Final Report
Evaluating the Effectiveness of Fuel Treatments in Alaska

JFSP Project 14-5-01-27

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List of Abbreviations

AFS	Alaska Fire Service
AICC	Alaska Interagency Coordination Center
AWFCG	Alaska Wildfire Coordinating Group
CFIS	Crown Fire Initiation and Spread
DCE	Discrete Choice Experiment
IC	Incident Command
TCC	Tanana Chiefs Conference
WTP	Willingness to Pay
WUI	Wildland Urban Interface

Keywords

Alaska, boreal, fuel treatment, treatment lifecycle, fire behavior, fire modeling, wildfire risk, WUI, expert elicitation, homeowner mitigation, suppression costs.

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Abstract

Wildland fire is the dominant disturbance agent of the boreal forest of Alaska. Currently, about 80% of the population of Alaska resides in communities potentially at risk from wildland fire. The wildland fire threat to these settlements is increasing because of increased suburban construction in or near forested areas. The primary objective of this research was to assess the effectiveness of maturing treatment projects in terms of previously defined risk reduction and fire behavior objectives in order to better understand the contribution of fuel treatments to the broader economics of wildfire management in Alaska. Along with contributing to our knowledge on the ecological maturation of existing fuel treatments we also examined what influence publicly funded fuel treatments had on wildland fire suppression costs in Alaska, whether suppression resource ordering is affected by the presence of a fuel treatment, and what role fuel treatments play in encouraging homeowners in WUI locations to reduce wildfire risk on their property. We found that fuel treatments in boreal black spruce induced surface layer species composition changes due to moss die-off without exposure of mineral soil, and to destabilization of soils and melting of frozen layers. Modeled fire behavior at the selected sites (BEHAVE 6.0) mostly indicate that shaded fuel breaks still retain most benefits of reduced fire behavior potential (due to the reduction of canopy density and ladder fuels) for at least 14 years. This finding fits with limited experiential evidence from prescribed and natural burning of fuel breaks. Findings from a discrete choice experiment (DCE) suggest that responding homeowners were more willing to incur the additional costs associated with private wildfire risk mitigation when a thinned/shaded fuel treatment was present on nearby public lands. This outcome does not hold in the presence of a cleared fuel break. Drawing on treatment site field data collected as part of this effort a set of four wildland fire scenarios were modelled and presented to Alaskan wildland management professionals as part of an elicitation exercise designed to examine suppression resource ordering behavior. As expected suppression resource ordering depended on both current fire weather conditions and whether a fuel treatment was present. Smaller initial attack packages were ordered when a fuel treatment was present and winds were 10 MPH and less in the scenario. Finally, State of Alaska wildfire suppression cost data was collected from a review of accounting records from over 200 fires and matched against fuels treatment data. The analysis identifies 14 wildfires of greater than 50 acres where a fuel treatment was found within 5km of the final reported fire perimeter. No statistically significant relationship between fuel treatments and wildfire suppression costs was identified. We argue that the geographic scale of the state and low population densities have an unobserved impact in the likelihood of a fuel treatment being present near or adjacent to a fire.

I. Objectives and Summary

As the frequency and cost of fires in the WUI increase, fuels reduction become increasingly important for creating defensible space and contributing to the Cohesive Strategy goals of resilient landscapes, fire-adapted communities, and effective response (Western Regional Strategy Committee 2013). The primary objective of this research program was to assess the effectiveness of maturing treatment projects in terms of previously defined risk reduction and fire behavior objectives in order to better understand the contribution of fuel treatments to the broader economics of wildfire management in Alaska. The research approach fully leveraged previous JFSP funded work (Project No. 00-2-34; Ott and Jandt, 2005), using previously collected data to develop a picture of fuel treatment lifecycle built on repeated field observations from 10 project locations across the Kenai Peninsula and Interior Alaska. Along with improving our understanding of ecological maturation of existing treatments this research also devoted significant effort towards identifying whether publicly funded fuel treatments reduce fire suppression costs, influence suppression resource ordering, or incentivize homeowners in WUI locations to reduce wildfire risk on their property.

Our study assessed operational and demonstration fuel breaks which were installed between 2001 and 2009. The costs of establishing and maintaining fuels treatments in Alaska can be very high, estimated at $181-$6,110/acre for a sample of State of Alaska fuel reduction treatments (St. Clair, 2006) but vary considerably depending on whether hand-treated or mechanical, and whether agency or contracted resources are used for implementation. Fuel treatments in boreal black spruce induced surface layer species composition changes due to moss die-off without exposure of mineral soil, and to destabilization of soils and melting of frozen layers. In general, we found the moss layer mostly recovered after 14 years, but canopy density showing only very modest increases. Modeling fire behavior using BEHAVE 6.0 mostly indicated that shaded fuel breaks still retain most benefits of reduced fire behavior potential (due to the reduction of canopy density and ladder fuels) for at least 14 years. This also fits with our limited experiential evidence from prescribed and natural burning of fuel breaks. A couple sites illustrated the adverse effects of an opened canopy on fire potential, including drying, increased flammable surface fuels, and higher mid-flame windspeeds. Our data illustrate profound ecological and site impacts—both intended and unintended—can result from forest treatments in boreal forest.

A second component of this research effort focused on identifying private wildfire risk mitigation activities taken by homeowners and evaluates how the presence and type of fuel treatment on nearby public lands influenced their willingness to incur the costs associated with pursuing risk mitigation activities on their own properties. At question here is whether public land fuel treatments have value in helping to encourage beneficial homeowner action in a setting where risk is shared on the landscape. As documented elsewhere (Lakoande 2006, Talbert *et al*. 2006, Prante *et al*. 2011) given the shared nature of wildfire risk facing many WUI neighborhoods, too little private mitigation activity is pursued. A survey of homeowners was used to collect data from homeowners living in Extreme, High, and Medium wildfire risk WUI locations in the study regions. As part of this effort, the survey included a discrete choice experiment (DCE) which examines private risk mitigation preferences in the presence of public fuel treatments. A total of 368 homeowners responded to the survey. Along with collecting basic socio-demographic information the survey asked homeowners about their perceptions of wildfire risk, prior experience with wildfire, and risk mitigation efforts they pursue. In general respondents' showed a strong preference for thinned/shaded fuel breaks and were more likely to incur the costs associated with private risk mitigation activities when present.

Third, an expert elicitation was used to evaluate how initial attack suppression resource orders in response to the presence of a fuel treatment. The expert elicitation brought together a diverse set of Alaska wildfire management officials including crew bosses, fire management officers, and fuels specialists. The expert group was presented with simulated fire scenarios in high risk WUI setting and asked to order from a structured menu of firefighting resources. The south Anchorage neighborhood of Campbell Tract served as a test WUI setting, having both a high level of wildfire risk present and presence of a fuel treatment included in the study. The simulated fire scenarios were built using fuel treatment assessment data collected as part of this project. The incorporation of up-to-date field information as well as the use of a well-known high risk WUI setting not only improves the accuracy of the scenarios but also provides a setting with which fire managers are familiar. The elicitation shows that reductions in resource ordering when a fuel treatment is present depend upon the current fire weather conditions.

Finally, State of Alaska wildfire suppression cost data was collected from a review of accounting records from over 200 fires. Cost data were supplemented with weather, fuels, and fire behavior data drawn from a variety of sources (*e.g,* ICS-209 reports). The analysis identifies 14 wildfires of greater than 50 acres where a fuel treatment was found within 5 km of the final reported fire perimeter. No statistically significant relationship, either positive or negative, between fuel treatments and wildfire suppression costs was identified.

II. Background

Wildland fire is the dominant disturbance agent of the boreal forest of Alaska, which represents about 15% of the forested area of the U.S. Currently, about 80% of the population of Alaska resides in communities potentially at risk from wildland fire. The wildland fire threat to these settlements is increasing because of increased suburban construction in or near forested areas. Warmer summers and longer fire seasons have also contributed to the risk to homeowners in these areas. Both mean annual temperature and summer maximum temperatures in interior Alaska have increased--by 0.7º F (0.5° C)/decade and 0.4º F (0.3º C)/decade respectively--over the past 50 years and could increase an additional 5-12º F (3-7ºC) by the end of the 21st century (NOAA 2018, Wolken *et al*. 2011). Warming is suspected to be the primary driver behind the doubling of multi-million-acre fire seasons observed in recent decades. Alaska is seeing earlier disappearance of snow, higher surface albedo heating (off snow-free vegetation and ice-free oceans), longer fire seasons, shrinking permafrost layers and changes in forest composition (Liston and Hiemstra 2011, Mann *et al.* 2012). The earliest wildfire ever attacked by smokejumpers (April 17) and a significant wildland urban interface (WUI) fire in October made the summer of 2016 one of longest fire seasons on record. The 2015 Alaska fire season, and more recently, the Horse River (Ft. McMurray) disaster in Alberta, illustrate the type of extreme fire seasons possible under warmer conditions. In June 2015, a week-long barrage of lightning in Alaska ignited 295 fires which spread rapidly, ultimately consuming 5.1 million acres and 80 homes. At a cost of $188 M[1] in state/federal firefighting expenditures, the 2015 set a new record for fire season cost in Alaska. Aerial support of firefighting tactics and mapping were hampered by thick smoke. Seventy days of quality alerts were issued in Alaska and the dispersing smoke was detected all the way to the Atlantic seaboard. The Alberta's Horse River fire in May 2016 burned nearly 1.5 million acres of boreal forest and over 2,400

[1] Unpublished data from Alaska Division of Forestry & Bureau of Land Management, Alaska Fire Service, Dec. 2016.

homes and buildings and is expected to result in over $3.5 billion in insured losses, the largest such insurance loss in Canadian history for any natural disaster (Cheadle 2016).

Dispersed settlements are difficult and costly to protect, so it is expected more infrastructure will be damaged by wildland fires in the coming decades. Agencies and the populace need adaptation and mitigation strategies to cope with the new challenges posed by these changes in fire regime. Fuel treatments are seen as one of the potential mitigation tools. As the frequency and cost of wildland fires increase, fuels reduction techniques become increasingly important for creating defensible space and contributing to the Cohesive Strategy goals of resilient landscapes, fire-adapted communities, and effective response. In boreal forest, fuel reduction projects are primarily intended to be used for strategic options like burning out, sprinklers, application of retardant or other active defenses. Since the late 1990s, several fuels reduction projects-- both cleared firebreaks and shaded fuel breaks-- in Alaska have been completed by various entities, including the state of Alaska, federal land management agencies, and Alaska Native corporations (DeFries 2002, Rogers 2003, Ott 2005). Some short-term follow-up studies are available (McMillan and Barnes, 2013) but there is little information about the effectiveness of these treatments over time. A JFSP-funded investigation of the short-term (3-year) ecological effects of shaded fuel breaks in interior Alaska indicates that there is potential for significant changes in vegetation and permafrost dynamics. Ecosystem resilience and treatment effectiveness in boreal forests may change significantly in the near future (Ott and Jandt 2005, Rupp *et al*. 2011).

