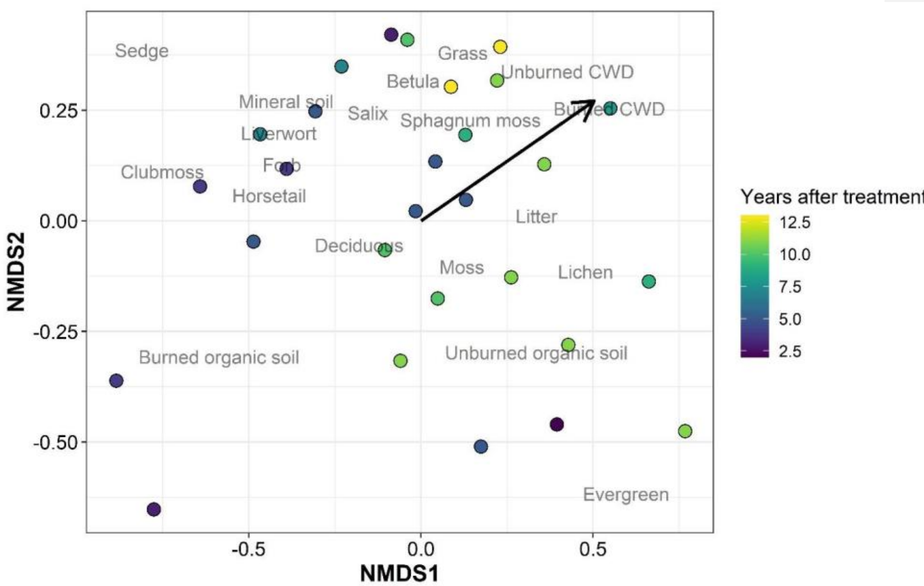


Figure 3. Non-metric multidimensional scaling ordination of plant and ground cover types in shearbladed sites (stress=0.178). Each point is a site and point colors represent years after treatment. The mean location in ordination space of plant and ground cover types is illustrated by the gray text and the arrow points in the direction of compositional change with years after treatment (Table S7). CWD = coarse woody debris.

Depth of SOL

In thinned and shearbladed sites SOL depth increased over time (0.84 ± 0.19 cm yr^{-1} in thinned and 0.33 ± 0.16 cm yr^{-1} in shearbladed; Figure 4; Table S8). At these rates, SOL depths would reach pre-treatments levels 17 years after thinning and 65 years after shearblading given similar environmental conditions. In 2018, SOL depth was greatest in unmanaged sites, followed by thinned and then shearbladed treatments (Appendix 2).

Thaw depth

Thaw depth difference (ΔTD; the difference between treatment and unmanaged) increased over time at a similar rate in thinned and shearbladed treatments (2.8 ± 0.89 cm yr^{-1} in thinned and 2.8 ± 0.84 cm yr^{-1} in shearbladed; Figure 5a and 5c; Table S9). Shearbladed treatments thawed most rapidly in the immediate years post-treatment as indicated by the higher intercept for shearbladed than thinned treatments (Figure 5c; Table S9). In both treatments, SOL depth influenced ΔTD, such that ΔTD declined as SOL depth increased (Figure 5b and 5d; Table S9). That is, the depth of thaw in treated sites approached that of unmanaged stands as the SOL reaccumulated. In 2018, thaw depth was greatest in shearbladed sites, followed by thinned treatments and then unmanaged sites (Appendix 2).

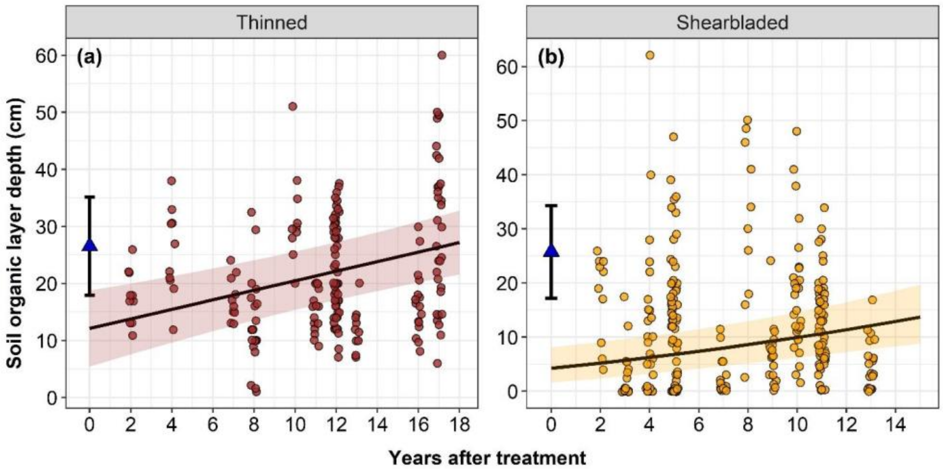


Figure 4. Results of linear mixed models (LMMs) depicting the influence of years after treatment on soil organic layer (SOL) depth in (a) thinned and (b) shearbladed treatments. Shading indicates the 95% confidence interval, each point is a SOL depth measurement along a transect, and significant relationships are represented by solid lines. See Table S8 for model results. Blue point and error bars at the 0 mark of years after treatment indicate the mean (±SD) of SOL in paired unmanaged sites.

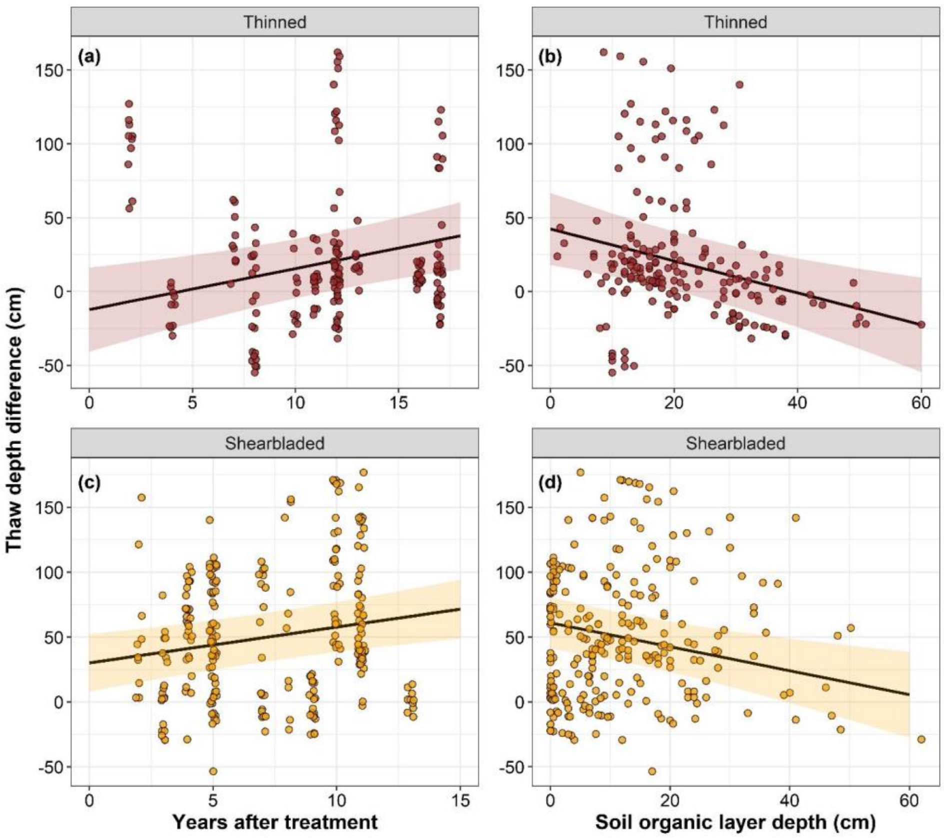


Figure 5. Results of linear mixed models (LMMs) depicting the response of thaw depth difference (ΔTD; treated-unmanaged) to (a, c) years after treatment and (b, d) soil organic layer (SOL) depth in thinned areas (top) and shearbladed areas (bottom). Shading indicates the 95% confidence interval, each point is a thaw depth measurement along a transect, and significant relationships are represented by solid lines. See Table S9 for model results.

Surface fire behavior

Thinned sites were classified as one of three fuel models (TU4, GS2, or GR2; Table S10), with the majority classified as the Timber-Understory (TU) fuel model. Our classification of shearbladed site fuel types varied more widely, and included Grass (GR1, GR2), Grass-Shrub (GS1, GS2), Timber Understory (TU1), and Shrub (SH1) fuel models (Table S10). Fire behavior in an untreated black spruce was modeled with SH5, TU3, or TU4. On average, thinning was effective at reducing surface ROS, flame length, and fireline intensity under all fuel moisture conditions compared with an untreated, black spruce stand represented by the SH5 fuel model (Figure 6). However, surface fire behavior characteristics were generally similar, and in some cases greater, in thinned sites relative to an untreated black spruce stand represented by TU3 or TU4 fuel models (Figure 6). Shearbladed treatments were, on average, effective at reducing surface fire behavior characteristics, besides ROS at dry and average fuel moisture, compared with an untreated black spruce stand represented by the SH5 fuel model (Figure 6). When using the TU3 or TU4 model for an untreated black spruce stand, surface fire behavior tended to be greater or similar in shearbladed treatments, except flame length and fireline intensity under wet fuel moisture (Figure 6). ROS was significantly lower in thinned than shearbladed treatments under dry fuel moisture, whereas flame length and fireline intensity were less in shearbladed than thinned treatments at average and wet fuel moisture (Figure 6; Tables S11 and S12). In both treatments, ROS, flame length, or fireline intensity did not significantly increase over time under any fuel moisture condition (Figure 7; Figures S1 and S2; Tables S13 and S14).

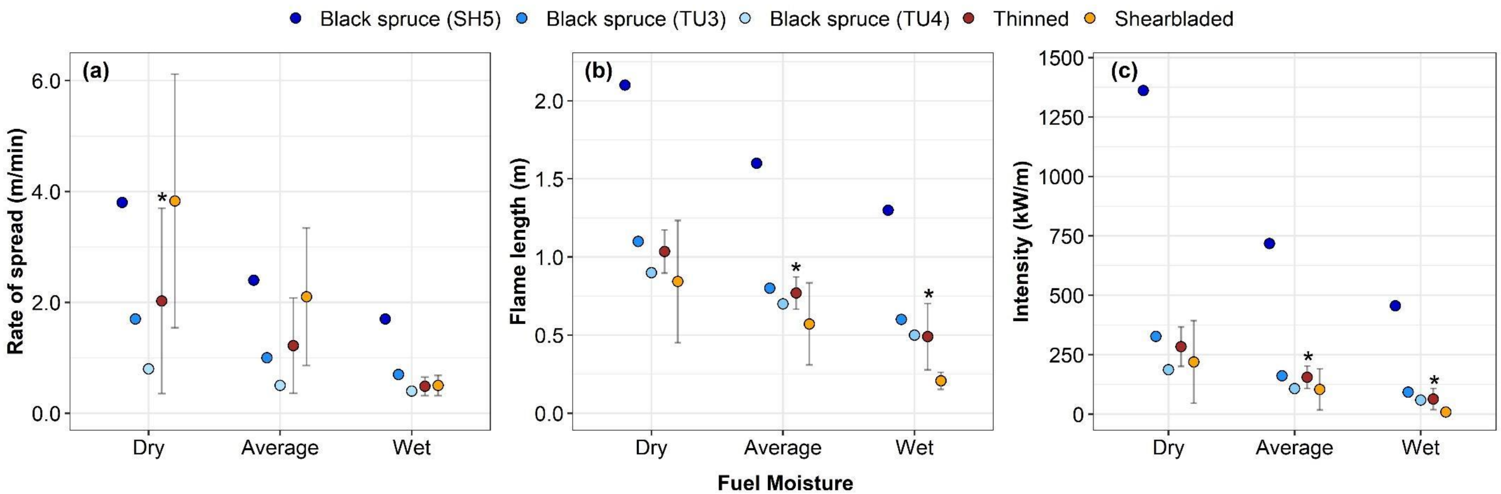


Figure 6. Predictions of (a) surface rate of fire spread, (b) flame length, and (c) fireline intensity at below average (dry), average, and above average (wet) fuel moisture. Asterisks denote a significant difference in surface rate of fire spread, flame length, or fireline intensity between thinned and shearbladed treatments within the relevant fuel moisture category based on post-hoc tests of estimated marginal means (Tables S11 and S12). Colors indicate treatment type. Predictions of fire behavior in an untreated black spruce stand depend on the fuel model used (SH5, TU3, or TU4). Points and error bars are the mean (± SD) of the raw data.

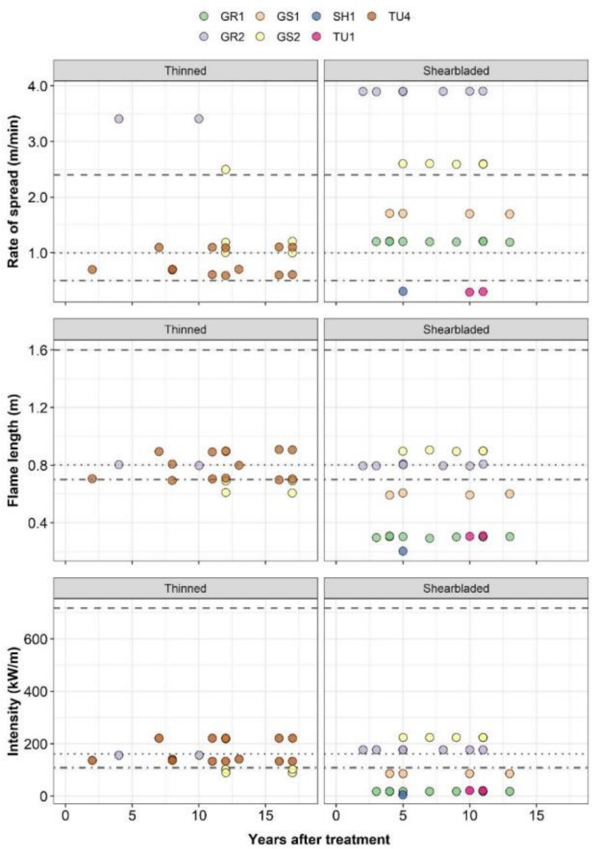


Figure 7. Predictions of surface rate of fire spread (top), flame length (center), and fireline intensity (bottom) at average fuel moisture over time faceted by treatment (left=thinned, right=shearbladed). The dashed, dotted, and dot-dash line indicate the value in an untreated black spruce stand using the SH5, TU3, and TU4 fuel model, respectively, for the relevant fire behavior variable. Point colors indicate the Scott and Burgan (2005) fuel model used in fire behavior predictions. In both treatments, there was no change in any characteristic of surface fire behavior over time (Tables S13 and S14). See Figures S1 and S2 for the same depiction of results at dry and wet fuel moisture, respectively. Points are slightly jittered to better see the data.