Previous Work

Previous fire behavior modeling in treated stands has indicated mixed effects with respect to rates of spread, crown fire potential, fuel moisture, and crown fraction burned in thinned stands of spruce. Also lacking are comparisons of various fuels reduction techniques, ecological effects, or their impact on local communities. An analysis of predicted fire behavior at one site (Figure 4, Site b) indicated slightly increased rates of spread but higher resistance to crown fire using BEHAVE (Theisen 2003). Subsequent analyses from three demonstration units in 2007 (Figure 4, Sites b-d) using NEXUS 2.0 (Scott 2004) found fuel treatments did not preclude crown fire behavior in predictions, but could exchange passive for active crown fire in some cases (Horschel 2007). However, she also projected the treated stands to have higher rates of spread in dry conditions. Simulations indicated no change or a moderate reduction in flame length and fire intensity in the treated sites, but substantial reduction in the crown fractions burned which might reduce spotting potential.

A few fuels treatment projects in Alaska have actually been tested by wildfire or experimental prescribed burning, including Ft Greely (1999), Nenana Ridge (2009 and 2015), Eagle Trail (2010), Funny River (2014) and Card Street (2015). These case studies provide important information to the fire management community on fire behavior in the presence of fuel treatment. The Nenana Ridge treatment site was challenged by both experimental and wildfire and in both cases reduced fire intensity and spread in mid-growing season (Butler *et al.* 2013, Miller 2015). In May 2014, the Funny River fire approached treatment projects established by US Fish and Wildlife Service and the Kenai Peninsula Borough. Managers were able to organize an opportunistic case study of fire behavior and treatment effects (Saperstein *et al*. 2015) and reports indicated that the treatments were critical in preventing fire spread into occupied neighborhoods. Similar observations were made on the Card Street (2015) fire near Anchorage (Perrine 2016). Clearly, there is much to be learned from preparing more detailed assessments of the interaction between fuel treatments, fire behavior, suppression efforts, and, economic outcomes.

Risk Classification and Management Structure

Alaskan agencies depend on defining ‘zones’ to trigger suppression response. The state is grouped into four suppression response zones. Critical protection zones necessitate immediate suppression and usually are close to larger urban areas, where people and property are in direct danger. Full protection areas may still require a strong response, though the risk to human life is smaller than in critical zones. Modified and limited protection areas are typically lower priority, in terms of suppression response. A map of the state divided into its constituent parts is provided in Figure 1.

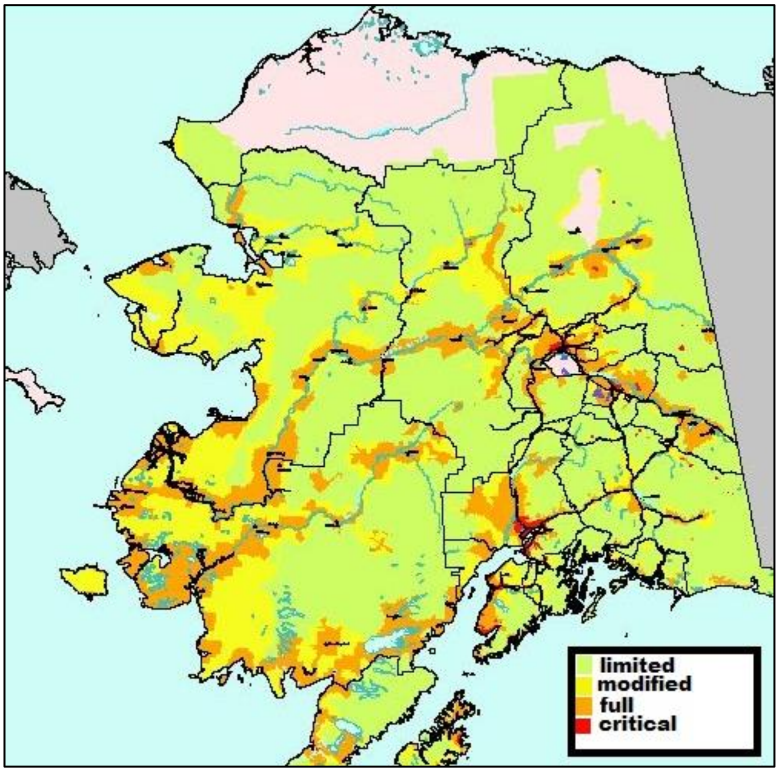


Figure 1: Map of Alaskan suppression response zones based on the Alaska Interagency Fire Management Plan 2010
Source: Alaska Division of Forestry Web, 2018

Wildfire costs are not independent of response zones. Because there is a greater risk to human health and property in full and critical zones, more resources are used on those wildfires than in the limited and modified zones. There also may be a strong push to over order resources in critical zones to ensure the protection of human health and property, as costs are not seen as a common decision factor when ordering suppression resources on those fires. While there should be a strong correlation between response zone and costs, there are still pockets within limited and modified zones that require a suppression response. Fire protection is mandated by statute for Alaskan Native allotments. Because these allotments are often difficult to access, these wildfires may increase in costs due to their inaccessibility. While many of the wildfires in remote Alaskan wilderness are allowed to burn under supervision, any wildfire threatening an Alaskan Native land allotment must be actively suppressed with federal or state firefighting resources.

Risk level may be a significant factor in the decision process for suppression activities by fire management agencies (both state and federal) and by individuals (homeowners). The analyses presented in this report account for risk by grouping data observations into three categories. We combine limited and modified zones to represent a single low-risk grouping. A survey of homeowners, presented in Section E, was focused on lands in the Fairbanks North Star Borough (FNSB) and the Kenai Peninsula Borough (KPB). Figure 2 and Figure 3 show the distribution of risk zones in the study areas.

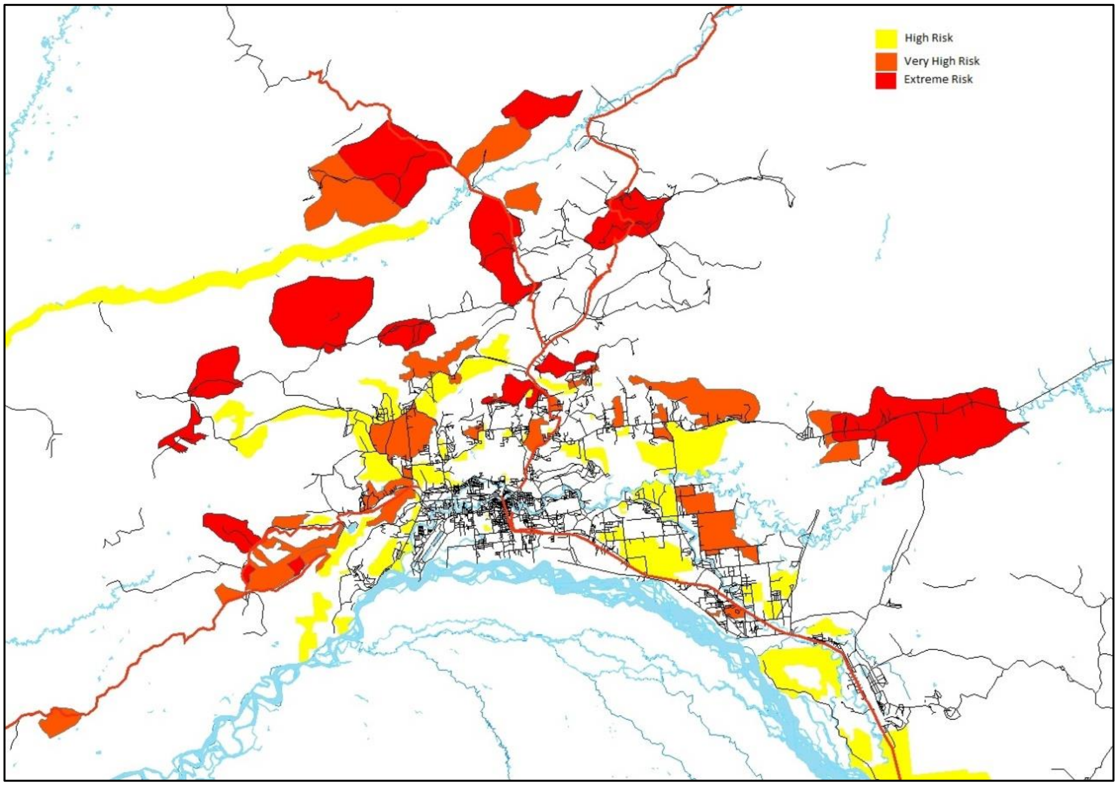


Figure 2. Zones of concern in the Fairbanks North Star Borough
Data Source: Alaska Department of Natural Resources

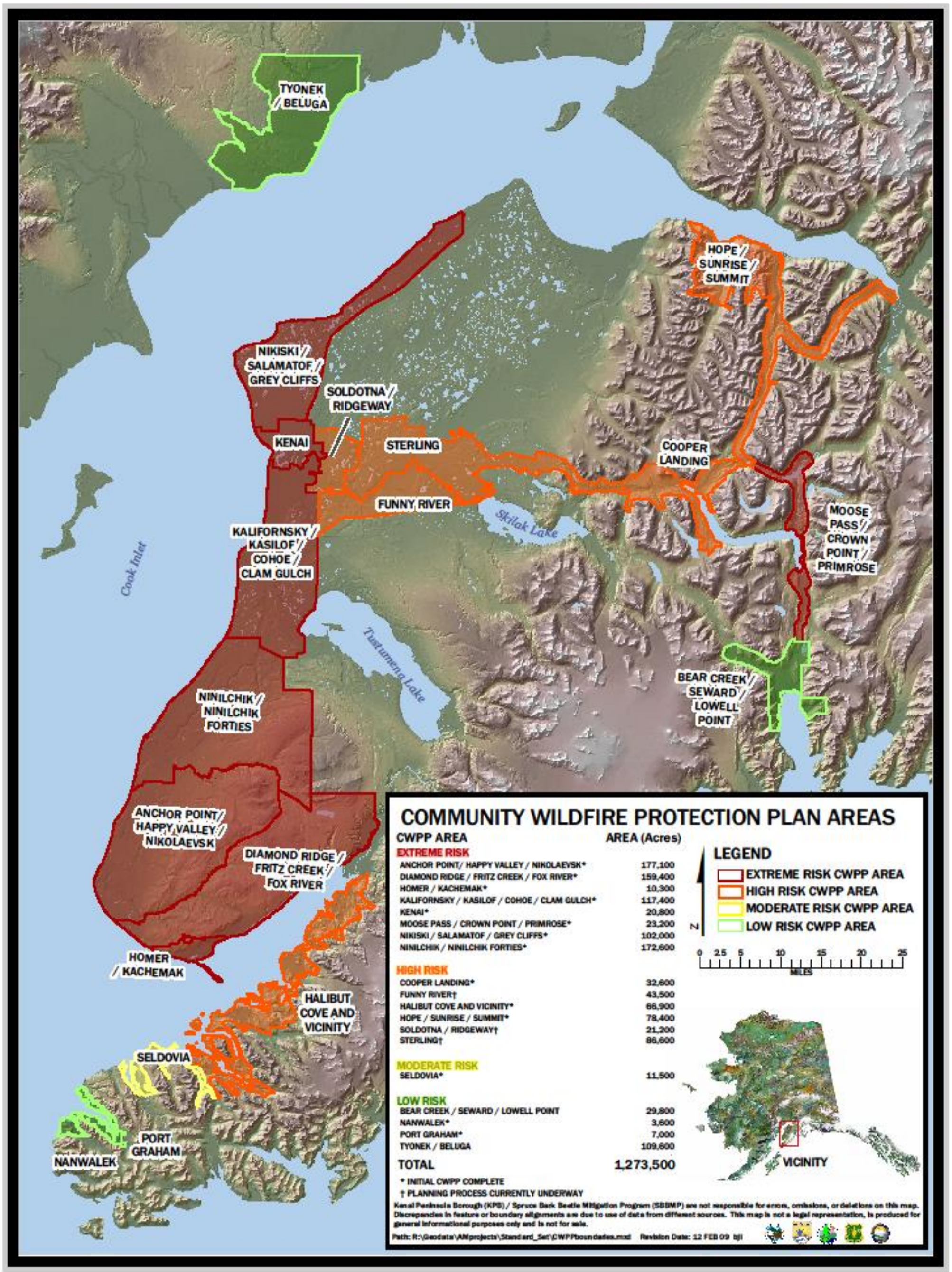


Figure 3. Zones of concern in the Kenai Peninsula Borough
Source: Kenai Peninsula Borough Web, 2011

III. Field Work, Data Collection, and Fire Modeling Methods

A. Study Areas

Fuel treatment study sites, their date of establishment, methods of treatment, and predominant vegetation type are presented by region below:

Interior Alaska

a) Nenana Ridge Project- This experiment compared 8 x 8 ft thinning with ladder fuels pruned to 4 ft under two different slash removal strategies: (1) haul away, (2) burn piles on site (2 blocks, N=10); additionally, they tested shear blading (2 blocks, plots N=10) with and without windrowing and burning on site. Treatments (with a control block, N=1) to 1-acre blocks of predominantly black spruce were

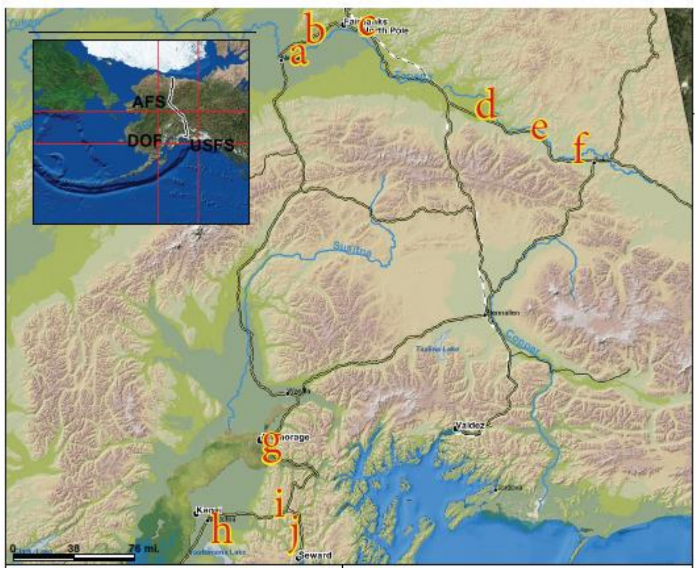


Figure 4. Study sites in Alaska, located in jurisdictions of all three primary fire protection agencies: Alaska Fire Service (BLM), Alaska State Department of Forestry (DOF) and the US Forest Service.

applied in 2006 and the Unit A treatments were subject to controlled burning in 2009 to assess impacts of treatments on fire behavior (Butler *et al.* 2013, Rupp *et al.* 2011). An additional array of 4 treatments (Unit B) had been prepared adjacent to Unit A but not burned. Replication occurred fortuitously in the form of a wildfire in 2015 (Miller 2016) that consumed parts of Unit B, which we re-sampled in 2015 as part of this project.

b) Fort Wainwright Demonstration Site – Experimental fuel treatment established in 2001 by TCC and BLM Alaska Fire Service with Joint Fire Science Program funding and interagency cooperation. This site has 4 thinning treatments (Plots N=4 each) and an untreated control (N=4) on 1-acre blocks in black spruce. Treatments thinned trees to 8 x 8 ft or 10 x 10 ft spacing with or without pruning ladder fuels. Blocks were previously re-sampled 2 and 5 years post-treatment (Ott and Jandt 2005).

c) Toghotthele Demonstration Site – Same as Fort Wainwright but located on private native corporation forest land south of Fairbanks.

d) Delta Bison Range Demonstration Site - Same as Fort Wainwright but treated in 2002 and located on state forest lands west of Delta.

e) Dot Lake - Established in 2008-2009, this site is a shaded fuel break in mature aspen with spruce understory was thinned to 12 x 12' spacing, on about 19 acres. Plots: N=5 treated and N=1 in untreated reference stand. This project was a cooperative effort of TCC and the Dot Lake Village Corporation.

f) Tanacross Fuel Treatment Project – This site is a WUI shaded fuel break in white spruce (see cover photo), implemented in 2 phases 2001-2005 (39 acres thinned to 12 x 12' spacing and pruned in 2001, 27 acres in 2005). Portions were impacted by Eagle Trail fire in 2010, a severe windstorm event in 2012 (Figure 6), and a 2013 fuelbreak rehabilitation project, which remediated 38.6 acres of windthrown timber. (Plots N=5 treated/1 untreated reference stand).

Southcentral Alaska

g) Campbell Tract – Established in 2003 and maintained in 2011, the site has a combination of WUI shaded fuel break in mixed spruce affected by bark beetle (plots N=10) and cleared fuelbreak where slash was piled and burned (plots N=8) covering roughly 200' by 2 miles. Photopoints (N=16) were established in untreated reference stands.

h) Funny River – This was a series of treatments extending about 10 miles near Soldotna established by USFWS and cooperators beginning in 1998. The site demonstrates both thinning with slash removal in mixed spruce affected by bark beetle (Plots N=12) and a 2009 masticated cleared fuelbreak (N=10). Both experienced fire in May 2014 (N=8) and reference photopoints (N=6) were established in untreated stands.

i) Hope Gate – This site was established in 2009 to reduce fire risk to communities of Hope and Sunrise. Various treatments were applied to different stands totaling about 900 acres on the Chugach National Forest, including thinning dense stands of spruce to 20-foot spacing and dense birch stands to 12-foot spacing, along with removing dead and dying beetle-killed spruce trees and piling and burning slash (Treated plots N=10 and untreated reference photopoints N=4).

j) North Bean – Was a 2012 project on the Chugach National Forest near Cooper Landing. Dead and dying spruce trees were removed on 750 acres near the Bean Creek Trail to reduce fire risk (USFS-CNF 2011; Plots N=10 and reference photopoints N=4). The action was identified as a mitigation strategy in the Cooper Landing Community Wildfire Protection Plan.

B. Fuel Treatment Assessments

Treatment Site Fieldwork

Field work was carried out by forestry personnel working for the Tanana Chiefs Conference (TCC) Forestry Program and the Chugachmiut Tribal Consortium (CTC) Forestry between June and August of 2015. In early June, members of both TCC and CTC forestry, personnel with the U.S. Fish and Wildlife Service, and State of Alaska Department of Natural Resources representatives held a field training session at the Campbell Tract near Anchorage. Data was collected on 161 plots in treatments and control/reference sites (Table 1), and photographs taken at another 30 untreated reference sites for fuel model classification. They refined data collection protocols to ensure continuity across the diverse set of fuel treatment locations.

The collected field data was used to determine fuel loading of surface and canopy fuels. A model of fire behavior, before and after the various fuel treatments, was used to assess ecological effects of the fuel treatments. Adding reference plots several years after treatment can be problematic. When no control plots were previously established, we used the Alaska photo fuels series (USFS 2018) to quantify canopy fuel for comparative fire behavior and forest floor fuel beds in untreated areas. Photographs were taken of all plots to show current condition and other disturbances like fire entry, wind-throw, drought stress, or change in surface fuels. These characteristics may have important consequences related to the maintenance and strategic use of fuel breaks in boreal fuel types.

Canopy and surface fuels data collected in plots included: overstory (> 1" DBH) tree stem count by diameter class, subcanopy (<1" DBH) trees and seedlings tallied by species in three 1 x 1 m subplots/transect, canopy tree height, canopy fuel base height[2], and crown width for determining the canopy fuel load. For fuel treatments with tagged trees (JFS demonstration sites, Figure 4, b-d) we re-measured DBH and height to assess tree growth response to treatment. Crown bulk densities for the fire behavior inputs were computed by estimating crown mass from crown lengths/diameters and tree densities and using allometric equations for total above-ground tree biomass by species (Yarie *et al.* 2007, Barney and VanCleve 1973). The fraction of tree crown mass that would be expected to burn in frontal passage is generally the foliage and twigs less than 1/4". This fraction, for example, has been measured at approximately 42% of total crown mass for upland black spruce (Barney *et al.* 1978). The combustible fraction of crown mass was multiplied by crown length to derive crown bulk density (Appendix Table 10a/b).

Point-intercept transects were used to estimate cover of understory vegetation by species, as well as substrate (moss, lichen, conifer litter, hardwood litter) cover, and canopy cover by species (using vertical densitometer). All vegetation intercepts were recorded (yielding absolute cover by species). Continuous understory fuel bed height was estimated at 4 points along transects to inform fire behavior models. We also measured depth of forest floor litter, upper and lower duff, down woody fuel load[3], and active layer depth[4].

[2] Canopy fuel base height is the height above the ground of the lowest live or dead concentration of branches that have the ability to move fire higher in the tree.