Discussion

Fuel reduction treatments used to create a defensible space for fire suppression and slow fire spread can introduce novel disturbance characteristics (Melvin et al. 2018), making longer-term outcomes on ecosystem structure and wildfire risk reduction uncertain. In this study, we assessed how successional trajectories, understory composition, active layer depth, and surface fire behavior changed over time across a network of thinned and shearbladed treatments in Interior Alaska. We found that disturbance to the SOL in both thinned and shearbladed fuel reduction treatments can promote alternative successional trajectories dominated by low-flammability broad-leaved deciduous trees. Shearblading had a greater impact on understory composition and permafrost degradation, as indexed by active layer depth, than thinning, and these effects persisted for the full two decades of measurement after treatment. Whether treatments reduced modeled surface fire behavior was dependent upon the fuel model used for an untreated black spruce stand, with treatments showing the greatest effectiveness when using the SH5 fuel model for untreated black spruce. Finally, surface fire behavior was predicted to be constant over time in shearbladed treatments despite documented changes in vegetation and therefore changing fuel dominance, highlighting the need for additional fuels-specific data to capture the unique structure of fuel treatments when modeling fire behavior.

Tree seedlings

Thinning promoted the recruitment of conifer tree seedlings, which remained constant over time at densities within the range of those seen after wildfire (Johnstone et al. 2020). This suggests that most establishment occurred in the first years after disturbance, which is consistent with tree seedling recruitment after wildfires. Both deciduous and conifer seedling density was negatively related to SOL depth. In five of the 11 sites, slash piles were burned; we observed the highest recruitment of seedlings in treatments where pile burning occurred (Table S15). Pile burning combusts patches of underlying SOL, which may have exposed mineral soil safe sites for seedling establishment (Johnstone et al. 2008). These observations raise the possibility that thinning with pile burning could drive development of multi-aged stands, which would be more flammable, have greater ladder fuels, and be less accessible to firefighters than mature, even-aged conifer stands. Three of the five piled burned stands had deciduous seedling establishment; more study of why these stands showed this pattern could provide insight into prescriptions that promote the establishment of low flammability deciduous trees.

Conifer recruitment in shearbladed treatments persisted over two decades, highlighting the novelty of this disturbance for successional dynamics as post-fire conifer establishment is greatest in just the first few years after fire in black spruce forests (Johnstone et al. 2020). Like thinned areas, the burning of harvested trees on site may have been a seed source initially after treatment. However, the low yet persistent conifer recruitment (~0.2 stems m^{-1} yr^{-1}) in shearbladed areas was likely from seed produced by mature black spruce on the edges of the treatments, as it was the dominant conifer species in the surrounding, unmanaged forest. Black spruce cones release seed without fire, albeit less rapidly than when heated by fire (Zasada et al. 1992, Greene and Johnson 1999). The shearbladed treatments we sampled were much smaller in area than typical boreal fire scars (Calef et al. 2015), yielding a larger edge to area ratio and shorter distance to unmanaged areas with mature black spruce (Turner and Chapin 2005).

Despite persistent conifer recruitment, there were about 20 times more deciduous than conifer seedlings within shearbladed sites due to high deciduous tree recruitment initially following disturbance (Melvin et al. 2018). This recruitment did not continue over time, thus following more typical post-fire tree recruitment dynamics (Johnstone et al. 2020). Deciduous seedlings dominated these sites in all sampling years (Appendix 2; Melvin et al. 2018) and the density of conifers relative to all trees and seedlings was lower in each shearbladed than paired unmanaged site (Appendix 2). Shearblading removes most or all organic soil, providing a viable seedbed for deciduous tree species (Johnstone et al. 2010b). Similarly, substantial site disturbance from mechanical clear-cut logging can shift black spruce forests to deciduous dominance (Carleton and Maclellan 1994). Because of high deciduous seedling dominance, these treatments may not return to black spruce and instead will be effective in mitigating fire risk as they mature into deciduous stands. However, the persistent recruitment of conifers indicates that there is still some uncertainty about the final trajectory of shearbladed treatments. Mixed stand trajectories may emerge that have a flammable conifer component that may, like thinned stands, benefit from conifer removal. Also, thick deciduous stands could impede firefighter access and fire mitigation efforts, indicating re-treatment of these areas to reduce deciduous tree density may be needed, especially if the intent of the treatment is to provide a defensible space for firefighters.

Vegetation composition and ground cover

Understory plant and ground cover composition did not change over time in thinned treatments while grasses, tall deciduous shrubs, litter, and woody debris increased in shearbladed treatments. Thinned areas also had a similar understory structure to unmanaged sites, which had low plant diversity where feather mosses dominated the ground cover and evergreen shrubs, such as *Vaccinium vitis-idea* and *Rhododendron groenlandicum*, were often present. Because SOL removal is an important driver of species composition change after fire in boreal forests (Hollingsworth et al. 2013) and as SOL disturbance was minimal and generally dispersed in patches where fuels were burned in thinned treatments, there was no detectable change in understory structure. Thinning is in part implemented rather than other fuel reduction methods to limit understory change (NPS 2021), and our findings indicate that thinning is effective at doing so, at least within the first two decades after treatment.

In shearbladed treatments understory composition shifted from high forb and horsetail abundance to grass and tall deciduous shrub dominance over time, similar to post-fire community succession (Duchesne and Hawkes 2000). Ground cover also changed over time with this treatment, from primarily burned organic soil and mineral soil to woody debris and plant litter. As deciduous trees and shrubs annually produce litter (Hart and Chen 2006, Melvin et al. 2015), this change in ground cover can be attributed to the high density of deciduous tree seedlings and increase in deciduous shrub abundance in shearbladed treatments. Such a temporal shift in understory composition could be expected to increase surface fire behavior. For example, grass accumulation would increase ROS as these fuels are highly flammable and readily carry fire (Pausas 2015), especially during dry conditions when these fuels quickly dry out (Knowling 2016). Increased dominance of tall shrubs would increase fireline intensity and flame length as these fuels give off more intense heat than herbaceous plants (Scott 2012). Dense thickets of deciduous shrubs could also impede firefighter access, but further research on this topic is needed as we did not directly measure shrub density. Lastly, understory composition consistently differed between shearbladed and unmanaged areas (Melvin et al. 2018; Appendix 2). This difference was influenced by the shallower SOL in shearbladed than unmanaged sites, highlighting the significant and persistent impacts of extensive SOL removal on understory composition. Overall, we show that hand thinning does not alter understory vegetation composition. Shearbladed treatments, by contrast, with widespread SOL disturbance have longer-term impacts on understory structure, with understory fuel composition changing within a few decades following treatment.

SOL depth

SOL depth increased over time in both thinned and shearbladed treatments and was consistently shallower than SOL in unmanaged areas. As thinning does not directly result in SOL removal, a decrease followed by a positive trend in SOL depth was unexpected. This could be explained by initial death of feathermoss (Little et al. 2018, Jandt et al. 2019) recovering over time combined with plant litter inputs (Lang et al. 2009; Turetsky et al. 2010), leading to SOL reaccumulation (Van Cleve and Viereck 1981). Recovery from treatment-related compaction may have also influenced this trend, as disturbances such as fuel treatments (Melvin et al. 2018), logging (Ivanov 1976), and seismic lines (Dabros et al. 2018, Davidson et al. 2020) can result in soil compaction in high-latitude forests.

While shearblading does not always result in significant soil disturbance (Nicholls 2006), it significantly decreased the SOL in our study sites (Figure 2; Appendix 2). Thus, the increase in SOL depth over time that we observed likely reflects recovery of the SOL that was partially or completely removed through shearblading. High deciduous tree establishment, extensive litter ground cover, and minimal moss presence in shearbladed treatments suggests SOL depth will not return to pre-treatment levels and will remain more like deciduous stands (Johnstone et al. 2010a).

SOL recovery could be further inhibited in any treated areas that are following a trajectory of deciduous dominance. Deciduous forests have shallower organic layers than black spruce stands (Van Cleve et al. 1983) since deciduous leaf litter inputs inhibit moss accumulation through shading or crushing (Jean et al. 2020) and litter quality (Natalia et al. 2008).

Furthermore, compared with black spruce forests, soils in deciduous stands are warmer and decomposition and nutrient turnover are more rapid (Melvin et al. 2015), which limits SOL accumulation (Van Cleve et al. 1986). We conclude that organic soil depths will likely recover to pre-treatment levels in thinned areas that maintain black spruce dominance whereas deciduous litter accumulation could constrain the temporal increase in SOL depth in thinned and shearbladed areas that are following a deciduous trajectory.

Thaw depth

Depth of thawed soil above the permafrost layer was greater in both treatments compared with unmanaged areas, increased over time, and was negatively associated with SOL depth. In thinned areas the positive trend in thaw depth over time was contrary to our predictions but could be attributed to slow recovery from SOL compaction in areas within this treatment or patchy SOL combustion from biomass burning that decreased the insulative properties of this layer (Viereck et al. 1983, Jorgenson et al. 2010, Williams and Quinton 2013). Canopy removal could be another important driver of increasing thaw across all thinned treatments, as greater solar radiation reaches the ground when the canopy is removed, heating the soil and in turn increasing thaw (Blok et al. 2010). Furthermore, a reduction in the crown layer via thinning increases the amount of snow that reaches the ground, which acts as an insulator and can reduce freezing depth (Sturm et al. 2001, Zhang 2005).

In shearbladed treatments thaw depth increased significantly over time, consistent with partial or complete removal of the SOL (Appendix 2; Melvin et al. 2018) and a slower rate of SOL accumulation than in thinned areas. Complete canopy removal in shearbladed areas also likely contributed to soil thaw due to greater solar radiation and snow cover as discussed above. Thaw was substantially greater in shearbladed than both thinned and unmanaged areas

(Appendix 2; Melvin et al. 2018), further highlighting the negative impacts of shearblading on permafrost stability. Considering that shearblading more substantially disturbs soils than thinning, our results highlight that a greater initial impact of treatment results in a longer period of recovery for soils and permafrost.

Permafrost degradation has widespread impacts on ecosystem structure (Jorgenson et al. 2001, Schuur and Mack 2018, Jin et al. 2020), including surface subsidence (Nelson et al. 2001, Rodenhizer et al. 2020) and decreased water table depth in areas of ice-rich permafrost (Jorgenson et al. 2013). Subsided areas are extremely difficult to navigate and could impede firefighter access. In many of the shearbladed sites we sampled, subsided areas and shallow water table depths were observed. Moreover, ground subsidence can disrupt the root zone and lead to tipping of trees (Schuur and Abbott 2011), creating hazards for firefighter egress. If these treatments are applied around or near buildings or other structures, thawing permafrost could substantially impact their integrity. By modifying soil hydrology, biogeochemical processes, and nutrient availability, soil thaw incites changes in plant community composition (Jin et al. 2020) such as increasing the dominance of deciduous shrubs and trees (Schuur and Mack 2018). Finally, permafrost soils store a considerable amount of carbon, and the emission of this carbon acts as a positive feedback to climate warming (Schuur et al. 2015). Yet it is also important to consider that permafrost-related carbon emissions would likely be greater after fire due to the greater area generally impacted by fire than by fuel treatments. As shearblading resulted in the greatest disturbance to the SOL and permafrost, we conclude that thinning is a better fire management choice in areas of relatively ice-rich permafrost to limit permafrost degradation and the associated impacts on ecosystem structure.

Surface fire behavior

Model results showed that treated stands reduced surface fire behavior compared with untreated black spruce stands, but only for the SH5 fuel type: not for the TU3 or TU4 fuel types. The Alaska Fuel model guide recommends TU3 for closed black spruce stands under moderate weather conditions but suggests that SH5 is more applicable in dry conditions (Alaska Fuel Model Guide Task Group 2018). Both SH5 (Drury 2019) and TU4 (Horschel 2007) have been used to predict black spruce fire behavior. Because our fire behavior analyses focused primarily on the comparison between treated and unmanaged stands, we compared treated stands to all three fuel types commonly used to model fire behavior in black spruce (e.g., Drury, 2019, Saperstein et al., 2014), holding moisture conditions and fire weather constant across categories. Our study focuses on surface fire behavior, not crown, because it is comparable among all treatments, including sherabladed sites where the crown has been removed. Thus, our interpretation is limited to relative differences in surface fire behavior across treatments and black spruce fuel types rather than absolute values.

The relative differences we found are consistent with other fire modeling studies in boreal Alaska. For example, Little et al. (2018) showed that, relative to a black spruce stand modeled with SH5, surface ROS, flame length, and fireline intensity were less in thinned treatments and a single shearbladed treatment at low 20-ft wind speeds. By contrast, when black spruce fire behavior was modeled with TU4, ROS was greater in thinned areas (Horschel 2007). Observations of fire behavior in fuel treatments in Interior Alaska are very limited. The single study showed reduced overall surface fire behavior in a thinned stand and reduced fireline intensity and flame length in a shearbladed stand relative to untreated forest (Butler et al. 2013). Our results show that treatment effectiveness for reducing surface fire behavior is dependent on the fuel type chosen for untreated stands. Drury (2019) observed that SH5 may more accurately represent fire behavior in black spruce than TU3 or TU4, but this is based on one fire. More observations of fire are needed in fuel treatments.

In both thinned and shearbladed stands, fire behavior did not change over time. This makes sense in thinned stands because understory vegetation and assigned fuel types were constant. In shearbladed stands, however, we were surprised that changes in understory vegetation and assigned fuel types did not impact fire behavior over time. Specifically, because we observed a temporal change from forb and horsetail to a greater abundance of grasses, tall deciduous shrubs, litter, and woody debris, which should increase fire behavior. One implication of these results is that vegetation change in shearbladed sites is not well represented by the fuel types in the Alaska Fuel Model Guide. Additionally, fuel-specific measurements (e.g., live herbaceous fuel load, live woody fuel load) may be needed to be included in BehavePlus model inputs to better characterize shearbladed sites.

Conclusions

With increasing wildfire activity in boreal forests, rural and urban communities are looking towards fuel reduction treatments to mitigate wildfire risk. In Interior Alaska, large-scale fuel treatments were initiated in the decade after the record 2004 wildfire season. Our study focused on decadal change and was thus limited to the relatively few spatially independent fuel treatments of this age: 12 thinned 14 shearbladed sites. Although our sample size was small, sites were spread out across approximately 500 km, covering a large range of Interior Alaska forest and distinct, statistically significant patterns emerged across these sites. In thinned treatments, we showed that patchy disturbance to the SOL can promote the establishment of conifer seedlings at greater densities than deciduous seedlings, which could lead to conifer infilling over time. In shearbladed treatments, conifer recruitment was slow and deciduous tree seedlings were 20 times more abundant, suggesting stand conversion to deciduous tree dominance. Active layer depth increased over time in both treatments but was greater in shearbladed sites, indicating that thinning instead of shearblading could reduce permafrost degradation. Our modeling results show uncertainty about treatment effectiveness for reducing fire behavior over time, highlighting the need for new fuel type characterizations and fuel model inputs to adequately model surface fire behavior in fuel treatments.

CRediT authorship contribution statement

Melissa Boyd: Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization, Project administration. **Xanthe J. Walker**: Investigation, Methodology, Supervision, Writing – Review and Editing. **Jennifer Barnes**: Validation, Writing – Review and Editing. **Gerardo Celis**: Software, Writing – Review and Editing. **Scott J. Goetz**: Writing – Review and Editing, Funding acquisition. **Jill F. Johnstone**: Writing – Review and Editing, Funding acquisition. **April M. Melvin**: Investigation, Writing – Review and Editing. **Lisa Saperstein**: Validation, Writing – Review and Editing. **Edward A.G. Schuur**: Writing – Review and Editing, Funding acquisition. **Michelle C. Mack**: Conceptualization, Methodology, Resources, Writing – Review and Editing, Supervision, Project administration, Funding acquisition

Declaration of Competing Interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project was supported by funding from the Strategic Environmental Research and Development Program (SERDP; RC-2754 & RC18-1183), and the Bonanza Creek LTER supported by the NSF (DEB-1636476) and the USDA Forest Service, Pacific Northwest Research Station (RJVA-PNW-01-JV-11261952-231). This work would not have been possible without Daniel Rees at Fort Wainwright, Ray Atwood at the Toghotthele Alaska Native Corporation, and Eric Miller at the Bureau of Land Management, who assisted us in accessing many of the sites for this project. We are also thankful to Garrett Frandson for his help in the field and Randi Jandt for her guidance on site access and navigation.

References

Alaska Fuel Model Guide Task Group. 2018. Fuel Model Guide to Alaska Vegetation. Alaska Wildland Fire Coordinating Group, Fire Modeling and Analysis Committee, Fairbanks, AK, USA.

Alexander, H.D., and Mack, M.C. 2016. A canopy shift in interior Alaskan boreal forests: Consequences for above- and belowground carbon and nitrogen pools during post-fire succession. Ecosystems **19**(1): 98–114. doi:10.1007/s10021-015-9920-7.

Andrews, P.L., Bevins, C.D., and Seli, R.C. 2005. BehavePlus Fire Modeling System, Version 4.0: User's Guide. General Technical Report, Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, USA.

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Glob. Change Biol. **15**(3): 578–600. doi:10.1111/j.1365-2486.2008.01679.x.

Bechtold, W.A. 2003. Crown-diameter prediction models for 87 species of stand-grown trees in the eastern United States. South. J. Appl. For. **27**(4): 269–278. doi:10.1093/sjaf/27.4.269.

Berman, M., Juday, G.P., and Burnside, R. 1999. Climate Change and Alaska's Forests: People, Problems, and Policies. *In* Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region. *Edited by* G. Weller and P.A. Anderson. Center for Global Change and Arctic System Research, University of Alaska Fairbanks, Fairbanks, AK, USA. pp. 21–42.

Beverly, J.L., Leverkus, S.E.R., Cameron, H., and Schroeder, D. 2020. Stand-level fuel reduction treatments and fire behaviour in Canadian boreal conifer forests. Fire **3**(3): 35. doi:10.3390/fire3030035.

Blok, D., Heijmans, M.M.P.D., Schaepman- Strub, G., Kononov, A.V., Maximov, T.C., and Berendse, F. 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. Glob. Change Biol. **16**(4): 1296–1305. doi:10.1111/j.1365-2486.2009.02110.x.

Brooks, M.E., Kristensen, K., Benthem, K.J. van, Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M., and Bolker, B.M. 2017. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. R J. **9**(2): 378–400.

Butler, B.W., Ottmar, R.D., Rupp, T.S., Jandt, R., Miller, E., Howard, K., Schmoll, R., Theisen, S., Vihnanek, R.E., and Jimenez, D. 2013. Quantifying the effect of fuel reduction treatments on fire behavior in boreal forests. Can. J. For. Res. **43**: 97–102. doi:10.1139/cjfr-2012-0234.

Calef, M.P., Varvak, A., McGuire, A.D., Chapin, F.S., and Reinhold, K.B. 2015. Recent changes in annual area burned in interior Alaska: The impact of fire management. Earth Interact. **19**(5): 1–17. doi:10.1175/EI-D-14-0025.1.

Carleton, T.J., and Maclellan, P. 1994. Woody vegetation responses to fire versus clear-cutting logging: A comparative survey in the central Canadian boreal forest. Écoscience **1**(2): 141–152. doi:10.1080/11956860.1994.11682238.

Cumming, S.G. 2001. Forest type and wildfire in the Alberta boreal mixedwood: What do fires burn? Ecol. Appl. **11**(1): 97–110. doi:10.1890/1051-0761(2001)011[0097:FTAWIT]2.0.CO;2.

Dabros, A., Pyper, M., and Castilla, G. 2018. Seismic lines in the boreal and arctic ecosystems of North America: Environmental impacts, challenges, and opportunities. Environ. Rev. **26**(2): 214–229. doi:10.1139/er-2017-0080.

Davidson, S.J., Goud, E.M., Franklin, C., Nielsen, S.E., and Strack, M. 2020. Seismic line disturbance alters soil physical and chemical properties across boreal forest and peatland soils. Front. Earth Sci. **8**: 281. doi:10.3389/feart.2020.00281.

DeFries, T. 2003. Analyses of a Fuels Treatment in the Northern Boreal Forest. Technical Fire Management Paper, Washington Institute and Colorado State University, Duvall, WA, USA.

Drury, S.A. 2019. Observed versus predicted fire behavior in an Alaskan black spruce forest ecosystem: an experimental fire case study. Fire Ecol. **15**(1): 35. doi:10.1186/s42408-019-0053-9.

Duchesne, L.C., and Hawkes, B.C. 2000. Fire in Northern Ecosystems. *In* Wildland Fire in Ecosystems - Effects of Fire on Flora. *Edited by* J.K. Brown and J.K. Smith. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, USA. pp. 35–50.

Fire Effects Information System. 2021. Available from https://www.fs.fed.us/database/feis/fire_regimes/AK_black_spruce/all.html.

Fox, J., and Weisberg, S. 2019. An R Companion to Applied Regression. *In* Third edition. Sage, Thousand Oaks, CA, USA.

Girardin, M.P., and Terrier, A. 2015. Mitigating risks of future wildfires by management of the forest composition: An analysis of the offsetting potential through boreal Canada. Clim. Change **130**(4): 587–601. doi:10.1007/s10584-015-1373-7.

Goodall, D.W. 1952. Some considerations in the use of point quadrats for the analysis of vegetation. Aust. J. Biol. Sci. **5**(1): 1–41. doi:10.1071/BI9520001.

Greene, D.F., and Johnson, E. 1999. Modelling recruitment of *Populus tremuloides*, *Pinus banksiana*, and *Picea mariana* following fire in the mixedwood boreal forest. Can. J. For. Res. **29**(4): 462–473. doi:10.1139/cjfr-29-4-462.

Hart, S.A., and Chen, H.Y.H. 2006. Understory vegetation dynamics of North American boreal forests. Crit. Rev. Plant Sci. **25**(4): 381–397. doi:10.1080/07352680600819286.

Hartig, F., and Lohse, L. 2021. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. Available from https://CRAN.R-project.org/package=DHARMa.

Haynes, W. 2013. Bonferroni Correction. *In* Encyclopedia of Systems Biology. *Edited by* W. Dubitzky, O. Wolkenhauer, K.-H. Cho, and H. Yokota. Springer, New York, NY, USA. pp. 154–154. doi:10.1007/978-1-4419-9863-7_1213.

Hegg, K.M. 1967. A Photo Identification Guide for the Land and Forest Types of Interior Alaska. Northern Forest Experiment Station, Forest Service, US Department of Agriculture, Juneau, AK, USA.

Hély, C., Bergeron, Y., and Flannigan, M.D. 2000. Effects of stand composition on fire hazard in mixed-wood Canadian boreal forest. J. Veg. Sci. **11**(6): 813–824. doi:10.2307/3236551.

Hoecker, T.J., Higuera, P.E., Kelly, R., and Hu, F.S. 2020. Arctic and boreal paleofire records reveal drivers of fire activity and departures from Holocene variability. Ecology **101**(9): e03096. doi:10.1002/ecy.3096.

Hollingsworth, T. N. 2004. Quantifying variability in the Alaskan black spruce ecosystem: Linking vegetation, carbon, and fire. PhD Dissertation. University of Alaska Fairbanks. Fairbanks, AK. USA.

Hollingsworth, T.N., Johnstone, J.F., Bernhardt, E.L., and Chapin, F.S. 2013. Fire severity filters regeneration traits to shape community assembly in Alaska's boreal forest. PLOS ONE **8**(2): e56033. doi:10.1371/journal.pone.0056033.

Horschel, E.A. 2007. Using NEXUS to Assess the Effectiveness of Experimental Black Spruce Forest Fuel Breaks to Reduce Crown Fire Potential in Alaska. University of Alaska, Fairbanks, Fairbanks, AK, USA.

Ivanov, B.N. 1976. Seasonal changes in the density of soil on felled areas in spruce forests. Lesovedenie **4**: 26–30.

Jafarov, E.E., Romanovsky, V.E., Genet, H., McGuire, A.D., and Marchenko, S.S. 2013. The effects of fire on the thermal stability of permafrost in lowland and upland black spruce forests of interior Alaska in a changing climate. Environ. Res. Lett. **8**(3): 035030. doi:10.1088/1748-9326/8/3/035030.

Jandt, R.R., Little, J.M., Drury, S.A., Molina, A., and Lane, B. 2019. Forest Treatments to Reduce Fire Hazard in Alaska: A Compilation of Case Studies. Special Report JFSP, University of Alaska-Fairbanks, Fairbanks, AK, USA.

Jean, M., Alexander, H.D., Mack, M.C., and Johnstone, J.F. 2017. Patterns of bryophyte succession in a 160-year chronosequence in deciduous and coniferous forests of boreal Alaska. Can. J. For. Res. **47**(8): 1021–1032. doi:10.1139/cjfr-2017-0013.

Jean, M., Melvin, A.M., Mack, M.C., and Johnstone, J.F. 2020. Broadleaf Litter Controls Feather Moss Growth in Black Spruce and Birch Forests of Interior Alaska. Ecosystems **23**(1): 18–33. doi:10.1007/s10021-019-00384-8.

Jin, X.-Y., Jin, H.-J., Iwahana, G., Marchenko, S.S., Luo, D.-L., Li, X.-Y., and Liang, S.-H. 2020. Impacts of climate-induced permafrost degradation on vegetation: A review. Adv. Clim. Change Res. **12**(1): 29–47. doi:10.1016/j.accre.2020.07.002.

Johnstone, J.F., Celis, G., Chapin, F.S., Hollingsworth, T.N., Jean, M., and Mack, M.C. 2020. Factors shaping alternate successional trajectories in burned black spruce forests of Alaska. Ecosphere **11**(5): e03129. doi:10.1002/ecs2.3129.

Johnstone, J.F., Chapin, F.S., Hollingsworth, T.N., Mack, M.C., Romanovsky, V., and Turetsky, M.R. 2010a. Fire, climate change, and forest resilience in interior Alaska. Can. J. For. Res. **40**(7): 1302–1312. doi:10.1139/X10-061.

Johnstone, J.F., Hollingsworth, T.K.N., Chapin, F.S., III, and Mack, M.C. 2010b. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. Ecol. Lett. **16**(4): 1281–1295. doi:10.1111/j.1365-2486.2009.02051.x.

Johnstone, J.F., Hollingsworth, T.N., and Chapin, F.S. 2008. A Key for Predicting Postfire Successional Trajectories in Black Spruce Stands of Interior Alaska. General Technical Report, US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA.

Johnstone, J.F., Rupp, T.S., Olson, M., and Verbyla, D. 2011. Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests. Landsc. Ecol. **26**: 487–500. doi:10.1007/s10980-011-9574-6.

Jorgenson, M.T., Harden, J., Kanevskiy, M., O'Donnell, J., Wickland, K., Ewing, S., Manies, K., Zhuang, Q., Shur, Y., Striegl, R., and Koch, J. 2013. Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes. Environ. Res. Lett. **8**(3): 035017. doi:10.1088/1748-9326/8/3/035017.

Jorgenson, M.T., Racine, C.H., Walters, J.C., and Osterkamp, T.E. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Clim. Change **48**(4): 551–579. doi:10.1023/A:1005667424292.

Jorgenson, M.T.J.T., Romanovsky, V.R., Harden, J.H., Shur, Y.S., O'Donnell, J.O., Schuur, E.A.G., Kanevskiy, M.K., and Marchenko, S.M. 2010. Resilience and vulnerability of permafrost to climate change. Can. J. For. Res. **40**(7): 1219–1236. doi:10.1139/X10-060.

Kasischke, E.S., Verbyla, D.L., Rupp, T.S., McGuire, A.D., Murphy, K.A., Jandt, R., Barnes, J.L., Hoy, E.E., Duffy, P.A., and Calef, M. 2010. Alaska's changing fire regime—implications for the vulnerability of its boreal forests. Can. J. For. Res. **40**(7): 1313–1324. doi:10.1139/X10-098.

Knowling, D. 2016. Ecological Restoration: Wildfire Ecology Reference Manual. Lulu Press, Inc., USA.

KPB. 2018. All Lands/All Hands Action Plan: Reducing Wildland Fire Risk on Alaska's Kenai Peninsula. Kenai Forest, Wildfire Protection, and Fuels Management Coordinating Committee, Kenai Peninsula, AK, USA.

Lang, S.I., Cornelissen, J.H.C., Klahn, T., Logtestijn, R.S.P.V., Broekman, R., Schweikert, W., and Aerts, R. 2009. An experimental comparison of chemical traits and litter decomposition rates in a diverse range of subarctic bryophyte, lichen and vascular plant species. J. Ecol. **97**(5): 886–900. doi:10.1111/j.1365-2745.2009.01538.x.

Commented [WK2]: None of their other publications have the J.T. Is this a mistake?

Lenth, R.V., Buerkner, P., Herve, M., Love, J., Riebl, H., and Singmann, H. 2021. emmeans: Estimated Marginal Means, aka Least-Squares Means. Available from https://CRAN.R-project.org/package=emmeans.