[3] Measured along transect lines using the planar intersect method (Brown 1974)

[4] Active layer is the layer of soil over permafrost that seasonally thaws. It varies through the season so single measurements are only useful for analysis of effects with a simultaneous control. Active layer was measured with 10 points per line, where reference untreated control blocks were available for comparison.

Table 1: Summary of field data measurements

Measurements, 2015	**Data sampled at each plot**
Vegetation cover (120 pts)	4 x 30m point-intercept transects
Canopy cover, by spp.	4 x 30m point-intercept transects
Stem density, by size class	4 x 30m belt transect
Sub-canopy (<1" dbh) tree tally	3 x 1m^2 subplots/belt transect
Tree height & DBH by spp.	6 trees/transect
Tree canopy base & crown width	6 trees/transect
Active layer depth (interior Alaska plots only)	10 points/transect
Forest floor layer thickness	2 points/transect
Downed, woody fuel loading	4 x 30m Brown's transects

C. Fire Behavior Modeling

Fire Behavior Model Options

We initially proposed to use IFTDSS V 2.0 (The Interagency Fuels Treatment Decision Support System, Drury *et al*. 2016) as our modeling platform for evaluating fire behavior changes due to fuels treatments. We were able to use IFTDSS for modeling landscape fire behavior for the expert elicitation on wildfire scenarios before IFTDSS was updated to version 3.0. However, the lack of stand-level fire behavior modeling capacity in IFTDSS 3.0 forced us to evaluate other fire behavior modeling systems including BehavePlus V 6, the Canadian Fire Effects Model (CanFire), a successor to the Canadian Fire Behavior Prediction Model (REDapp) and the Crown Fire Initiation and Spread Model System (CFIS).

Fire Behavior Model Evaluation

The fire behavior modeling systems BehavePlus 6 (https://www.frames.gov/partner-sites/behaveplus/software-manuals/); CanFIRE (de Groot 2012), REDapp (http://redapp.org), and the Crown Fire Initiation and Spread model (CFIS; http://www.frames.gov/cfis) were all evaluated using a set of unpublished observations for the 1997 Magitchlie Creek Fire. We evaluated how close the fire behavior modeling systems performed when compared to direct observations including flame length, rate of spread, fireline intensity, and fire type (torching or crown fire).

Fire Behavior Fuel Model Selection

Fire behavior fuel models (FBFM) were selected for use with BehavePlus 6 based on consultations with fire behavior analysts in Alaska, a review of the latest version of the Alaska Fire Behavior Fuel Model Guide (Cella *et al*. 2008; henceforth referred to as the guide), and analysis of fire behavior observations from the 1997 Magitchlie Creek Fire. Initial FBFM selection was then compared with site photographs and the field sampled vegetation and fuels data to confirm or suggest other FBFM.

Modeled Fire Behavior in Fuels Treatment

Flame length, rates of spread, fireline intensity, and fire type were modeled for each treatment location and treatment type. Surface fuel models that serve as fire behavior fuels inputs for the surface fire prediction models were selected using the field collected vegetation data summaries, visually inspection of site photos. Canopy fuels inputs were calculated using the field data summaries following standard biomass algorithms in Barney and Van Cleve (1977) for black spruce trees and Yarie *et al*. (2007) for white spruce and hardwood trees. Weather inputs at 70th and 90th weather percentiles for rH and temperature were determined using historical weather records from Remote Automated Weather Stations (RAWS) and calculated using FireFamilyPlus 4.2 (Bradshaw and McCormick 2000). In addition, FireFamilyPlus 4.2 was used to determine fuel moisture values for 1 hr, 10 hr, and 100 hr fuel moisture inputs for 70th and 90th percentile weather. Live herbaceous fuel moisture, live woody fuel moisture, and foliar moisture values were set based on existing literature and expert opinion. The influence of wind speed on fire behavior potential was evaluated using stepwise modeling at wind speeds of 0, 2.5, 5, 10, 15, 20, 25, 30, 35 and 40 mph. Modeling fire behavior with increasing winds allowed us to produce charts of when strategic firefighting tactics could be employed and under what wind speeds a fire would be expected to transition from surface to torching to an active crown fire.

IV. Field Work, Data Collection, and Fire Modeling Results and Discussion

A. Fuel Treatment Life Cycle Changes

Tree Density and Forest Cover Changes

In interior Alaska black spruce treatments (Sites b – d, Figure 4), average live tree densities ranged from 3,566 to 5,337 stems/acre pre-treatment, with the vast majority (95 to 100%) composed of black spruce (Ott and Jandt, 2005: Table A-1). Treatment initially reduced these densities by 79-91% (2 years post-treatment). After 14 years, the overstory tree densities (> 1" DBH) in thinned blocks were still just 12-24% of the densities in the control plots. Prior to treatment, average overstory cover values ranged from 40% to 53% in the black spruce demo sites, whereas post-treatment they ranged from 12-21% tree cover—converting them from "closed forest" to "woodland" classification. After 14 years, thinned demonstration units in black spruce had gained 4-7% overstory tree cover (Table A-1). 2015 canopy cover ranged from 0% in shearbladed or masticated treatments to 47% in the mostly aspen Dot Lake shaded fuelbreak, and 48% in the birch-dominated Campbell Tract fuelbreak (Table A-2, A-3). All treated units were more open than their reference sites, often dramatically. For example, at Tanacross the shaded fuelbreak was 6% cover *vs.*43% at the reference site (cover photo; Table A-3). Interestingly, we did not detect a meaningful increase in sub-canopy trees (<4.5' tall) or seedlings after 14 years in the thinned black spruce units, in spite of the dramatic canopy openings created (Table A-4). However, at 8 years post-treatment in a more aggressively thinned mixed spruce stand (Tanacross), regeneration started to become more noticeable in the treatments. A profound shift in species composition of regenerating trees (toward white spruce and aspen and away from black spruce and birch) was noted (Jandt 2009; Table A-3).

Canopy Fuel Load

Canopy fuel loadings varied widely among treatment types and across ecotypes but were predictably lower at treated sites. Previously sampled JFS Demonstration shaded fuel break units in interior Alaska (Sites b – d, Figure 4) showed slight gains in crown mass and crown bulk density values, but were not substantially changed over the 14 years since treatment relative to control sites (Tables A-2, A-5). At Nenana Ridge (Site a, Figure 4) crown bulk density in shaded fuelbreak units was 16-30% of control values after 8 years (Table A-2).

Figure 5. Field data collection at Campbell Tract by TCC and Chugachmiut forestry staff. (photo: N. Lojewski, 2015)

Figure 6. Tanacross fuel treatment after wind event in 2012 (photo by F. Keirn, TCC).

Tree Damage in Treatments

An important finding in boreal shaded fuel breaks was the unintended tree damage and loss that can occur after initial treatments. Tanacross provided a good example of this. The original thinning specifications were for 12 x 12' thinning in mixed forest predominated by white spruce (average 63% canopy cover), but results were closer to 14 x 14' spacing (220 stems/acre, 22% cover). Northern spruce engraver beetle (*Ips perturbatus*) activity was heavy during the summer after treatment in trees and log decks salvaged for firewood. Insects, combined with thinning shock and pruning wounds led to the loss of up to 25% of the remnant trees (Jandt 2009). A wind event in September, 2012 with gusts up to 100 mph, also resulted in extensive damage (photo-Figure 6) in the treated area and in natural openings (News-Miner 2012). As a result, after 15 years the canopy cover was just 6% in the "shaded" fuelbreak area: 4% white spruce and 2% aspen (Table A-3). We also followed the fate of tagged trees in the JFS Demonstration fuelbreaks to determine the effects of treatment. Of 709 tagged trees, 3% died by 2006--14 on treatment blocks, and 6 on control blocks. Windthrow was especially evident in the treatment block. After 4 years, 21 tagged trees (as well as many non-tagged trees) had been downed by windthrow on the treatment blocks and a host of others were leaning, most notably at DBR (Figure 4, site d). No tagged trees were windthrown on the control plots, although dead and damaged trees (especially spruce budworm at TOG: Figure 4, site c) were observed. Black spruce (especially when growing on sites underlain by permafrost) are very shallow-rooted.

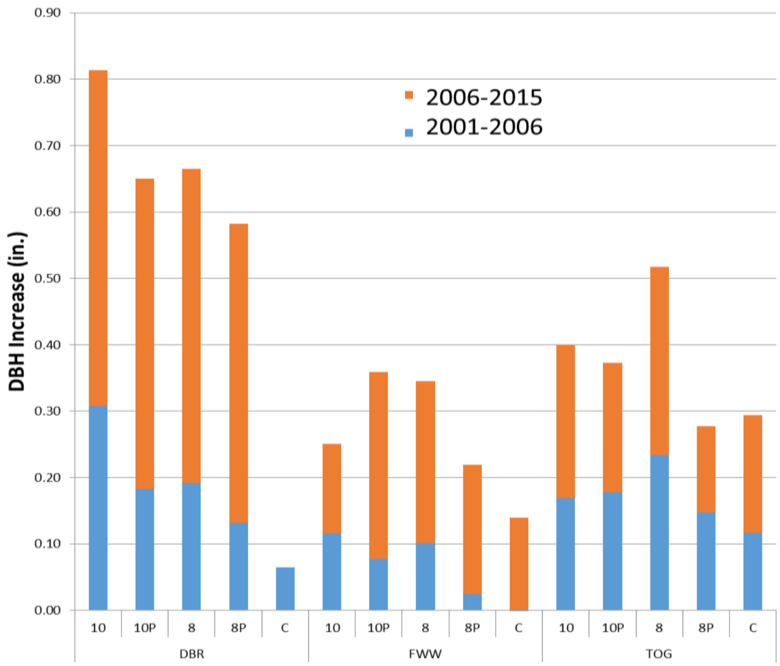


Figure 7. Graph of changes in height of tagged black spruce trees in JFS Demonstration fuelbreak units (Figure 4, sites b-d).

Tree Growth Responses

Recent work in interior Alaska has documented the sensitivity of Alaska spruce to increased drought and temperature (Wolken *et al*. 2016, Juday *et al*. 2012). This might be expected in thinned stands so we did not know how treatment would impact tree growth. However, records from over 700 tagged trees from demonstration fuel breaks sampled up to 5 years post-thinning indicated black spruce in treatment blocks had greater diameter growth than controls (except in the least-thinned 8 x 8 blocks) Figure 7 (ANOVA:

Appendix A- 20). During the second growth period (2006-2015) we could not detect significant differences due small sample size of control DBH samples (Table A-6) but all treated units had trees which gained at least 0.5" in diameter while none were observed in control blocks. With respect to tree height, there was a trend for trees in the treatments to grow more during the first 5 years than the control (by double: Appendix A- 7), but the difference was not significant due to the variation induced by leaning, dead tops, windthrow, *etc*. (Table A-7).