Little, J.M., Jandt, R.R., Drury, S., Molina, A., and Lane, B. 2018. Evaluating the Effectiveness of Fuel Treatments in Alaska. Final Report to the Joint Fire Science Program, University of Alaska, Fairbanks, Fairbanks, AK, USA.

Mack, M.C., Walker, X.J., Johnstone, J.F., Alexander, H.D., Melvin, A.M., Jean, M., and Miller, S.N. 2021. Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. Science **372**(6539): 280–283. doi:10.1126/science.abf3903.

McCune, B.P., and Grace, J. 2002. Analysis of Ecological Communities. MjM Software Design, Gleneden Beach, OR, USA.

Melvin, A.M., Celis, G., Johnstone, J.F., McGuire, A.D., Genet, H., Schuur, E.A.G., Rupp, T.S., and Mack, M.C. 2018. Fuel-reduction management alters plant composition, carbon and nitrogen pools, and soil thaw in Alaskan boreal forest. Ecol. Appl. **28**(1): 149–161. doi:10.1002/eap.1636.

Melvin, A.M., Mack, M.C., Johnstone, J.F., McGuire, A.D., Genet, H., and Schuur, E.A.G. 2015. Differences in ecosystem carbon distribution and nutrient cycling linked to forest tree species composition in a mid-successional boreal forest. Ecosystems **18**(8): 1472–1488. doi:10.1007/s10021-015-9912-7.

Mooney, C. 2013. Can Light Stand Thinning Weaken an Advancing Crown Fire? A Case Study in Black Spruce (*Picea mariana*). Final Report, FP Innovations, Point-Claire, QC, Canada.

Natalia, S., Lieffers, V.J., and Landhäusser, S.M. 2008. Effects of leaf litter on the growth of boreal feather mosses: Implication for forest floor development. J. Veg. Sci. **19**(2): 253–260. doi:10.3170/2008-8-18367.

Nelson, F.E., Anisimov, O.A., and Shiklomanov, N.I. 2001. Subsidence risk from thawing permafrost. Nature **410**(6831): 889–890. doi:10.1038/35073746.

Nicholls, D.L. 2006. Wood and Coal Cofiring in Interior Alaska: Utilizing Woody Biomass from Wildland Defensible-space Fire Treatments and Other Sources. Res. Note, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA.

NOAA. 2021. Comparative Climate Data (CCD). Available from https://www.ncei.noaa.gov/products/land-based-station/comparative-climatic-data [accessed 20 April 2021].

NPS. 2021. East Meets West: Active Fuels Management Collaboration in Wrangell-St. Elias (U.S. National Park Service). Available from https://www.nps.gov/articles/000/ak-wrst-fuels-management.htm [accessed 6 January 2022].

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., and Wagner, H. 2020. vegan: Community Ecology Package. Available from https://CRAN.R-project.org/package=vegan.

Osterkamp, T.E., Viereck, L., Shur, Y., Jorgenson, M.T., Racine, C., Doyle, A., and Boone, R.D. 2000. Observations of thermokarst and its impact on boreal forests in Alaska, U.S.A. Arct. Antarct. Alp. Res. **32**(3): 303–315. doi:10.2307/1552529.

Ott, R.A., and Jandt, R.R. 2005. Fuels Treatment Demonstration Sites in the Boreal Forests of Interior Alaska. Final Report to the Joint Fire Science Program, Tanana Chiefs Conference Forestry Program and the USDI Bureau of Land Management, Alaska Fire Service, Fairbanks, AK, USA.

Pausas, J.G. 2015. Evolutionary fire ecology: Lessons learned from pines. Trends Plant Sci. **20**(5): 318–324. doi:10.1016/j.tplants.2015.03.001.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and R Core Team. 2021. nlme: Linear and Nonlinear Mixed Effects Models. Available from https://CRAN.R-project.org/package=nlme.

Pyrologix. 2018. Available from http://pyrologix.com/downloads/ [accessed 12 January 2022].

R Development Core Team. 2021. R: A language and environment for statistical computing. Vienna, Austria. Available from https://www.R-project.org/.

Rodenhizer, H., Ledman, J., Mauritz, M., Natali, S.M., Pegoraro, E., Plaza, C., Romano, E., Schädel, C., Taylor, M., and Schuur, E. 2020. Carbon thaw rate doubles when accounting for subsidence in a permafrost warming experiment. J. Geophys. Res. Biogeosciences **125**(6): e2019JG005528. doi:10.1029/2019JG005528.

Saperstein, L., Fay, B., O’Conner, J., and Reed, B. 2014. Use and Effectiveness of Fuel Treatments During the 2014 Funny River Fire, Alaska. US Fish and Wildlife Service, Branch of Fire Management, Anchorage, AK, USA.

Schuur, E.A.G., and Abbott, B. 2011. High risk of permafrost thaw. Nature **480**(7375): 32–33. doi:10.1038/480032a.

Schuur, E.A.G., and Mack, M.C. 2018. Ecological response to permafrost thaw and consequences for local and global ecosystem services. Annu. Rev. Ecol. Evol. Syst. **49**(1): 279–301. doi:10.1146/annurev-ecolsys-121415-032349.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., Olefeldt, D., Romanovsky, V.E., Schaefer, K., Turetsky, M.R., Treat, C.C., and Vonk, J.E. 2015. Climate change and the permafrost carbon feedback. Nature **520**(7546): 171–179. doi:10.1038/nature14338.

Scott, J.H. 2012. Introduction to Wildfire Behavior Modeling. National Interagency Fuels, Fire, & Vegetation Technology Transfer.

Scott, J.H., and Burgan, R.E. 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel’s Surface Fire Spread Model. General Technical Report, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.

Sheather, S. 2009. A Modern Approach to Regression with R. Springer-Verlag, New York, NY, USA. doi:10.1007/978-0-387-09608-7.

Shur, Y.L., and Jorgenson, M.T. 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafr. Periglac. Process. **18**(1): 7–19. doi:10.1002/ppp.582.

Sturm, M., Holmgren, J., McFadden, J.P., Liston, G.E., Chapin, F.S., and Racine, C.H. 2001. Snow–shrub interactions in arctic tundra: A hypothesis with climatic implications. J. Clim. **14**(3): 336–344. doi:10.1175/1520-0442(2001)014<0336:SSIIAT>2.0.CO;2.

Theisen, S. 2003. An Analysis of Shaded Fuel Breaks on Fire Behavior. BLM Alaska Fire Service, Fairbanks, AK, USA.

Thompson, D.K., Schroeder, D., Wilkinson, S.L., Barber, Q., Baxter, G., Cameron, H., Hsieh, R., Marshall, G., Moore, B., Refai, R., Rodell, C., Schiks, T., Verkaik, G.J., and Zerb, J. 2020. Recent crown thinning in a boreal black spruce forest does not reduce spread rate nor total fuel consumption: Results from an experimental crown fire in Alberta, Canada. Fire **3**(3): 28. doi:10.3390/fire3030028.

Trainor, S.F., Calef, M., Natcher, D., Chapin, F.S., McGuire, A.D., Huntington, O., Duffy, P., Rupp, T.S., DeWilde, L., Kwart, M., Fresco, N., and Lovecraft, A.L. 2009. Vulnerability and adaptation to climate-related fire impacts in rural and urban interior Alaska. Polar Res. **28**(1): 100–118. doi:10.1111/j.1751-8369.2009.00101.x.

Turetsky, M.R., Mack, M.C., Hollingsworth, T.N., and Harden, J.W. 2010. The role of mosses in ecosystem succession and function in Alaska's boreal forest. Can. J. For. Res. **40**(7): 1237–1264. doi:10.1139/X10-072.

Turner, M.G., and Chapin, F.S. 2005. Causes and Consequences of Spatial Heterogeneity in Ecosystem Function. *In* Ecosystem Function in Heterogeneous Landscapes. *Edited by* G.M. Lovett, M.G. Turner, C.G. Jones, and K.C. Weathers. Springer, New York, NY, USA. pp. 9–30. doi:10.1007/0-387-24091-8_2.

Van Cleve, K., Chapin, F.S., Dyrness, C.T., and Viereck, L.A. 1991. Element cycling in taiga forests: State-factor control. BioScience **41**(2): 78–88. doi:10.2307/1311560.

Van Cleve, K., Chapin, F.S., Flanagan, P.W., Viereck, L.A., and Dyrness, C.T. 1986. Forest Ecosystems in the Alaskan Taiga: A Synthesis of Structure and Function. Springer, New York, NY, USA.

Van Cleve, K., Dyrness, C.T., Viereck, L.A., Fox, J., Chapin, F.S., and Oechel, W. 1983. Taiga ecosystems in Interior Alaska. BioScience **33**(1): 39–44. doi:10.2307/1309243.

Van Cleve, K., and Viereck, L.A. 1981. Forest Succession in Relation to Nutrient Cycling in the Boreal Forest of Alaska. *In* Forest Succession, Concepts and Application. *Edited by* D.C. West, H.H. Shugart, and D.B. Botkin. Springer-Verlag, New York, NY, USA. pp. 184–211.

Viereck, L.A., Dyrness, C.T., Batten, A.R., and Wenzlick, K.J. 1992. The Alaska Vegetation Classification. General Technical Report, US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA.

Viereck, L.A., Dyrness, C.T., Cleve, K.V., and Foote, M.J. 1983. Vegetation, soils, and forest productivity in selected forest types in interior Alaska. Can. J. For. Res. **13**(5): 703–720. doi:10.1139/x83-101.

Viereck, L.A., Van Cleve, K., and Dyrness, C.T. 1986. Forest Ecosystem Distribution in the Taiga Environment. *In* Forest Ecosystems in the Alaskan Taiga: A Synthesis of Structure and Function. *Edited by* K. Van Cleve, F.S. Chapin, P.W. Flanagan, L.A. Viereck, and C.T. Dyrness. Springer, New York, NY, USA. pp. 22–43. doi:10.1007/978-1-4612-4902-3_3.

Viereck, L.A., Werdin-Pfisterer, N.R., Adams, P.C., and Yoshikawa, K. 2008. Effect of wildfire and fireline construction on the annual depth of thaw in a black spruce permafrost forest in interior Alaska: A 36-year record of recovery. *In* Proceedings of the Ninth International Conference on Permafrost. *Edited by* D.L. Kane and K.M. Hinkel. Fairbanks, AK, USA. pp. 1845–1850.

Walker, L.R., Wardle, D.A., Bardgett, R.D., and Clarkson, B.D. 2010. The use of chronosequences in studies of ecological succession and soil development. J. Ecol. **98**(4): 725–736. doi:10.1111/j.1365-2745.2010.01664.x.

Williams, T.J., and Quinton, W.L. 2013. Modelling incoming radiation on a linear disturbance and its impact on the ground thermal regime in discontinuous permafrost. Hydrol. Process. **27**(13): 1854–1865. doi:10.1002/hyp.9792.

Zasada, J.C., Sharik, T.L., and Nygren, M. 1992. The Reproductive Process in Boreal Forest Trees. *In* A Systems Analysis of the Global Boreal Forest. *Edited by* H. Shugart, R. Leemans, and G.B. Bonan. Cambridge University Press, Cambridge, UK. pp. 85–125.

Zhang, T. 2005. Influence of the seasonal snow cover on the ground thermal regime: An overview. Rev. Geophys. **43**(4): RG4002. doi:10.1029/2004RG000157.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., and Smith, G.M. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer-Verlag, New York, NY, USA.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT authorship contribution statement

Melissa Boyd: Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization, Project administration. **Xanthe J. Walker**: Investigation, Methodology, Supervision, Writing – Review and Editing. **Jennifer Barnes**: Validation, Writing – Review and Editing. **Gerardo Celis**: Software, Writing – Review and Editing. **Scott J. Goetz**: Writing – Review and Editing, Funding acquisition. **Jill F. Johnstone**: Writing – Review and Editing, Funding acquisition. **April M. Melvin**: Investigation, Writing – Review and Editing. **Nicholas T. Link:** Formal analysis, Writing – Review and Editing. **Lisa Saperstein**: Validation, Writing – Review and Editing. **Edward A.G. Schuur**: Writing – Review and Editing, Funding acquisition. **Michelle C. Mack**: Conceptualization, Methodology, Resources, Writing – Review and Editing, Supervision, Project administration, Funding acquisition.

APPENDIX 1

Determining model error distribution and zero inflation

Methods

To determine the error distribution and zero-inflation parameter for generalized linear mixed effects models (GLMMs) that were fit with seedling density as the response variable and years after treatment as a fixed effect (see *Statistical Methods*), we built models with a 1) Poisson distribution where the variance is equal to the mean, 2) a type I negative binomial distribution where the variance increases linearly with the mean, 3) and a type II negative binomial distribution where the variance increase quadratically with the mean (Hardin and Hilbe 2007). Each model was fit without zero-inflation and with a zero-inflation parameter applied to all observations. For each analysis, the best fitting model was determined by calculating small sample corrected Akaike Information Criterion (AIC_C; Brooks et al. 2017). We then used the 'DHARMa' package (Hartig and Lohse 2021) for residual diagnostics of GLMMs.

Results

For thinned areas, seedling density was modeled with a type I negative binomial distribution and a single zero-inflation parameter applied to all observations because this was the model with the most support and model misspecification was not apparent in residual plots (Table A1.1). In the model with more support (Model 1; Table A1.1), model assumptions were violated as revealed by patterns in residual plots. For shearbladed areas, seedling density was modeled with a type II negative binomial distribution and a single zero-inflation parameter applied to all observations because this was the model with the most support and residual plots did not indicate model misspecification (Table A1.2).

Table A1.1. Small sampled corrected Akaike Information Criterion (AIC_C) of generalized linear effects mixed models for thinned sites with seedling density as the response variable, the fixed effects of years after treatment, seedling type (deciduous and conifer), their first order interaction, soil organic layer (SOL) depth, and the random intercept of site. Final model selected in **bold**.

Model number	*Family*	*Zero-inflation*	*AICc*	*⊗AIC*	*Loglik*	*weight*
1	I negative binomial	No	427.4	0.000	-206.5	0.728
2	**I negative binomial**	**Yes**	**429.3**	**1.980**	**-206.5**	**0.271**
3	II negative binomial	No	442.1	14.75	-213.9	0.000
4	II negative binomial	Yes	442.2	14.84	-212.9	0.000
5	Poisson	Yes	490.6	63.28	-238.2	0.000
6	Poisson	No	682.0	254.7	-334.9	0.000

Table A1.2. Small sampled corrected Akaike Information Criterion (AIC_C) of generalized linear effects mixed models for shearbladed sites with seedling density as the response variable, the fixed effects of years after treatment, seedling type (deciduous and conifer), their first order interaction, soil organic layer (SOL) depth, and the random intercept of site. Final model selected in **bold**.