Understory Vegetation Change

Because of the variety of forest types covered by the study, it's hard to generalize on changes in cover. However, substantial vegetation shifts occurred in most fuel treatments and were more dramatic in cleared breaks than in shaded fuelbreaks. In the southern Alaska treatments, understory cover was dominated by the forbs horsetail and dwarf dogwood, with 30/60% cover of fireweed in masticated/burned areas (Table A-8). The most common shrubs were willow, crowberry, and Labrador tea. Graminoid cover ranged from 6% at North Bean to 61% on the Funny River burn area. The 1-year-old Funny River burned unit had much more graminoid cover than either of the fuel treatment units (Table A-8). Birch was the main remaining tree cover in all shaded fuelbreaks except North Bean (Table A-8). In the central Alaska fuel treatments, substantial changes in understory species composition occurred in shearbladed treatments. Within a few years after shearblading, mosses declined by 50% and grasses and sedges increased by 4000% (Butler *et al*. 2013). By 2015, *Calamagrostis* cover was 78% in the shearbladed treatments, 12% in controls, and 13-35% in thinned treatments where slash was removed and burned at Nenana Ridge (Table A-9). At Tanacross, graminoid cover increased from 6% pre-treatment to 15-16% by years 2-8, and 22% after 14 years (Jandt 2009; Table A-9). In demonstration shaded fuelbreaks, individual treatment units in black spruce (Figure 4, b-d) showed trends in vegetation toward forb or shrub cover in 2015 (Table A-10). On these more conservative thinning treatments, less dramatic shifts in understory species cover occurred, although grass—especially *Calamagrostis*--tended to increase on thinned blocks overall while sedges like cottongrass declined marginally (Table A-11). There was indication of increased shrubbiness on treated *vs*. control blocks (Table A-11), but this was not consistent between sites.

Ground Cover and Substrate Change

Notable shifts in ground cover occurred soon after treatment on shaded fuelbreak units in central Alaska. Live feather mosses were the most common pre-treatment ground cover, averaging 56 to 67% at JFS demonstration units. No dead feather moss ground cover was recorded in pre-treatment measurements. After treatment, live feather moss was reduced in all treatment blocks, ranging from 24 to 41% (compared to 47% for controls) after two years. Dead moss cover accounted for 21 to 28% of ground cover in treatments after the same period of time (Table A-12). After 14 years, feather moss ground cover seemed to have recovered on treatments, averaging 55 to 63% (66% on controls). Early changes were even more pronounced at Tanacross, where live moss was 50% of ground cover pre-treatment. After 2 years less than 5% was recorded as live and 22% of the substrate cover was dead feather moss (Jandt 2009). After 8 years there was still only 5% live moss, but by 14 years 16% of substrate was recorded as live moss. After 14 years, litter was still the second most common ground cover with average values ranging from 25-27% on treatment blocks, but only 10% on controls (Table A-12). After 14 years the average total forest floor thickness was marginally less in thinned treatments than controls, but not significantly different (Table A-13) in JFS demonstration units. Forest floor layer measurements for all study sites in 2015 are tabulated in Table A-14.

Dead and Downed Fuel Loading

Downed woody fuel was not a major component of the fuelbed biomass at any of the interior Alaska study sites pre-treatment. Values ranged from 2.7 tons/acre at Tanacross to 1.5 to 4.7 tons/acre at JFS demonstration units for all locations/size classes combined (Jandt 2009; Table A-15). Thinning and pruning initially (2 yrs) reduced overall woody fuel loads from 35-63% with the higher reductions occurring in non-pruned units, as pruning transiently increased fine fuel loading at JFS demonstration units (Table A-15). By 2015 there was not much difference in overall woody fuel loadings among treatments (1.1-2.0 T/ac) and controls (3.1 T/ac; Table A-16a). Shearbladed treatments had 5 times as much 100-hour (1-3 in. diameter) woody fuel as thinned or control units at Nenana Ridge (Table A-16a). At Tanacross, where downed aspen and white spruce were removed by thinning crews, fuel loading was initially halved. (1.4 T/ac) But by 2015 it was up sharply to 7.6 T/ac on the shaded fuelbreak, and up to 9.3 T/ac on the control (Table A-16a). Southern Alaska study sites had more downed woody fuel, ranging from 2.6 T/ac at the Campbell Tract fuelbreak to 15.3 T/ac on the burned portion of the Funny River shaded break (Table A-16b). The 6-year-old Funny River masticated break had 4.6 T/ac of fine woody debris (< 3 in.; Table A-16b).

Active Layer Changes

Fuel treatments clearly affected the depth of seasonal thaw (active layer) in central Alaska units, where permafrost is relatively close to the surface. However, the date of sampling and the unique annual weather conditions (especially snow depth) strongly influence thaw depth. Differences between treatments and controls tended to be clearer in late summer than in early summer (Table A-17). There are several years of observations from the JFS demonstration fuelbreaks which illustrate that the degree of canopy opening generally correlates with thaw depth (Table A-18; Figure 8). A set of observations from 2008 when all three demonstration fuel treatments were sampled in September best illustrates this (Appendix A- 21). Shearbladed units were thawed more than twice as deep on average as the control, by early to mid-summer of 2015 (Table A-17) Again, the date of sampling was a significant factor. At one of the Nenana Ridge shaded fuelbreak treatments, the average active layer depth was almost 3x the control depth by mid-August (139 cm *vs* 52 cm; Table A-17). At Dot Lake, in 2015 (July 8-10), shaded fuelbreak active layer was marginally deeper than the control (p= 0.05) but variation was quite large. Tanacross fuelbreak active layer depth ranged widely, from 0 to >100 cm (N= 49), with the mean being slightly *less* than mean thaw on reference transect (N=10) at the early sample date of July 9th, 2015. Previous years of sampling near the end of July had indicated the shade fuelbreak areas tended to have deeper active layers by late summer.

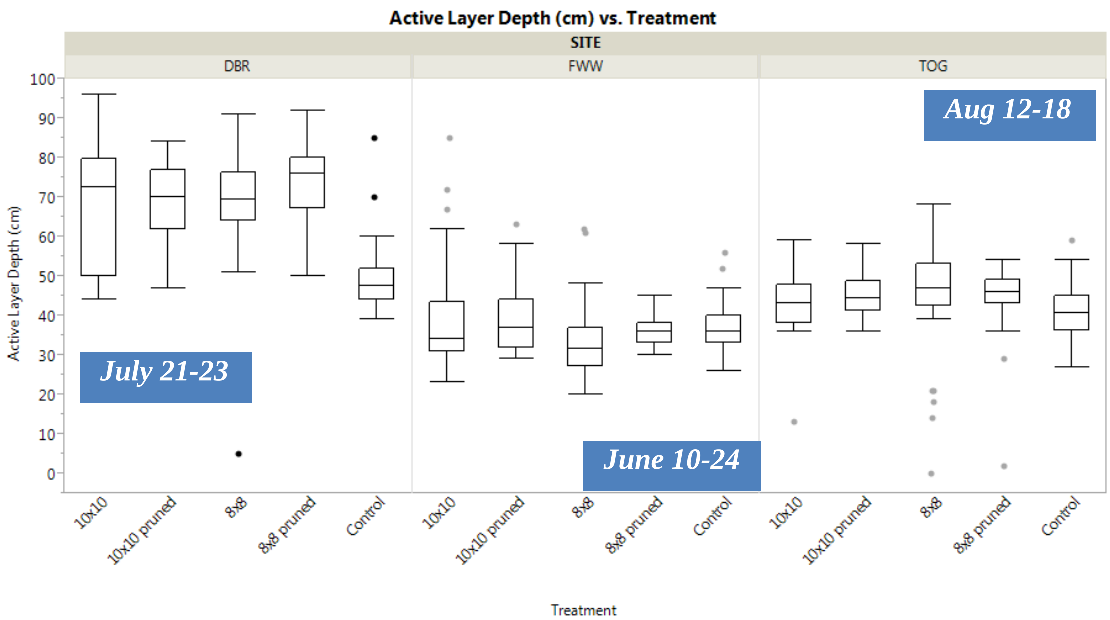


Figure 8. Active layer depths at JFS demonstration fuel treatments in interior Alaska, 2015 (sample dates in blue boxes).

B. Fire Behavior Modeling Results

Fire Behavior Model Selection

BehavePlus 6 and CFIS were selected for modeling fire behavior potentials within and among the Alaska fuels treatments. These models were selected in part to provide upper and lower limits for modeling fire behavior potentials in fuels treatments. When compared with direct fire behavior observations from the Magitchlie Creek Fire (Table 2 BehavePlus 6 provided lower estimates for flame length (2.5 m vs > 10 m), slower rates of spread (5.7 m/min vs 8.8 m/min), and predicted less energy produced (1364 kW/m vs 9489 kW/m) than we directly observed on the Magitchlie Creek Fire. Moreover, BehavePlus 6 predicted either a surface fire or a torching fire depending on fuel model used (Table 2) while we observed active crown fire behavior nearly immediately after igniting the experimental fire area at the rear of the Magitchlie Creek Fire (Figure 9).

The crown fire initiation and spread modeling system (CFIS) did a better job of predicting active crown fire behavior than BehavePlus 6 but over predicted crown fire rate of spread (13.6 m/min vs 8.8 m/min; Table 2.). CFIS did not predict flame length nor fireline intensity.

Table 2. Summaries of fire behavior model runs verses observed results on the 1997 Magitchlie Creek Fire.

	Observed	BehavePlus6 (TU 4)	BehavePlus6 (SH 5)	REDapp	CanFire	CFIS
Rate of Spread	8.8 m/min	0.8 m/min	5.7 m/min	10.2 m/min	10.2 m/min	13.6 m/min
Head Fire Intensity	9489 kW/m	87 kW/m	1364 kW/m	11953 kW/m	10095 kW/m	N/E
Flame Length	10-25 m	0.5 m	2.5 m	N/E	N/E	N/E
Crown Fraction Burned	Active crown	Surface	Torching	Active crown	Active crown	Active crown

Both current variants of the Canadian Fire Behavior Prediction system (FBP, Stocks *et al.* 1989) REDapp and CanFIRE provided better estimates of observed fire behavior characteristics in untreated interior black spruce forests (Table 2) than either BehavePlus 6 or CFIS. REDapp and CanFire slightly over estimated observed rate of spread values (10.2 m/min vs 8.8 m/min) and head fire intensity (fireline intensity, 9489 kW/m vs 11953 kW/m; 10095 kW/m; Table 2). However, neither REDapp nor CanFIRE were selected for modeling potential changes to fire behavior due to fuels treatments as neither modeling system accurately captured fuels treatment induced changes to the live vegetation or the dead fuels. Moreover a more complete analysis of the third Canadian modeling system, CFIS, revealed that CFIS was not sensitive to changes in canopy biomass and predicted few differences among treated and untreated reference sites.