Model number	*Family*	*Zero-inflation*	*AICc*	*⊗AIC*	*Loglik*	*weight*
1	**II negative binomial**	**Yes**	**1595.5**	**0.000**	**-789.6**	**0.976**
2	II negative binomial	No	1603.0	7.526	-794.4	0.023
3	I negative binomial	No	1608.9	13.46	-784.8	0.001
4	I negative binomial	Yes	1611.0	15.58	-797.4	0.000
5	Poisson	Yes	2142.5	547.0	-1064	0.000
6	Poisson	No	3012.3	1417	-1488	0.000

APPENDIX 2

Comparison of treated and unmanaged stands

Methods

To compare conifer and deciduous seedling density within and between unmanaged, thinned, and shearbladed sites in 2018, we fit a generalized linear mixed effects model (GLMM) using the methods described in the main text (see *Statistical Methods*). The full model included seedling density as the response variable, the fixed effects of stand type (unmanaged/thinned/shearbladed), seedling type (deciduous/conifer), their first order interaction, and the random intercept of site. The optimal model structure was determined by comparing models with various error distributions and the presence or absence of zero inflation as described in Appendix 1. This model was fit with a type I negative binomial distribution and a single zero-inflation parameter applied to all observations (Table A2.1).

We compared tree seedling and mature tree composition in unmanaged sites to treated sites using seedling measurements from 2018 and live, mature tree ($\geq$ 1.4 m tall) measurements taken in 2012/2013. The density of mature trees was measured differently than seedlings such that all mature trees within 1 m of either side of the transect line were counted and identified by species (see Melvin et al. 2018 for details). Thus, to calculate conifer and deciduous seedling and tree density at each site, mature tree measurements were standardized to the total area in which seedling measurements were taken for each treated and paired unmanaged stand. Seedling and mature tree density measurements were then added to obtain site-level density of conifer and deciduous seedlings and trees, and this was used to calculate conifer density relative to total seedling and tree density each unmanaged and treated site. Site NRTH2 was excluded from this analysis as tree density was not measured.

To compare understory composition between unmanaged sites in 2012/2013 and thinned and shearbladed sites in 2018, we applied the Bray-Curtis dissimilarity index to understory vegetation and ground cover types, and visually evaluated the dissimilarity indices using the statistical methods described in the main text. These indices were calculated from an initial matrix of 48 samples (one mean value per site and treatment) and the 10 vegetation and nine ground cover types also described in the methods (see *Understory vegetation composition and ground cover* in *Statistical Methods*). The unmanaged site paired with NRTH2 was not included in this analysis as plant and ground cover were not measured. To determine if plant and ground cover types differed between stand types and if soil organic layer depth (SOL) influenced the observed differences, we fit stand type and SOL as environmental vectors onto the ordination using the ‘envfit’ function in ‘vegan’ (Oksanen et al. 2020). Post-hoc tests comparing stand types were then performed using the ‘pairwise.factorfit’ function in ‘RVAideMemoire’ (Hervé 2021) with a Bonferroni p-value correction for multiple comparisons (Haynes 2013). The best NMDS solution was based on 20 random starts with 200 iterations (McCune and Grace 2002). Results are presented in two-dimensions although the stress was slightly high (stress=0.201) because the addition of a third dimension did not change the interpretation of these results.

To compare SOL depth and thaw depth between unmanaged, thinned, and shearbladed sites in 2018 we fit linear mixed effects models (LMMs) using the methods described in the main text (see *Statistical Methods*). Models were fit with SOL depth or thaw depth as the response variable, stand type (unmanaged/thinned/shearbladed) as a fixed effect, and the random intercept of site. SOL depth was square root transformed to ensure normality. We also compared thaw depth difference (ΔTD) between thinned a shearbladed sites in 2018 by fitting a LMM with ΔTD as the response variable, stand type (thinned/shearbladed) as a fixed effect, and the random intercept of site. Sites FTG1 and FTG2 were excluded from thaw depth analyses as thaw could not be accurately measured at these sites due to high soil resistance. In the SOL depth, thaw depth, and ΔTD model a variance structure (varIdent) was included to account for different variances per treatment as revealed by residual plots (Zuur et al. 2009).

Results

There was no difference in conifer or deciduous seedling density in thinned treatments, but deciduous seedlings dominated shearbladed treatments. Additionally, there were more conifer seedlings in both treatments than in unmanaged areas, and more deciduous seedlings in shearbladed than thinned or unmanaged areas (Table A2.2 and A2.3). All shearbladed sites were following a trajectory of deciduous dominance while conifer dominance was maintained in 80% of thinned sites (Figure A2.1). Stand type had a significant influence on understory plant and ground cover types (Table A2.4), which were different in shearbladed than thinned and unmanaged sites (Table A2.5). Thinned and unmanaged sites were dominated by evergreen shrubs, moss, and lichen whereas shearbladed sites were dominated by grass, tall deciduous shrubs, and litter (Figure A2.2). SOL depth was correlated with plant composition and ground cover (Table A2.4). Deeper SOLs were positively correlated with thinned and unmanaged sites (Figure A2.2). The deepest SOLs were in unmanaged sites, followed by thinned and then shearbladed sites. Thaw depth was greatest in shearbladed sites followed by thinned and then unmanaged sites. Thaw depth difference was also greater in shearbladed than thinned sites (Table A2.3)

Table A2.1. Small sampled corrected Akaike Information Criterion (AIC_C) of generalized linear effects mixed models for all sites in 2018 with seedling density as the response variable, the fixed effects of stand type, seedling type, their first order interaction, and the random intercept of site. Final model selected in **bold**.

Model number	*Family*	*Zero-inflation*	*AICc*	*⊗AIC*	*Loglik*	*weight*
1	**I negative binomial**	**Yes**	**1331.1**	**0.000**	**-656.4**	**0.735**
2	I negative binomial	No	133.4.4	3.310	-659.1	0.141
3	II negative binomial	Yes	1334.7	3.590	-658.3	0.122
4	II negative binomial	No	1343.5	12.39	-663.7	0.001
5	Poisson	Yes	1607.0	276.0	-795.4	0.000
6	Poisson	No	2310.5	979.4	-1148	0.000

Table A2.2. Results of the final generalized linear mixed effects model for modeling seedling density and linear mixed effects models for modeling soil organic layer (SOL) depth, thaw depth, and thaw depth difference (ΔTD; treated – unmanaged) in 2018. Seedling results are on the log scale and SOL depth is square root transformed.

Response variable	***Fixed effects***	***Estimate ± SE***	***z- or t-value***	***p-value***
Seedling density	Intercept (unmanaged)	-2.95 ± 0.58	-5.11	<0.001
	Treatment (shearbladed)	4.31 ± 0.54	8.00	<0.001
	Treatment (thinned)	1.41 ± 0.72	1.96	0.05
	Seedling type (conifer)	0.85 ± 0.61	1.40	0.16
	Treatment (shearbladed) x seedling type (conifer)	-2.45 ± 0.65	-3.78	<0.001
	Treatment (thinned) x seedling type (conifer)	0.46 ± 0.81	0.57	0.57
SOL depth	Intercept (unmanaged)	5.15 ± 0.16	32.0	<0.001
	Treatment (shearbladed)	-1.78 ± 0.11	-15.0	<0.001
	Treatment (thinned)	-0.64 ± 0.12	-5.20	<0.001
Thaw depth	Intercept (unmanaged)	47.5 ± 5.26	5.06	<0.001
	Treatment (shearbladed)	24.7 ± 4.78	4.51	<0.001
	Treatment (thinned)	49.2 ± 4.89	4.89	<0.001
ΔTD	Intercept (thinned)	2.50 ± 12.2	0.02	0.839
	Treatment (shearbladed)	77.5 ± 10.6	7.32	<0.001

Table A2.3. Estimated marginal means of site measurements in 2018. Different letter denotes significant differences in seedling density within and between stand types and in thaw depth, soil organic layer (SOL) depth, and thaw depth differed (ΔTD) between stand types from post-hoc tests of estimated marginal means based on final models (Table A2.2). Estimated marginal means for SOL depth are square root transformed.

Variable	**Treatment**		
	Thinned	*Shearbladed*	*Unmanaged*
Conifer seedling density (stems/m^2)	0.79 ± 0.33[b]	0.78 ± 0.27[b]	0.12 ± 0.05[a]
Deciduous seedling density (stems/m^2)	0.21 ± 0.12[ab]	3.89 ± 1.23[c]	0.05 ± 0.03[a]
SOL depth (cm)	4.51 ± 0.19[a]	3.37 ± 0.19[b]	5.15 ± 0.16[c]
Thaw depth (cm)	72.3 ± 6.30[a]	96.7 ± 6.74[b]	47.5 ± 5.06[c]
ΔTD (cm)	2.5 ± 12.2[a]	80.0 ± 12.2[b]	NA

Table A2.4. Significance of soil organic layer (SOL) depth and stand type on the ordination of vegetation and ground cover composition in thinned, shearbladed, and unmanaged sites. See Figure A2.2 for depiction of results.

Variable	*NMDS1*	*NMDS2*	R^2	*p-value*
Soil organic layer (SOL) depth	-0.76	-0.65	0.21	0.005
Stand type (Thinned)	-0.16	-0.14	0.26	0.001
Stand type (Shearbladed)	0.37	-0.02		
Stand type (Unmanaged)	-0.15	0.08		

Table A2.5. Pairwise comparisons of vascular plant composition and ground cover between stand types.

	Shearbladed	***Thinned***
Thinned	0.002	NA
Unmanaged	0.002	0.155

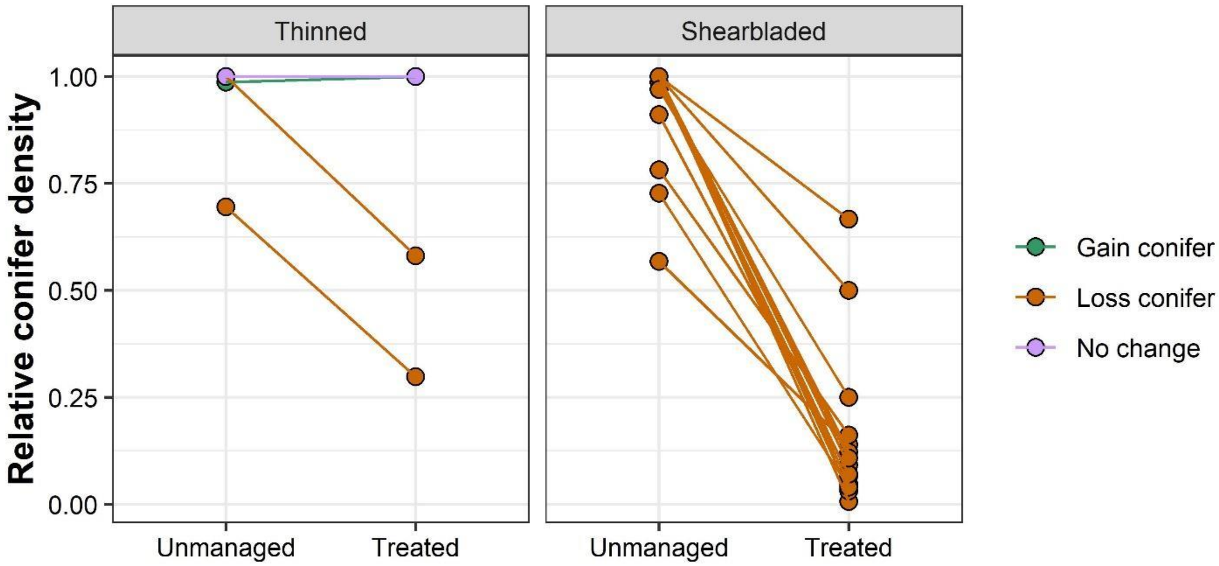


Figure A2.1. Relative conifer tree and seedling density at each unmanaged and treated stand faceted by treatment type (thinned and shearbladed). Lines connect each paired unmanaged and treated site. Green points and lines denote an increase, orange points and lines denote a decrease, and purple points and lines denote no change in relative conifer tree and seedling density in the treated versus unmanaged stand. There are 14 shearbladed and 10 thinned sites plotted.

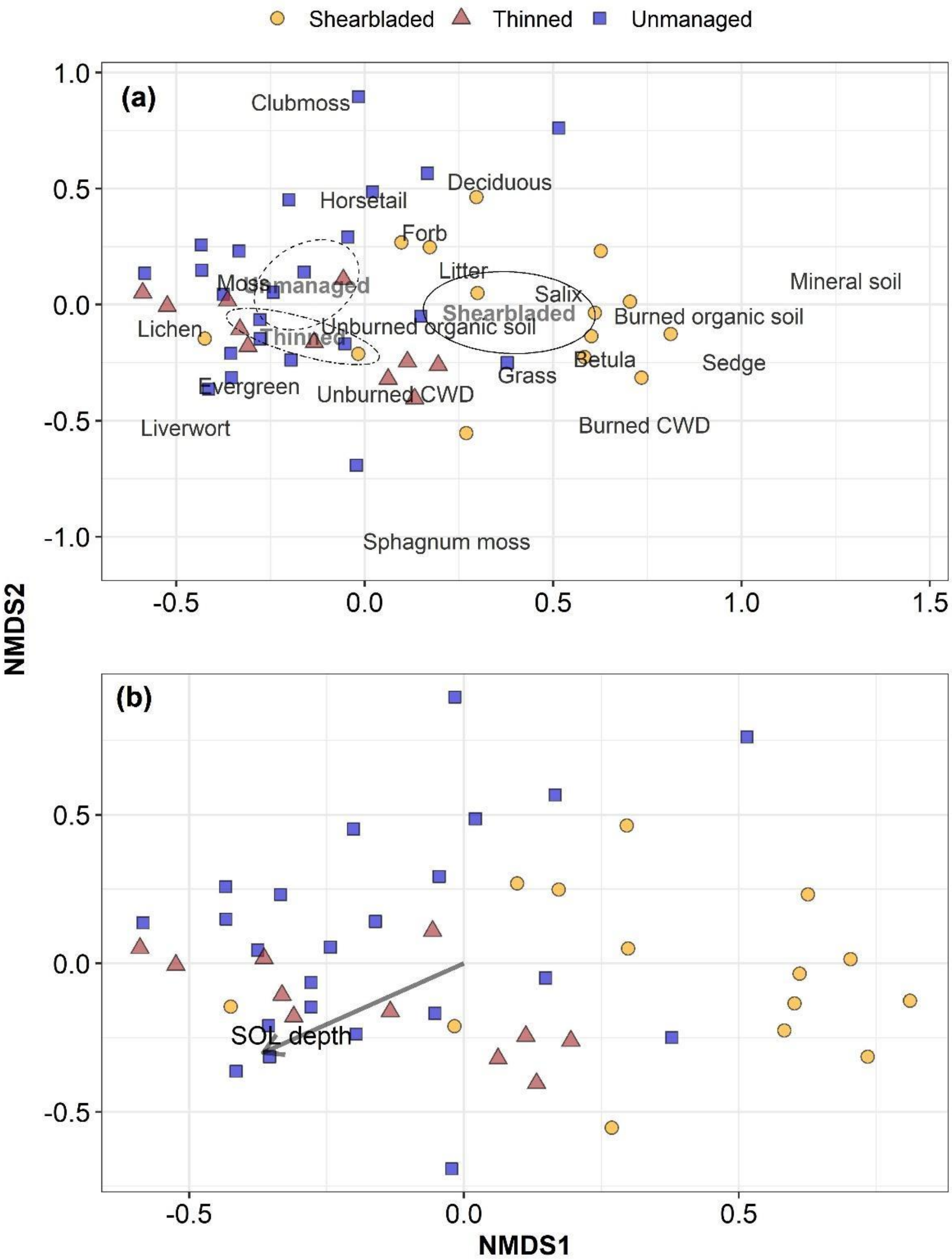


Figure A2.2. Non-metric multidimensional scaling ordination of plant and ground cover types in unmanaged sites in 2012/2013 and thinned and shearbladed sites in 2018. Each point is a site and thinned sites are represented by brown triangles, shearbladed sites by yellow circles, and unmanaged sites by blue squares. In (a) the mean location in ordination space of plant and ground cover types is illustrated by the gray text and circles indicate 95% confidence intervals for each treatment centroid type. In (b) the arrow points in the direction of the most rapid change in soil organic layer (SOL) depth (Table A2.4). See Table A2.5 for results of pairwise comparisons between stand types. CWD = coarse woody debris.