Initially, REDapp, CanFire, and CFIS were selected for further analysis. But during initial modeling efforts it was found that these models were relatively unable to detect changes in fire behavior due to fuels treatments. REDapp was quickly ruled out as a fire behavior modeling system for evaluating fuels treatment effectiveness in Alaska as the system was dependent on the Canadian fire prediction system fuel models (De Groot 1993) as inputs to the FBP fire behavior prediction algorithms. REDapp does not allow users to change the fuels inputs if fuel characteristics are not changed enough to necessitate a change in fuel model. CanFire did not require the use of fuel models but internally the model assigns fuel models based on stand type and vegetation attributes and then uses FBP fire behavior prediction algorithms to predict fire behavior (De Groot personal communication). The vegetation changes due to fuels treatments were not significant to require an alteration in how the fuel models were applied and no changes in fire behavior due to fuels treatment were predicted. A sensitivity analysis was conducted with CFIS after it was determined that few differences were noted among treated and untreated areas. Holding most CFIS input steady while varying crown bulk density (a measure of canopy biomass available to burn and canopy connectivity) revealed very little change in canopy fire potential or canopy rate of spread in treated verses untreated stands.

Figure 9. Thirty-seconds after igniting the experimental fire monitoring area at the rear of the Magitchlie Creek Fire. Experimental fire was ignited with the wind to burn a mature black spruce stand within the 1997 Magitchlie Creek fire footprint. Note the main fire is backing against the wind towards monitoring area and burned around the experimental fire area as a backing or flanking fire three hours after the experimental fire was ignited on the Innoko National Wildlife Refuge. SDrury Photo

Fire Behavior Fuel Model Selection

BehavePlus 6 is dependent on fire behavior fuel models (FBFM; Anderson 1982; Scott and Burgan 2005) for all surface fuel inputs. Fire behavior analysts (personal communication), the guide, and analysis of the Magitchlie Creek fire behavior observations (Table 3) suggested that the shrub FBFM SH5 coupled with the crown fire initiation algorithm commonly referred to as the Scott and Reinhardt switch was appropriated for modeling fire behavior in intact black spruce stands (Table 3). BehavePlus 6 with the SH5 FBFM produced fire behavior outputs which most closely represented field observations on the Magitchlie Creek Fire. A second possible FBFM selection, the timber understory FBFM TU4, was ruled out for intact black spruce stands as the flame length and rates of spread values produced by BehavePlus 6 using this FBFM dramatically underestimated Magitchlie Creek observations. TU4 was selected to model fire behavior in the interior Alaska shaded fuel breaks as the treatment opened up the over story changing the treated areas from a SH5 shrub to a more open TU4 stand.

Table 3. Fuel models used for each unit and treatment.

Interior black spruce stands

Unit name	Treatment type	Fire Behavior Fuel Model
Fort Wainwright	Control	SH 5
	Shaded fuels break	TU 4
Delta Bison Range	Control	SH 5
	Shaded fuels break	TU 4
Toghotthele	Control	SH 5
	Shaded fuels break	TU 4
Nenana Ridge	Control	SH 5
	Shaded fuels break	TU 4
	Shear blade	SB1

White spruce, mixed spruce, mixed hardwood stands

Unit name	Treatment type	Fire Behavior Fuel Model
Dot Lake	Control	TU 5
	Shaded fuels break	TU 5
Tanacross	Control	TU 1
	Shaded/blowdown	GS 3
Campbell Tract	Control (PS AKHD 13)	TU 1
	Shaded fuels break	TU 1
	Cleared fuel break	GS 3
Funny River	Control (PS AKHD 09)	TU 5
	Shaded fuels break	TU 1
	Burned fuels break	TU 1
	Masticated fuels break	GS 1
Hope Gate	Control (PS AKHD 13)	TU 1
	Shaded fuels break	TU 1
Bean Creek	Control (PS AKWS 12)	TU 5
	Shaded/mortality mitigation	TU 5

Untreated white spruce, mixed spruce, and mixed hardwood stands were modeled as FBFM TU 5 or TU 1 based on the relative amounts of spruce and hardwoods (Table 3, Cella *et al.* 2008). Stands that were closer to pure white spruce stands were assigned to TU5 while stands that were closer to hardwood or mixed-spruce hardwood stands were designated TU1 stands (Cella *et al.* 2008). Shaded fuel breaks in white spruce or mixed spruce hardwood stands were also designated TU1 or TU5 based on relative percentage of spruce or hardwood.

More heavily altered treatments such as mastication (Funny River), shaded fuel break with associated post-treatment damage (Tanacross), and shear blading (Nenana Ridge) were assigned SB1, GS1, or GS3 depending on the understory field data and site photographs.

Fire Behavior Modeling

Fuel break induced changes in fire behavior potentials were identified as much as 14 years post fuel treatment particularly in interior Alaskan black spruce forests. Fire behavior potentials modeled with Behave Plus 6 under average summer conditions (70^{th} percentile weather) and drier summer conditions (90^{th} percentile) illustrated how treating fuels lowered and or changed modeled fire behavior characteristics including flame lengths, rates of spread, and fireline intensity.

Modeled Fire Behavior in Interior Alaska Black Spruce Stands

Fuels treatment as much as 14 years post-treatment continued to mitigate fire behavior potentials in black spruce stands. Modeled flame lengths within shaded fuels treatments were as much as a factor of three less relative to the controls (Figure 10) when modeled with BehavePlus 6 for both the 70th and 90th percentile conditions. The demonstration sites where individual trees were pruned from below tended to have the lowest flame lengths when compared with the other treatments and the controls (Figure 10). Modeled rates of spread and fireline intensity values were also lower in the treated areas than the controls (Figure 10) although the differences among rates of spread rapidly diminished as 20-foot wind speeds approached or exceeded 15 to 20 mph. Interestingly, the greatest reduction in modeled flame lengths and rates of spread were found in the units thinned to 8 x 8 spacing with the lower branches pruned from below. This suggests that increasing treatment intensity may not result in additional reduction in fire behavior potential.

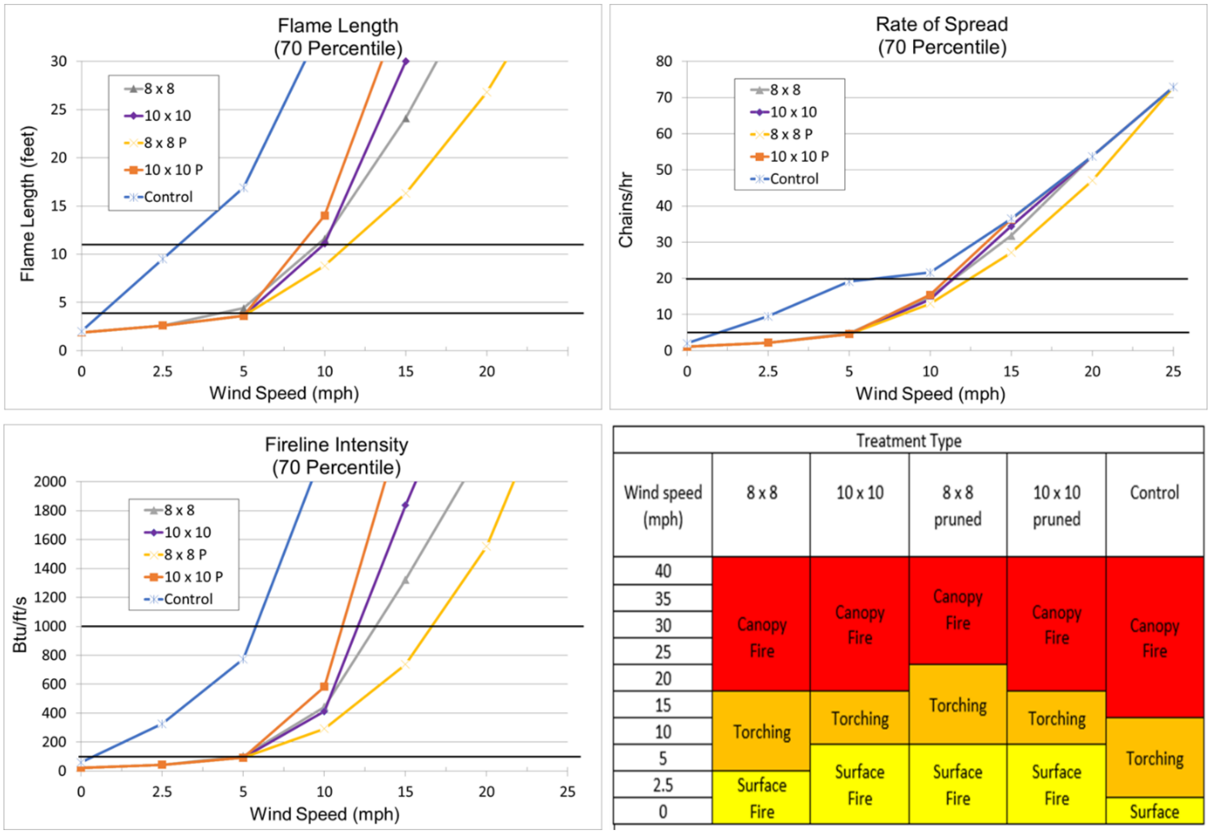
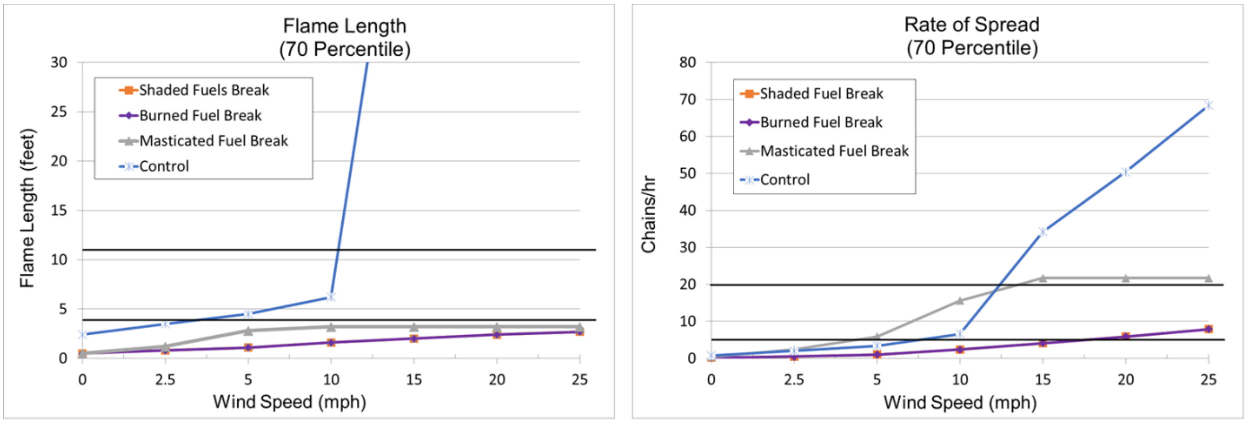


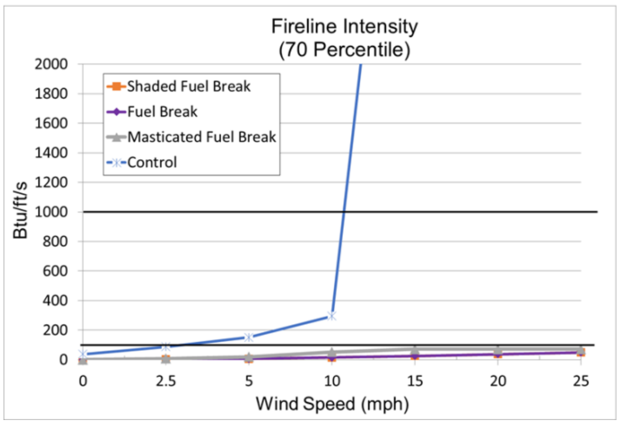
Figure 10. Behave Plus 6 modeling results from the Toghotthele study area. Differences among treatment types for flame length (ft), rate of spread (chains/hr), fireline intensity (Btus/ft/s), and fire type for each of the treatments. The control site (light blue line) continues to show higher fire behavior potentials than the treated sites. Fuels treatments had the greatest impact on reducing modeled flame lengths across all treatments. Rate of spread was reduced by all treatments at the lower wind speeds but as wind speeds approached 15 mph the shaded fuel treatments and control rates of spread converge. Note that in all cases, the greatest reduction in modeled flame length and rate of spread was in the 8 x 8 treatment where the branches were pruned from below to raise crown base heights.

Shearblading in black spruce stands resulted in the lowest flame lengths, rates of spread, and fireline intensity

Fire Behavior Modeling in White Spruce and Mixed Forest

Modeled fire behavior potentials varied considerably more in the mixed white spruce hardwood study sites than in the interior black spruce stands. Much greater vegetation changes were made when treating some white spruce mixed spruce areas than occurred in the black spruce stands. Fuels treatments in white spruce hardwood stands included cleared fuel breaks and masticated stands which greatly influenced modeled fire behavior outputs. Shaded fuel breaks tended to be more effective for avoiding canopy fires in white spruce hardwood stands by reducing flame lengths and rates of spread relative to the reference controls. However, in areas where the canopy was completely removed (cleared fuel breaks, masticated fuels) rates of spread were often higher (Figure 11) relative to the controls. Our Tanacross site (Figure 12) illustrates this potential as the site was initially thinned to 12 x 12 spacing then experienced a wind event which toppled additional trees. The additional trees on the ground and the subsequent recovery of shrubs and hardwood regeneration switched the fuel model from a timber understory fuel model TU1 to a grass-shrub fuel model GS3 with the associated increased modeled flame lengths and rates of spread (Figure 13).

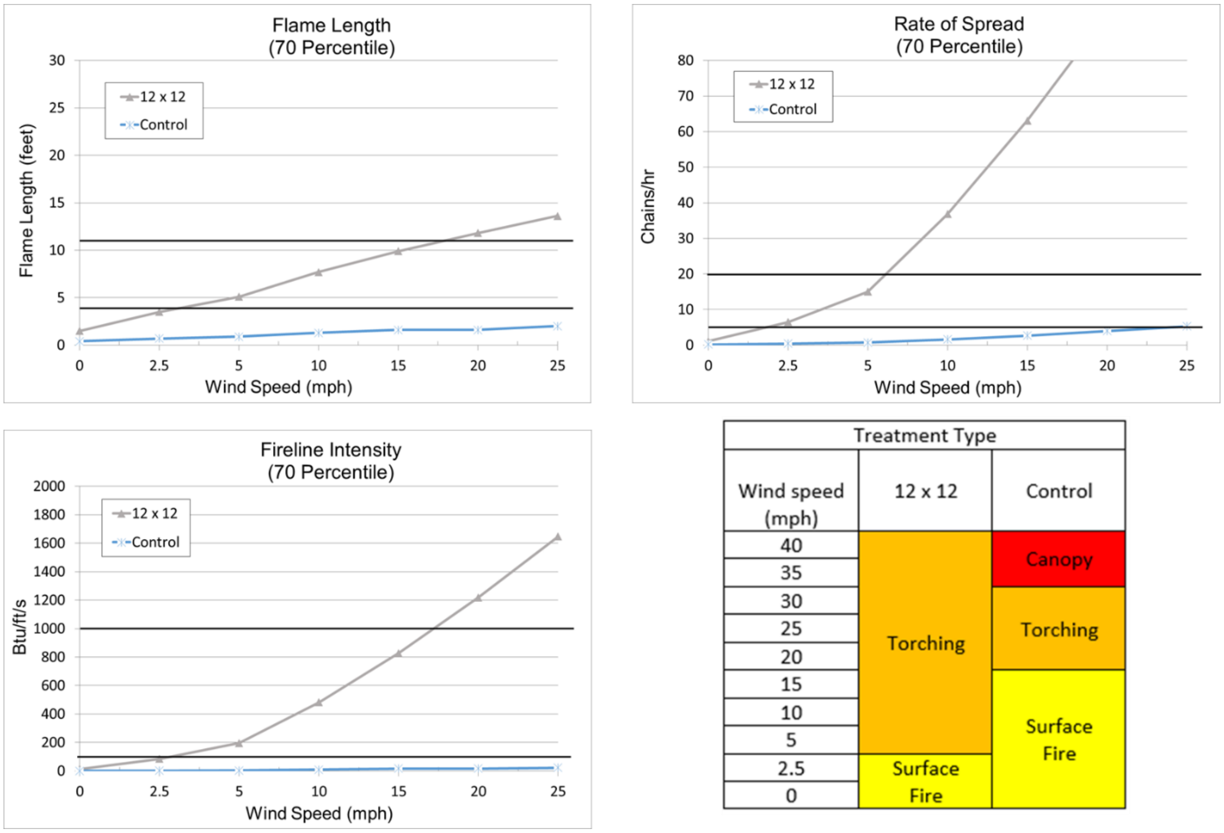




Treatment Type				
Wind speed (mph)	Shaded Fuel Break	Burned Fuel Break	Masticated Fuel Break	Control (AKWS 09)
40				
35				
30				Canopy Fire
25				
20	Surface Fire	Surface Fire	Surface Fire	
15				
10				
5				Surface Fire
2.5				
0				

Figure 11. Behave Plus 6. Flame length (ft), rates of spread (chains/hr), fireline intensity (Btus/ft/s) and fire type differences among treatment types at the Funny River Study Area. The control site (light blue line) continues to show higher fire behavior potentials than the treated sites. Modeled canopy fire potential was reduced to zero for each treatment.

Figure 12. Tanacross fuel treatment illustrating the shaded fuel treatment on the left and the control unit on the right.



	Treatment Type	
Wind speed (mph)	12 x 12	Control
40	Torching	Canopy
35	Torching	Canopy
30	Torching	Torching
25	Torching	Torching
20	Torching	Torching
15	Torching	Surface Fire
10	Torching	Surface Fire
5	Torching	Surface Fire
2.5	Surface Fire	Surface Fire
0	Surface Fire	Surface Fire

Figure 13. Behave Plus 6 modeling results from the Tanacross study area. Differences among treatment types for flame length (ft), rate of spread (chains/hr), fireline intensity (Btus/ft/s), and fire type for each of the treatments. At the Tanacross site, modeled fire behavior potentials were higher in the shaded fuels treatment area when compared with the control site. This may be due to the fact that the fuels treatments and associated disturbances changed the fuel model from TU1 to a GS3 grass shrub model. Modeled crown fire potential was also interesting as no potential for an active crown fire was predicted in the treated area while an active crown fire was possible at very high wind speeds.

Discussion: Fuels Treatment Wildfire Interactions

Fuels treatments in Alaska were tested by wildfire during the Eagle Trail (2010), Funny River (2014), Card Street (2015), and Nenana Ridge (2015) fires. In addition fuels treatments were tested at the planned research fire at Nenana Ridge (2009). Moreover, anecdotal evidence suggests that a fuels treatment was instrumental in protecting Ft Greely from the Donnelly Flats Fire in 1999 (Brown 2009). In all documented cases the Alaskan fuel breaks changed fire behavior as the fire moved through untreated wildland fuels as an active crown fire and dropped to a surface fire in the treatment areas (Butler *et al.* 2013, Lojewski 2015, Miller 2015, Saperstein *et al.* 2014, Perrine 2016, Maisch 2017). Field sampled and photo evidence also indicate that the lower fire behavior potentials in the treated areas coupled with the increased ease of movement and lack of visual obstructions due to the removal of canopy trees and surface fuels facilitated fire suppression activities such as burning out the treated areas or using treatments as anchors for back firing operations (Figure 14).

Figure 14. Backfiring and burning out during the Funny River fire (2015). USFWS photos.

Our fire behavior modeling effort provides convincing evidence that the fuels treatments do reduce fire behavior potentials especially under a range of weather conditions and lower wind speeds. The benefits decrease, sometimes exponentially, at wind speeds greater than 20-mph. However, none of the fuel breaks studied would stop an advancing wildfire on its own. In fact, the more the area is cleared or affected by post-treatment disturbance such as wind throw the more likely the rates of spread will be increased due to increased drying of the surface fuels, conversion of forest to shrub and grass fuel types, and increased wind speeds at the surface when the canopy is removed.

C. Homeowner Behavior and Risk Mitigation

Private Wildfire Risk Mitigation

Addressing wildfire risk at a homeowner level is an important policy issue. Because of the shared nature of wildfire risk, mitigation activities pursued by homeowners on private lands can provide benefits to individuals and communities in the Wildland Urban Interface (WUI). Subsequently, a fundamental question to address is how homeowners value wildfire risk reductions and whether fuel treatments on nearby public lands can encourage homeowners to pursue costly private risk mitigation activities on their own properties.