Table S1. Name, abbreviation, location, treatment year, sampling year, and how fuels were burned at each area sampled. Table is modified from Melvin et al. (2018).

Name	*Latitude*	*Longitude*	*Cut Year*	*Sampling Years*	*Burn Method*
Thinned					
Badger Rd. (BAD8P & BAD10P)[A]	64° 49' 22.55"	-147° 32' 58.75"	2001	2013, 2018	None
Delta (DEL8P & DEL10P)[A]	63° 49' 49.00"	-144° 58' 26.34"	2002	2013, 2018	None
Eielson Air Force Base (EAFB)	64° 41' 38.83"	-146° 56' 13.86"	2008	2012, 2018	Piles
Fort Greely Thinned (FTGTH)	63° 59' 22.83"	-145° 37' 59.66"	2005	2013, 2018	Piles
Harding Lake 3 (HDL3)	64° 26' 48.51"	-146° 54' 11.82"	2010	2012, 2018	Piles
Nenana Ridge 1 (NRTH1)	64° 37' 41.02"	-148° 43' 18.85"	2006	2013, 2018	Piles
Nenana Ridge 2 (NRTH2)[B]	64° 37' 31.08"	-148° 42' 37.19"	2006	2011, 2018	Piles
Toghotthele (TOG8P & TOG10P)[A]	64° 43' 7.47"	-148° 46' 42.44"	2001	2013, 2018	None
Shearbladed					
Cache Creek Rd. 1 (CCR1)	64° 52' 44.97"	-148° 19' 7.94”	2007	2012, 2018	Windrows
Cache Creek Rd. 2 (CCR2)	64° 52' 44.31"	-148° 18' 59.97”	2007	2012, 2018	Windrows
Cache Creek Rd. 3 (CCR3)	64° 52' 46.51"	-148° 18' 36.61”	2007	2012, 2018	Windrows
Chena Hot Springs Rd. North (CHSRN)	64° 53' 59.17"	-147° 16' 31.47"	2007	2012, 2018	None
Chena Hot Springs Rd. South (CHSRS)	64° 52' 46.42"	-147° 13' 7.26"	2010	2012, 2018	Windrows
Eielson Air Force Base (EAFB)	64° 41' 41.02"	-146° 56' 24.59"	2008	2012, 2018	Piles
Fort Greely 1 (FTG1)	63° 59' 18.25"	-145° 37' 48.29"	2007	2012, 2018	Piles
Fort Greely 2 (FTG2)	63° 58' 21.09"	-145° 36' 50.20"	2005	2012, 2018	Piles
Fort Greely 3 (FTG3)	63° 59' 10.31"	-145° 38' 14.99"	2005	2012, 2018	Piles
Harding Lake 1 (HDL1)	64° 26' 33.37"	-146° 49' 57.09"	2009	2012, 2018	Windrows
Harding Lake 2 (HDL2)	64° 26' 42.74"	-146° 47' 20.21"	2009	2012, 2018	Windrows
Harding Lake 4 (HDL4)	64° 25' 48.90"	-146° 48' 28.10"	2008	2012, 2018	Windrows
Old Murphy Dome Rd. East (OMDE)	64° 57' 44.45"	-148° 2' 39.44"	2008	2012, 2018	Windrows
Old Murphy Dome Rd. West (OMDW)	64° 57' 11.79"	-148° 11' 15.75"	2007	2012, 2018	Windrows

[A] 9x9 m plots thinned to 2.4 x 2.4 m or 3 x 3 m tree spacing; plots with different tree spacing were handled as individual sites

[B] Tree seedling data collected in 2011

Table S2. Biometrics for the overstory species for each area sampled. We report the number of trees per site (Density) and the Cumulative Basal Area (BA) per site in cm2/m2. We also report both the mean and standard deviation of the Diameter at Breast Height measurements (DBH) in cm as well as the range (minimum to maximum). Species only shown in table if recorded at area sampled.

Name	***Species***	***Treatment***	***Density***	***Basal Area***	***DBH Mean (SD)***	***DBH Range***
Thinned						
Badger Rd. (BAD8P & BAD10P)[A]	*Picea mariana*	Treated	30	7.3	5.8 (2.3)	2.2 - 14.4
		Control	70	4.9	2.8 (1.9)	0.4 - 8.2
Delta (DEL8P & DEL10P)[A]	*Picea mariana*	Treated	19	8.1	8.1 (1.9)	6.1 – 13.9
		Control	58	12.0	5.2 (2.4)	0.6 - 9.2
Eielson Air Force Base (EAFB)	*Picea mariana*	Treated	3	0.9	6.7 (2.3)	4.0 – 8.2
		Control	159	11.6	3 (1.6)	0.2 – 8.1
	Betula neoalaskana	Treated	-	-	-	-
		Control	2	0.5	6.3 (2.3)	4.6 – 7.9
Fort Greely Thinned (FTGTH)	*Picea mariana*	Treated	14	9.6	10.1 (3.1)	4.8 – 16.9
		Control	-	-	-	-
	Betula neoalaskana	Treated	-	-	-	-
		Control	7	7.17	12.2 (4.1)	5.8 – 18.2
	Picea glauca	Treated	-	-	-	-
		Control	40	11.3	5.3 – 4.3	0.7 – 2.8
	Populus tremuloides	Treated	-	-	-	-
		Control	6	3.1	8.0 (4.8)	2.9 – 15.0
Harding Lake 3 (HDL3)	*Picea mariana*	Treated	9	8.8	12.2 (2.7)	9.8 – 18.7

		Control	47	11.9	5.1 (3.8)	0.2 – 120
	Betula neoalaskana	Treated	1	0.7	10.9 (0)	-
		Control	1	0.4	7.9 (0)	0
Nenana Ridge 1 (NRTH1)	*Picea mariana*	Treated	9	4.2	8.5 (2.1)	4.9 – 11.6
		Control	33	10.9	6.3 (3.6)	1.0 – 19.5
Nenana Ridge 2 (NRTH2)[B]	*Picea mariana*	Treated	34	6.2	5.2 (1.4)	2.1 – 8.5
		Control	65	13.8	4.9 (3.1)	0.7 – 19.6
Toghotthele (TOG8P & TOG10P)[A]	*Picea mariana*	Treated	22	10.9	8.2 (3.6)	2.3 – 16.6
		Control	60	6.2	3.1 (2.7)	0.4 – 12.5
Shearbladed						
Cache Creek Rd. 1 (CCR1)	*Picea mariana*	Treated	-	-	-	-
		Control	25	15.5	8.5 (5.3)	1.0 - 23.0
	Betula neoalaskana	Treated	-	-	-	-
		Control	30	9.9	6.6 (3.2)	1.3 – 12.5
Cache Creek Rd. 2 (CCR2)	*Picea mariana*	Treated	-	-	-	-
		Control	60	7.8	4.0 (2.3)	0.5 - 10.0
Cache Creek Rd. 3 (CCR3)	*Picea mariana*	Treated	-	-	-	-
		Control	11	4.6	7.1 (4.3)	1.4 - 13.8
Chena Hot Springs Rd. North (CHSRN)	*Picea mariana*	Treated	1	0.02	2 (0)	-
		Control	57	13.2	5.1 (3.4)	0.2 - 16.4
	Betula neoalaskana	Treated	-	-	-	-

		Control	3	0.5	4.6 (2.9)	2.9 – 8.0
Chena Hot Springs Rd. South (CHSRS)	*Picea mariana*	Treated	1	0.002	0.5 (0)	-
		Control	88	4.8	2.3 (1.8)	0.2 – 13.6
Eielson Air Force Base (EAFB)	*Picea mariana*	Treated	-	-	-	-
		Control	159	11.6	3 (1.6)	0.2 – 8.1
	Betula neoalaskana	Treated	-	-	-	-
		Control	2	0.5	6.3 (2.3)	4.6 – 7.9
Fort Greely 1 (FTG1)	*Picea mariana*	Treated	-	-	-	-
		Control	202	21.3	3.4 (2.4)	0.2 – 15.7
Fort Greely 2 (FTG2)	*Picea mariana*	Treated	-	-	-	-
		Control	47	7.3	4.6 (2.0)	0.4 – 8.6
Fort Greely 3 (FTG3)	*Picea mariana*	Treated	-	-	-	-
		Control	135	18.5	4.1 (2.3)	0.4 – 11.6
Harding Lake 1 (HDL1)	*Picea glauca*	Treated	-	-	-	-
		Control	8	21.0	18.6 (9.3)	4.9 – 30.3
	Betula neoalaskana	Treated	-	-	-	-
		Control	6	13.6	18.7 (4.2)	13.6 – 23.6
Harding Lake 2 (HDL2)	*Picea mariana*	Treated	-	-	-	-
		Control	69	21.1	6.0 (3.6)	0.3 – 15.3
Harding Lake 4 (HDL4)	*Picea mariana*	Treated	-	-	-	-
		Control	90	11.4	4.0 (2.0)	0.3 – 9.5

Old Murphy Dome Rd. East (OMDE)	*Picea mariana*	Treated	-	-	-	-
		Control	103	10.0	3.4 (2.0)	0.3 – 8.4
Old Murphy Dome Rd. West (OMDW)	*Picea mariana*	Treated	-	-	-	-
		Control	32	8.2	5.4 (3.4)	0.3 – 11.8
	Betula neoalaskana	Treated	-	-	-	-
		Control	3	0.64	5.5 (2.5)	2.9 – 7.8

[A] 9x9 m plots thinned to 2.4 x 2.4 m or 3 x 3 m tree spacing; plots with different tree spacing were handled as individual sites
[B] Tree seedling data collected in 2011

Table S3. Mean and standard deviation (SD) for the soil organic layer depth and thaw depth in cm for each area sampled.

Name	***Treatment***	***Soil Organic Layer Mean (SD)***	***Thaw Depth Mean (SD)***
Thinned			
Badger Rd. (BAD8P & BAD10P)[A]	Treated	18.0 (6.6)	117.2 (49.6)
	Control	24.6 (6.2)	72.5 (15.1)
Delta (DEL8P & DEL10P)[A]	Treated	15.3 (5.6)	72.8 (7.3)
	Control	29.5 (2.7)	75.6 (5)
Eielson Air Force Base (EAFB)	Treated	29.3 (6.9)	100.5 (18.3)
	Control	29.9 (3.9)	104 (47.2)
Fort Greely Thinned (FTGTH)	Treated	11.8 (3.5)	81.5 (9.4)
	Control	13.6 (1.5)	64.5 (8.6)
Harding Lake 3 (HDL3)	Treated	13.6 (9.6)	61 (11.7)
	Control	22.1 (6.2)	55.5 (9.3)
Nenana Ridge 1 (NRTH1)	Treated	37.2 (5)	144 (28.7)
	Control	30.4 (7.5)	168.5 (29.4)
Nenana Ridge 2 (NRTH2)[B]	Treated	30.4 (3.4)	105 (10.8)
	Control	29.2 (6)	123 (24.5)
Toghotthele (TOG8P & TOG10P)[A]	Treated	38.6 (8.7)	60 (10)
	Control	31.5 (11.9)	53.8 (3.5)
Shearbladed			
Cache Creek Rd. 1 (CCR1)	Treated	6.2 (3.5)	104.5 (54.2)
	Control	17.4 (9.7)	65 (33)
Cache Creek Rd. 2 (CCR2)	Treated	17.9 (7.9)	106.5 (51.9)
	Control	29 (4.8)	51 (10.7)
Cache Creek Rd. 3 (CCR3)	Treated	15.8 (4.8)	150.5 (26.5)
	Control	15.1 (3.2)	80 (11.5)
Chena Hot Springs Rd. North (CHSRN)	Treated	11.1 (6.3)	180.5 (27.1)
	Control	21.5 (6)	77 (20.6)
Chena Hot Springs Rd. South (CHSRS)	Treated	29.9 (16.2)	124.5 (59.2)
	Control	32 (4.8)	62.5 (7.9)
Eielson Air Force Base (EAFB)	Treated	21.6 (14.3)	182 (25.3)
	Control	29.9 (3.9)	104 (47.2)
Fort Greely 1 (FTG1)	Treated	5.4 (6)	79 (26.7)
	Control	16.8 (4.1)	144 (42.5)
Fort Greely 2 (FTG2)	Treated	7.6 (4.8)	109.5 (6.9)
	Control	14.9 (3)	98 (10.3)
Fort Greely 3 (FTG3)	Treated	2.1 (2.2)	71.5 (7.8)
	Control	19.9 (2.2)	89.5 (5.5)
Harding Lake 1 (HDL1)	Treated	8 (5.8)	53.5 (6.3)
	Control	20.9 (6.1)	58 (10.9)
Harding Lake 2 (HDL2)	Treated	4.6 (3.3)	49.5 (9.3)
	Control	27.9 (4.6)	87.5 (10.3)

Harding Lake 4 (HDL4)	Treated	17.4 (8.6)	189 (19.3)
	Control	40.4 (9.9)	60 (3.3)
Old Murphy Dome Rd. East (OMDE)	Treated	9.3 (4.9)	96.9 (15.1)
	Control	21.5 (4.3)	56.8 (12.1)
Old Murphy Dome Rd. West (OMDW)	Treated	7.2 (2.4)	83 (9.2)
	Control	20 (5.9)	54.5 (11.9)

[A] 9x9 m plots thinned to 2.4 x 2.4 m or 3 x 3 m tree spacing; plots with different tree spacing were handled as individual sites

[B] Tree seedling data collected in 2011

Table S4. Results of the final generalized linear mixed effects models selected based on small sample corrected Akaike Information Criterion (AICc) for modeling seedling density in thinned and shearbladed sites. The random intercept of site was included. Full models included the fixed effects of soil organic layer (SOL) depth, years after treatment, seedling type (deciduous/conifer), the first-order interaction between years after treatment and seedling type, and random intercept of site. Results are given on the log scale.

Response variable	***Fixed effects***	***Estimate ± SE***	***z-value***	***p-value***
Seedling density (Thinned)	Intercept	0.44 ± 0.80	0.55	0.59
	SOL depth	-0.14 ± 0.03	-5.11	< 0.001
	Seedling type (conifer)	1.21 ± 0.38	3.18	0.001
Seedling density (Shearbladed)	Intercept (deciduous)	1.83 ± 0.38	4.76	< 0.001
	Seedling type (conifer)	-4.70 ± 0.58	-8.11	0.33
	Years after treatment	-0.03 ± 0.03	-0.98	< 0.001
	Seedling type (conifer) x Years after treatment	0.23 ± 0.06	3.59	< 0.001

Table S5. Estimated marginal means of seedling density when SOL depth is held constant in the model in thinned sites (Table S4). Means were estimated from the final model selected for modeling seedling density in thinned sites (Table S4) and back transformed from the log scale. Different letters denote significant difference in means between seedling types.

Means				
Seedling type	***mean ± SE***	***df***	***lower CL***	***upper CL***
Deciduous[a]	0.09 ± 0.06	370	0.020	0.372
Conifer[b]	0.29 ± 0.19	370	0.077	1.072

Table S6. Estimated marginal means of seedling density when years after treatment is held constant in the model and estimated marginal means of linear trends between seedling density and years after treatment in shearbladed sites (Table S4). Means and trends were estimated from the final model selected for modeling seedling density in shearbladed sites (Table S4) and back transformed from the log scale. Different letters denote significant differences in means or trends between seedling types.

Means				
Seedling type	***mean ± SE***	***df***	***lower CL***	***upper CL***
Deciduous[a]	4.95 ± 1.43	553	2.81	8.74
Conifer[b]	0.25 ± 0.09	553	0.13	0.48
Trends				
Seedling type	***trend ± SE***	***df***	***lower CL***	***upper CL***
Deciduous[a]	-0.03 ± 0.03	553	-0.09	0.03
Conifer[b]	0.20 ± 0.06	553	0.08	0.31

Table S7. Significance effects of years after treatment on ordinations of vegetation and ground cover composition in thinned and shearbladed sites.

Treatment	***Variable***	***NMDS1***	***NMDS2***	R^2	***p-value***
Thinned	Years after treatment	0.86	0.51	0.04	0.160
Shearbladed	Years after treatment	0.88	0.47	0.33	0.001

Table S8. Results of the final linear mixed effects model selected based on small sample corrected Akaike Information Criterion (AICc) for soil organic layer (SOL) depth in thinned and shearbladed areas. The random intercept of site was included. The full model included the fixed effect of years after treatment. Estimates for shearbladed sites are square-root transformed.

Response variable	***Fixed effects***	***Estimate ± SE***	***t-value***	***p-value***
SOL depth (Thinned)	Intercept	12.1 ± 3.38	3.59	< 0.0001
	Years after treatment	0.84 ± 0.19	4.48	< 0.0001
SOL depth (Shearbladed)	Intercept	2.06 ± 0.40	5.15	< 0.0001
	Years after treatment	0.11 ± 0.03	4.33	< 0.0001

Table S9. Results of the final linear mixed effects model selected based on small sample corrected Akaike Information Criterion (AICc) for modeling thaw depth difference (ΔTD; treated – unmanaged) in thinned and shearbladed areas. The random intercept of site was included. Full models included the fixed effects of soil organic layer (SOL) depth and years after treatment.

Response variable	***Fixed effects***	***Estimate ± SE***	***t-value***	***p-value***
ΔTD (Thinned)	Intercept	10.8 ± 14.6	0.74	0.461
	Years after treatment	2.77 ± 0.89	3.12	0.002
	SOL depth	-1.08 ± 0.33	-3.27	0.001
ΔTD (Shearbladed)	Intercept	41.0 ± 11.4	3.59	<0.001
	Years after treatment	2.76 ± 0.84	3.30	0.001
	SOL depth	-0.92 ± 0.28	-3.25	0.001

Table S10. Fuel model and canopy cover or wind adjustment factor (WAF) used in fire behavior modeling for each site, treatment, and sampling year. For shearbladed treatments we used the provided WAF from BehavePlus 6. See Table S1 for treatment descriptions and ages. A 20-ft wind speed of 8.85 km/hour was used for modeling fire behavior in each site.

Site	Treatment	Year Measured	Fuel Model	Canopy cover (%)	WAF
BAD8P	Thinned	2012/2013	TU4	45.3	NA
BAD8P	Thinned	2018	TU4	45.3	NA
BAD10P	Thinned	2012/2013	TU4	27.4	NA
BAD10P	Thinned	2018	TU4	27.4	NA
DEL8P	Thinned	2012/2013	TU4	44.8	NA
DEL8P	Thinned	2018	TU4	44.8	NA
DEL10P	Thinned	2012/2013	TU4	20.5	NA
DEL10P	Thinned	2018	TU4	20.5	NA
EAFB	Thinned	2012/2013	GR2	5.81	NA
EAFB	Thinned	2018	GR2	5.81	NA
FTGTH	Thinned	2012/2013	TU4	37.9	NA
FTGTH	Thinned	2018	TU4	37.9	NA
HDL3	Thinned	2012/2013	TU4	42.4	NA
HDL3	Thinned	2018	TU4	42.4	NA
NRB3	Thinned	2012/2013	TU4	20.9	NA
NRB3	Thinned	2018	GS2	20.9	NA
TOG8P	Thinned	2012/2013	GS2	34.5	NA
TOG8P	Thinned	2018	GS2	34.5	NA
TOG10P	Thinned	2012/2013	GS2	46.2	NA
TOG10P	Thinned	2018	GS2	46.2	NA
CCR1	Shearbladed	2012/2013	GR1	NA	0.3
CCR1	Shearbladed	2018	GR1	NA	0.3
CCR2	Shearbladed	2012/2013	GS2	NA	0.4
CCR2	Shearbladed	2018	GS2	NA	0.4
CCR3	Shearbladed	2012/2013	GS1	NA	0.4
CCR3	Shearbladed	2018	GS2	NA	0.4
CHSRN	Shearbladed	2012/2013	GR2	NA	0.4
CHSRN	Shearbladed	2018	GR2	NA	0.4
CHSRS	Shearbladed	2012/2013	GR2	NA	0.4
CHSRS	Shearbladed	2018	GR2	NA	0.4
EAFB	Shearbladed	2012/2013	GS1	NA	0.4
EAFB	Shearbladed	2018	GS1	NA	0.4
FTG1	Shearbladed	2012/2013	GR2	NA	0.4
FTG1	Shearbladed	2018	GR1	NA	0.3

FTG2	Shearbladed	2012/2013	GS2	NA	0.4
FTG2	Shearbladed	2018	GS1	NA	0.4
FTG3	Shearbladed	2012/2013	GR1	NA	0.3
FTG3	Shearbladed	2018	GR1	NA	0.3
HDL1	Shearbladed	2012/2013	GR2	NA	0.4
HDL1	Shearbladed	2018	GR1	NA	0.3
HDL2	Shearbladed	2012/2013	GR1	NA	0.3
HDL2	Shearbladed	2018	GS2	NA	0.4
HDL4	Shearbladed	2012/2013	GR1	NA	0.3
HDL4	Shearbladed	2018	GR2	NA	0.4
OMDE	Shearbladed	2012/2013	GR1	NA	0.3
OMDE	Shearbladed	2018	TU1	NA	0.3
OMDW	Shearbladed	2012/2013	SH1	NA	0.4
OMDW	Shearbladed	2018	TU1	NA	0.3
NA	Unmanaged	NA	SH5, TU3, or TU4	60	NA

Table S11. Linear mixed effects model results with surface rate of fire spread, flame length, or fireline intensity as the response variable effect and treatment type (thinned and shearbladed) as the fixed effect. Models were built separately for each fuel moisture category. The random intercept of site was included.

Response variable	***Moisture conditions***	***Explanatory variable***	***Estimate ± SE***	***t-value***	***p-value***
Rate of spread	*Dry (below average)*	Intercept (Thinned)	2.19 ± 0.53	4.17	< 0.001
		Shearbladed	1.44 ± 0.67	2.15	0.042
	Average	Intercept (Thinned)	1.32 ± 0.28	4.64	< 0.001
		Shearbladed	0.66 ± 0.36	1.83	0.080
	Wet (above average)	Intercept (Thinned)	0.53 ± 0.05	10.6	< 0.001
		Shearbladed	-0.06 ± 0.06	-0.97	0.340
Flame length	*Dry (below average)*	Intercept (Thinned)	1.03 ± 0.08	12.8	< 0.001
		Shearbladed	-0.19 ± 0.10	-1.86	0.075
	Average	Intercept (Thinned)	0.77 ± 0.06	13.7	< 0.001
		Shearbladed	-0.20 ± 0.07	-2.81	0.010
	Wet (above average)	Intercept (Thinned)	0.44 ± 0.05	10.7	< 0.001
		Shearbladed	-0.18 ± 0.05	-3.81	< 0.001
Fireline intensity	*Dry (below average)*	Intercept (Thinned)	286 ± 37.3	7.66	< 0.001
		Shearbladed	-68.3 ± 47.4	-1.44	0.163
	Average	Intercept (Thinned)	157 ± 19.2	8.16	< 0.001
		Shearbladed	-53.3 ± 24.3	-2.19	0.038
	Wet (above average)	Intercept (Thinned)	56.8 ± 8.08	7.03	< 0.001
		Shearbladed	-41.7 ± 9.74	-4.28	< 0.001

Table S12. Mean (±SE) of the raw data or estimated marginal mean (±SE) for surface rate of fire spread, flame length, and fireline intensity for each treatment and fuel moisture category. Estimated marginal means (±SE) are in *italics* and were only compared between treatments when the fixed effect of treatment type was significant (Table S11). Different letters denote significant differences in surface rate of fire spread, flame length, or fireline intensity between treatments within each fuel moisture category based on post-hoc tests. Untreated, black spruce surface fire behavior, although not included in the models from Table S11, is presented for reference.

Fire characteristic	**Fuel moisture**	**Treatment**		
		Unmanaged (SH5, TU3, TU4)	*Thinned*	*Shearbladed*
Rate of spread (m/min)	*Dry (below average)*	3.8, 1.7, 0.8	*2.19 ± 0.53*[a]	*3.63 ± 0.45*[b]
	Average	2.4, 1, 0.5	1.22 ± 0.19[a]	2.10 ± 0.23[a]
	Wet (above average)	1.7, 0.7, 0.4	0.49 ± 0.04[a]	0.50 ± 0.03[a]
Flame length (m)	*Dry (below average)*	2.1, 1.1, 0.9	1.04 ± 0.03[a]	0.84 ± 0.07[a]
	Average	1.6, 0.8, 0.7	*0.77 ± 0.06*[a]	*0.57 ± 0.05*[b]
	Wet (above average)	1.3, 0.6, 0.5	*0.44 ± 0.04*[a]	*0.26 ± 0.04*[b]
Fireline intensity (kW/m)	*Dry (below average)*	1361, 327, 187	284 ± 18.5[a]	220 ± 32.8[b]
	Average	718, 161, 108	*157 ± 19.2*[a]	*103 ± 16.3*[b]
	Wet (above average)	456, 93, 59	*56.8 ± 8.08*[a]	*15.1 ± 6.99*[b]

Table S13. Results of linear mixed effects models with surface rate of fire spread, flame length, or fireline intensity as the response variable at average, below average, and above average moisture conditions, and years after treatment as the explanatory variable in thinned treatments. Models were built separately for each moisture category. None of the trends were significant. The random intercept of site was included. Flame length at average moisture was modeled as a simple linear regression (see *Statistical Methods*).

Response variable	***Moisture conditions***	***Explanatory variable***	***Estimate ± SE***	***t-value***	***p-value***
Rate of spread	*Dry (below average)*	Intercept	1.72 ± 0.79	2.17	0.058
		Years after treatment	0.03 ± 0.05	0.52	0.613
	Average	Intercept	1.07 ± 0.41	2.60	0.029
		Years after treatment	0.01 ± 0.03	0.51	0.620
	Wet (above average)	Intercept	0.51 ± 0.06	8.62	< 0.001
		Years after treatment	-0.00 ± 0.00	-1.02	0.336
Flame length	*Dry (below average)*	Intercept	1.01 ± 0.05	20.1	<0.001
		Years after treatment	0.00 ± 0.00	0.84	0.422
	Average	Intercept	0.80 ± 0.07	11.5	<0.001
		Years after treatment	-0.00 ± 0.00	-0.30	0.700
	Wet (above average)	Intercept	0.56 ± 0.11	5.23	< 0.001
		Years after treatment	-0.01 ± 0.01	-0.85	0.420
Fireline intensity	*Dry (below average)*	Intercept	270 ± 30.9	8.76	< 0.001
		Years after treatment	1.14 ± 1.29	0.88	0.401
	Average	Intercept	156 ± 15.5	10.0	<0.001
		Years after treatment	-0.04 ± 0.04	-0.96	0.364
	Wet (above average)	Intercept	78.5 ± 25.3	3.11	0.013
		Years after treatment	-1.31 ± 1.81	-0.72	0.488

Table S14. Results of linear mixed effects models with rate of surface fire spread, flame length, or fireline intensity as the response variable at average, below average, and above average moisture conditions, and years after treatment as the explanatory variable in shearbladed treatments. Models were built separately for each moisture category. None of the trends were significant. The random intercept of site was included.

Response variable	***Moisture conditions***	***Explanatory variable***	***Estimate ± SE***	***t-value***	***p-value***
Rate of spread	*Dry (below average)*	Intercept	4.64 ± 0.99	4.70	<0.001
		Years after treatment	-0.11 ± 0.11	-0.95	0.358
	Average	Intercept	2.44 ± 0.53	4.59	<0.001
		Years after treatment	-0.05 ± 0.06	-0.75	0.464
	Wet (above average)	Intercept	0.56 ± 0.07	7.63	<0.001
		Years after treatment	-0.01 ± 0.01	-1.06	0.310
Flame length	*Dry (below average)*	Intercept	0.89 ± 0.18	5.03	<0.001
		Years after treatment	-0.01 ± 0.02	-0.30	0.769
	Average	Intercept	0.57 ± 0.12	4.92	< 0.001
		Years after treatment	-0.00 ± 0.01	-0.02	0.987
	Wet (above average)	Intercept	0.21 ± 0.02	9.30	<0.001
		Years after treatment	0.00 ± 0.00	0.10	0.923
Fireline intensity	*Dry (below average)*	Intercept	230 ± 79.4	2.90	0.012
		Years after treatment	-1.38 ± 9.28	-0.15	0.884
	Average	Intercept	105 ± 39.3	2.68	0.019
		Years after treatment	-0.20 ± 4.59	-0.04	0.967
	Wet (above average)	Intercept	8.64 ± 2.22	3.90	0.001
		Years after treatment	0.00 ± 0.26	0.00	0.999

Table S15. Deciduous and conifer seedling density per meter squared (mean ± SE and sum) for each site, treatment, and burn category (Yes=fuels burned on site, No=fuels not burned on site) averaged across all years that a site was sampled. See Table S1 for full treatment area descriptions.

Subsite	*Treatment*	*Burned*	**Deciduous**		**Conifer**	
			Mean (± SE)	*sum*	*Mean (± SE)*	*sum*
BAD8P	Thinned	No	0.00 ± 0	0	0.00 ± 0	0
BAD10P	Thinned	No	0.00 ± 0	0	0.13 ± 0.13	2
DEL8P	Thinned	No	0.00 ± 0	0	0.00 ± 0	0
DEL10P	Thinned	No	0.00 ± 0	0	0.00 ± 0	0
EAFB	Thinned	Yes	0.85 ± 0.58	17	0.00 ± 0	0
FTGTH	Thinned	Yes	1.75 ± 0.90	35	0.35 ± 0.17	7
HDL3	Thinned	Yes	2.45 ± 1.53	49	3.50 ± 1.88	70
NRTH1	Thinned	Yes	0.00 ± 0	0	3.20 ± 1.04	64
NRTH2	Thinned	Yes	0.00 ± 0	0	0.20 ± 0.2	2
TOG8P	Thinned	No	0.00 ± 0	0	0.31 ± 0.20	5
TOG10P	Thinned	No	0.00 ± 0	0	0.06 ± 0.06	1
CCR1	Shearbladed	Yes	3.25 ± 1.05	65	0.30 ± 0.13	6
CCR2	Shearbladed	Yes	0.20 ± 0.12	4	0.05 ± 0.05	1
CCR3	Shearbladed	Yes	0.15 ± 1.11	3	0.15 ± 0.08	3
CHSRN	Shearbladed	No	5.55 ± 3.65	111	0.00 ± 0	0
CHSRS	Shearbladed	Yes	1.35 ± 0.68	27	0.10 ± 0.07	2
EAFB	Shearbladed	Yes	2.40 ± 0.73	48	0.10 ± 0.07	2
FTG1	Shearbladed	Yes	9.25 ± 3.16	185	0.15 ± 0.11	3
FTG2	Shearbladed	Yes	2.50 ± 0.69	50	0.25 ± 0.12	5
FTG3	Shearbladed	Yes	19.9 ± 2.58	397	0.40 ± 0.18	8
HDL1	Shearbladed	Yes	5.10 ± 1.36	102	0.20 ± 0.09	4
HDL2	Shearbladed	Yes	4.55 ± 1.76	91	0.45 ± 0.29	9
HDL4	Shearbladed	Yes	4.00 ± 1.30	80	0.20 ± 0.12	4
OMDE	Shearbladed	Yes	14.3 ± 3.33	285	0.85 ± 0.37	17
OMDW	Shearbladed	Yes	0.60 ± 0.4	12	0.40 ± 0.13	8

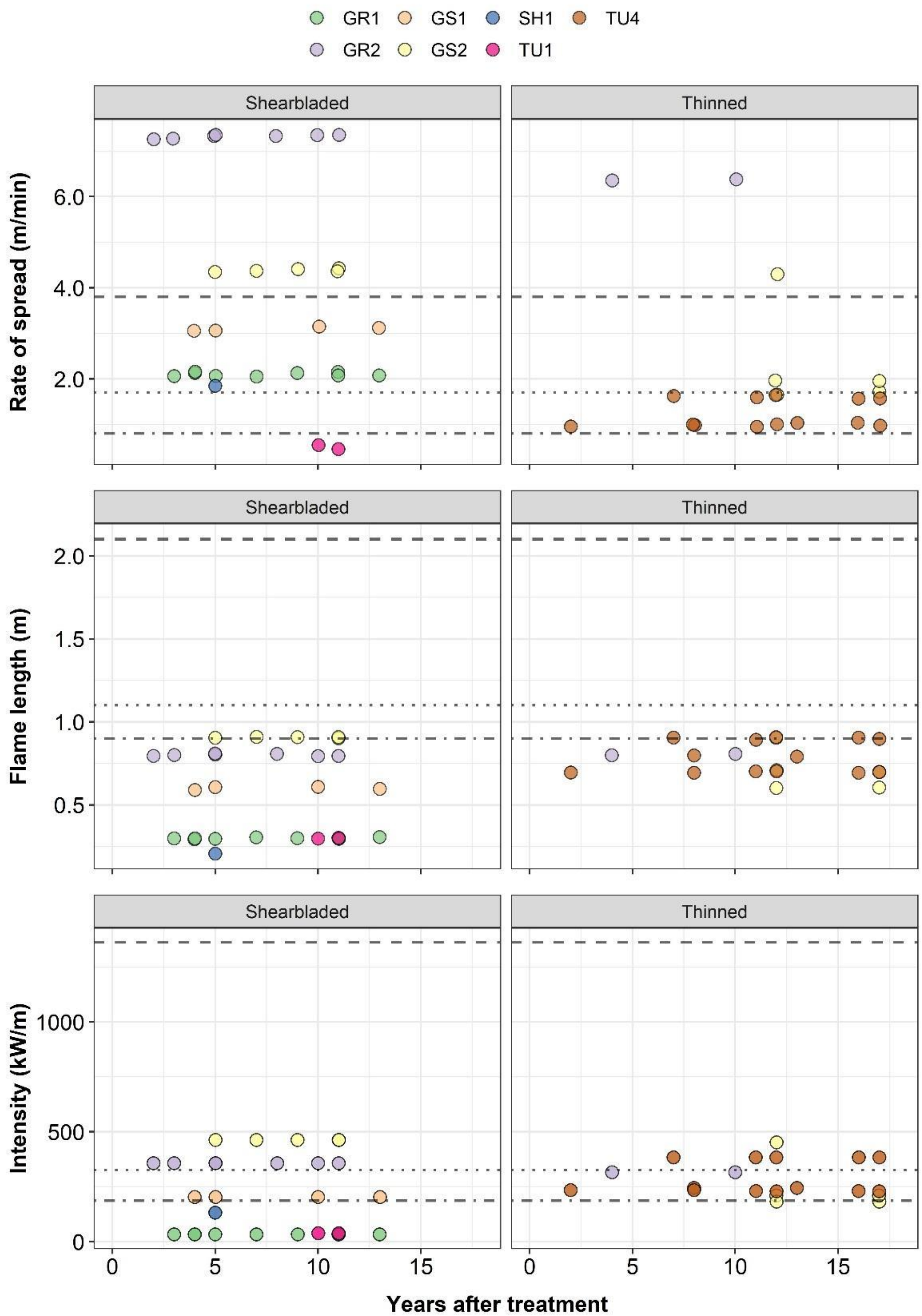


Figure S1. Surface rate of fire spread (top), flame length (center), and fireline intensity (bottom) at below average ('dry') fuel moisture conditions over time faceted by treatment (right=thinned, left=shearbladed). The dashed, dotted, and dot-dash line indicate the value in an untreated black spruce stand using the SH5, TU3, and TU4 fuel model, respectively, for the relevant fire behavior variable. Point colors indicate the Scott and Burgan (2005) fuel model used in fire behavior predictions. In both treatments, there was no change in any characteristic of surface fire behavior over time (Tables S11 and S12). Points are slightly jittered to better see the data.

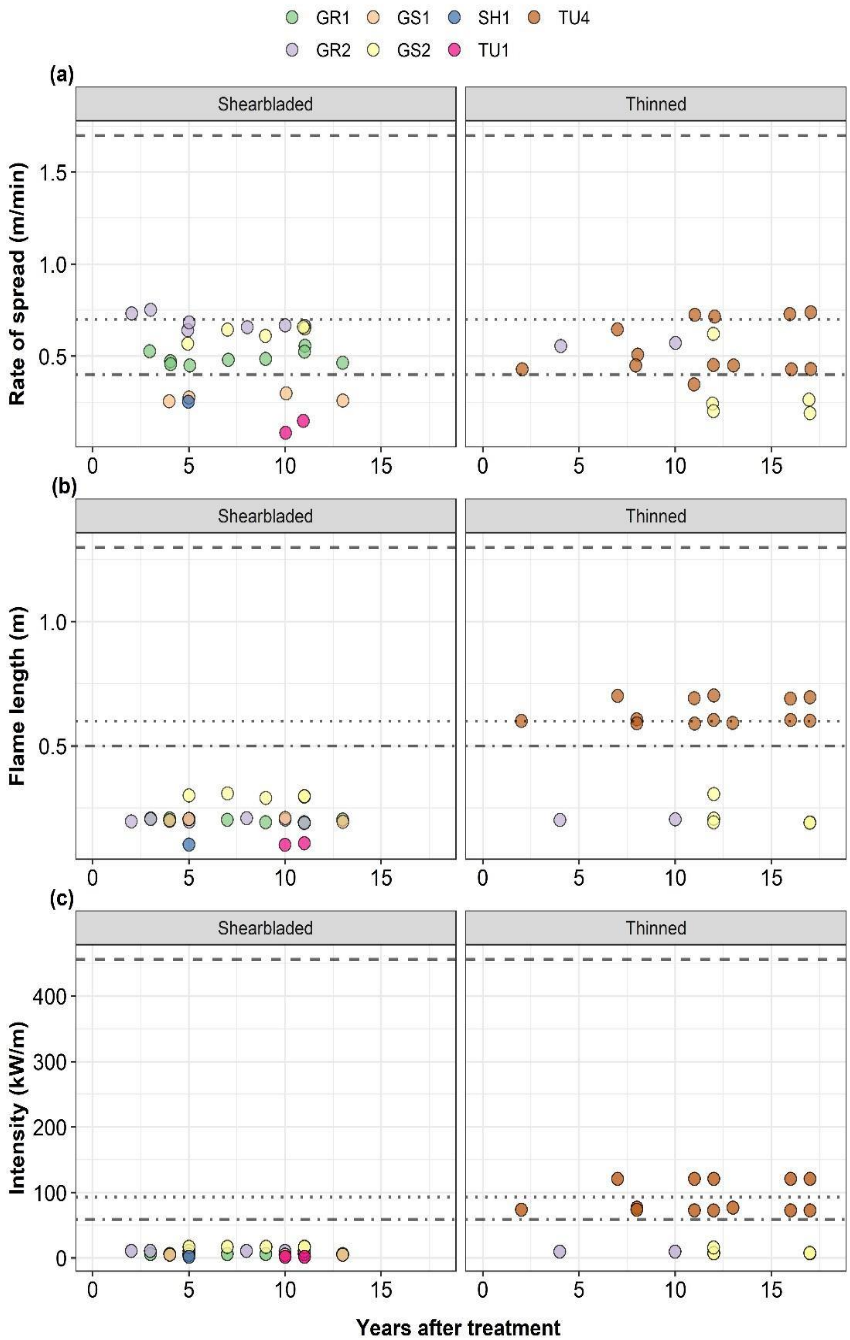


Figure S2. Predicted surface rate of fire spread (top), flame length (center), and fireline intensity (bottom) at above average ('wet') fuel moisture conditions over time faceted by treatment (right=thinned, left=shearbladed). The dashed, dotted, and dot-dash line indicate the value in an untreated black spruce stand using the SH5, TU3, and TU4 fuel model, respectively, for the relevant fire behavior variable. Point colors indicate the Scott and Burgan (2005) fuel model used in fire behavior predictions. In both treatments, there was no change in any characteristic of surface fire behavior over time (Tables S11 and S12). Points are slightly jittered to better see the data.

References

Brooks, M.E., Kristensen, K., Benthem, K.J. van, Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M., and Bolker, B.M. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J. **9**(2): 378–400. doi:10.32614/RJ-2017-066.

Hardin, J.J., and Hilbe, J.M. 2007. Generalized Linear Models and Extensions. *In* 2nd edition. Stata Press, College Station, TX, USA.

Hartig, F., and Lohse, L. 2021. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. Available from https://CRAN.R-project.org/package=DHARMa.

Haynes, W. 2013. Bonferroni Correction. *In* Encyclopedia of Systems Biology. *Edited by* W. Dubitzky, O. Wolkenhauer, K.-H. Cho, and H. Yokota. Springer, New York, NY, USA. pp. 154–154. doi:10.1007/978-1-4419-9863-7_1213.

Hervé, M. 2021. RVAideMemoire: Testing and Plotting Procedures for Biostatistics. Available from https://CRAN.R-project.org/package=RVAideMemoire.

McCune, B.P., and Grace, J. 2002. Analysis of Ecological Communities. MjM Software Design, Gleneden Beach, OR, USA.

Melvin, A.M., Celis, G., Johnstone, J.F., McGuire, A.D., Genet, H., Schuur, E.A.G., Rupp, T.S., and Mack, M.C. 2018. Fuel-reduction management alters plant composition, carbon and nitrogen pools, and soil thaw in Alaskan boreal forest. Ecol. Appl. **28**(1): 149–161. doi:10.1002/eap.1636.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., and Wagner, H. 2020. vegan: Community Ecology Package. Available from https://CRAN.R-project.org/package=vegan.

Scott, J.H., and Burgan, R.E. 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. General Technical Report, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., and Smith, G.M. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer-Verlag, New York, NY, USA.