The Wildland Urban Interface (WUI) has been the focus of many studies evaluating how wildfires affect the general economic losses to individual properties and communities (Holmes *et al.* 2009, Hammer *et al.* 2009, Stein *et al*. 2013). WUI areas are particularly vulnerable to wildfire, since they are directly adjacent to open wildlands. Probabilistic fire events occurring in open wildlands near WUI communities give residents very little time to react. Individuals in these communities do not have much direct control over factors that may reduce wildfire ignition or spread, beyond the scope of their property lines. Even so, homeowners can make decisions that affect the rate of wildfire spread through their neighborhood, and house ignition probabilities. From a suppression perspective, additional investment into pre-suppression tactics decreases wildfire spread, and therefore overall suppression costs (Yoder and Lankoande 2006). Because these risk mitigation activities are an important component to suppressing wildfires in WUI communities, programs like FIREWISE help build community resilience to wildfires via education and social support networks. Wildfire suppression agents rely heavily on the pre-suppression activities of individual private homeowners. It is therefore of interest to understand what motivates them to pursue these activities on their own property. A discreet choice experiment (DCE), was used to estimate Willingness-To-Pay (WTP) for wildfire risk reduction on their own property

Under-provision of wildfire risk mitigation actions

Wildfire risk mitigation actions are generally underprovided by homeowners in WUI communities (Brenkert-Smith *et al*. 2006). Pre-suppression[5] activities are generally underutilized and marginally more cost effective than direct suppression actions when fighting wildfires (Yoder and Lankoande 2006). Why do homeowners underprovide these *services*, given that they directly benefit from them? Spatially, homeowners who are closer to the open wildland will suffer more of the damages. It has been shown via simulation that communities with a buffer strategy[6] to home ignition risk mitigation stop the spread of wildfire through neighborhoods faster than other mitigation methods (Butry and Donovan, 2008). This may create an incentive for homeowners who are further away from the frontlines to 'free ride' and receive indirect ignition risk reductions. There is also a direct link between the attitudes of people living in WUI homes and the actual value of the homes. Mitigation activities are less common among renters, and 'dwelling cash value' is highly motivating at the homeowner level. (Collins 2008)

Amenity and privacy values account for some of the under-provision of mitigation actions (Kobayashi *et al*. 2010). WUI residents are also often reluctant to change the landscaping on their property until wildfire is eminent (Brenkert-Smith *et al*. 2006). Further evidence is observed in a lower homeowner WTP for mitigation actions on their own property than on public land (Holmes *et al*. 2009). In an experimental setting, there is evidence of a 'crowding out' phenomena where individual homeowners react to increased (or potential increases to) public mitigation activities by decreasing their mitigation spending, even though there were higher participation rates (Prante *et al* 2011). There is also a belief that protection from wildfire should come in the form of government suppression agencies. A study by Vogt, Winter and Fried (2002) found that in general, homeowners trusted the government to protect private property from wildfire. Furthermore, the perception of wildfire risk can drive behavior more than actual wildfire risk, and homeowners often underestimate the true risk levels in their neighborhood (Brenkert-Smith *et al*. 2012). Increased risk information has also been shown to motivate mitigation behavior more than prior wildfire experience (Martin *et al*. 2009). These established findings were considered while constructing the survey instrument and choice experiment.

Homeowners have been shown to participate in wildfire mitigation activities under a variety of circumstances. Even while fully insured, homeowners in WUI communities had statistically significant WTP for wildfire risk reduction via pre-suppression activities (Talberth *et al*. 2006). While insurance can protect individual homeowners by reducing loss, these protections rarely cover the full value of damages (Winter and Fried 2001). WTP estimates for risk reduction via wildfire-risk mitigation actions have been attempted in the past. A Contingent Valuation (CV) study estimated a significant WTP in a theoretical market for 50% risk reduction via risk reducing activities (Winter and Fried 2001). WTP for risk reduction via mitigation activities for homeowners in California, Montana and Florida were also estimated (Loomis and Gonzalez-Caban 2008). These estimates were found to be significant and positive, ranging from $190 to $500 depending on the individual and location.

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[5] Defined to be costs associated with planning, prevention, detection equipment, and other similar expenditures.
[6] Defined to be a spatial arrangement of fuel reduction that focuses on the contact boundary between open wildlands and a WUI community.

Developing the sample frame

Regional Community Wildfire Protection Plans (CWPP) were used to identify the spatial distribution of wildfire risk in WUI locations. In the Fairbanks North Star Borough, there are three risk zones: high risk, very high risk, and extreme risk. These zone boundaries are often defined by their hazardous fuels and topographical features. The Kenai Peninsula Borough (KPB) defines four risk areas: low, moderate, high and extreme risk. While these zones do not exactly align with the zones defined by the Fairbanks North Star Borough (FNSB), there are clear similarities on the high risk side. When comparing the two CWPP risk zones in the survey, the top three levels of each are considered equivalent[7]. These risk zones are also considered the authoritative risk indicators for a neighborhood.

Homeowners invited to participate in the survey had to fit several criteria. First, the homeowner needed to live in an area of wildfire risk. Their risk zone, as defined from the CWPP, was noted in their contact letter and in the online survey. Second, since all information about homeowners came from the borough tax database, homeowners needed to have paid taxes on their property. Lastly, the mailing address on file needed to match up with the homeowner's actual mailing address. Any old or outdated information from the respective boroughs made the homeowner of that parcel inaccessible. Once the eligible homeowners were pooled, 1,000 homeowners were randomly selected from each borough (FNSB and KBP). This 1000 homeowner sample was pulled from each borough's wildfire risk population. After the initial contact (via physical letter), homeowners self-selected into the sample by choosing to take the online survey. After multiple follow-ups, a total of 337[8] homeowners participated in, and completed the experiment (A response rate of 16.85%). The total time required to take the survey was estimated at 30-45 minutes

Survey design

Discreet choice experiments (DCE) are a key tool used to estimate the value of attributes of goods and services. In this context, the DCE was designed to derive the willingness to pay (WTP) for alternative types of fuel treatments and levels of wildfire risk reduction facing their and their neighbors' properties. The survey relied on an adaptive choice based conjoint experiment (ACBC). Using an adaptive based approach requires a different technique to ensure near-optimal choice design[9]. By explicitly asking for favored attribute levels and required attribute levels, the software can create choice sets which maximize the information available using the fewest number of repetitions needed. In this experiment the choice design was generated while the respondent took the survey. Respondents were asked to choose between different risk reducing alternatives that included 5 variables and associated levels (Table 4). The attributes used to describe each alternative included private wildfire mitigation costs associated with making their property "firewise" compliant, level of neighbor participation, public fuel treatment type, and level of wildfire risk reduction to their and their neighbors' properties.

Analysis of the choice experiment allows for estimates of utility, and ultimately willingness to pay (WTP) for each attribute. Positive WTP reflects the added benefit an attribute provides the respondent. Willingness to pay in this case is defined by the private wildfire risk mitigation costs associated with

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[7] FNSB 'high' is equivalent to Kenai 'moderate', FNSB 'very high' is equivalent to Kenai 'high', and FNSB 'extreme' is equivalent to Kenai 'extreme'.

[8] Certain portions of the survey had higher response rates due to the optional nature of the survey questions.

[9] From Sawtooth Software's help file: 'The [survey design] algorithm cannot be said to produce optimal designs, but its designs are near-orthogonal, and have proven to work exceptionally well in many methodological studies to date comparing ACBC to standard CBC [predefined D-optimal designs].'

making a property “firewise” compliant. The attributes levels associated with the presence and type of public land fuel treatment are of particular interest. Additionally, we also evaluated whether respondents were willing to pay for private mitigation knowing that such activities reduced risk for their neighbors as well.

Table 4. Variables and corresponding variable levels used in choice experiment

Variable	Variable Level 1	Variable Level 2	Variable Level 3	Variable Level 4	Variable Level 5
Cost of preparing your property	No action on your property	$500	$1,000	$1,500	$2,000
Number of nearby neighbors preparing their property	No neighbors preparing their property	1-4 neighbors preparing their property	5 or more neighbors preparing their property		
Fuel treatments on neighboring public lands	No fuel treatment on nearby public lands	Nearby public lands have been thinned to create shaded fuel breaks	Nearby public lands have cleared fuel breaks where all trees have been removed		
Reduction in wildfire risk to your property	No reduction in wildfire risk	25% reduction in risk over 10 years (from a 20/1,000 chance to a 15/1,000 chance)	50% reduction in risk over 10 years (from a 20/1,000 chance to a 10/1,000 chance)		
Reduction in wildfire risk to your neighbors	No reduction in wildfire risk	25% reduction in risk over 10 years (from a 20/1,000 chance to a 15/1,000 chance)	50% reduction in risk over 10 years (from a 20/1,000 chance to a 10/1,000 chance)		

Descriptive statistics

Descriptive statistics for age, education level and income were tabulated for each of the fire risk levels (Appendix A- 22) In terms of age, the single largest age group within a risk level was 60-69 year olds in the 'High' risk area (35.63%). Most respondents fall into the 50-59 or 60-69 year old categories for age. Income and education values are assumed to be correlated since higher levels of education should lead to higher income levels. In all risk areas, 57.4% of respondents had at least a bachelor's degree. The same trend follows when looking across the different risk zones. The only outlier seems to be a slightly larger upward shift to education levels in the 'High' risk fire zones

When asked about wildfire mitigation activities (Appendix A- 23), 84% of all respondents indicated that they had pursued at least one mitigation activity on their property (Appendix A- 24). The set of mitigation activities was defined broadly Actions like clearing a yard of leaf litter, keeping long grasses trimmed, or pruning trees were considered wildfire-mitigating activities. Responses to mitigation activity questions were incorporated into section III of the AWFCG Wildfire Risk Rating for Homes in the Wildland Urban Interface spreadsheet. In terms of structure preparedness (Table 5) respondents from both regions fell in the 'moderate' category.

Table 5. Preparedness Scores by Region

Region	Preparedness Score
All	13.22938
FNSB	13.09877
KPB	13.54483

Maintaining a defensible space around a home is a key component in protecting homes from wildfire risk. This includes keeping flammable fuel sources and unmaintained vegetation away from the structure, at least 100ft away from the home. Across all risk zones approximately 65% of respondents indicated that they maintained 30 feet or less of defensible space, approximately 33% of respondents indicated that they maintained defensible space between 30 and 100 feet.

Table 6. Defensible space by risk zone respondent counts

Space Zone	High	Very High	Extreme
0-10 ft	24	38	44
10-30 ft	36	61	17
30-100 ft	35	49	24
Further than 100 ft	1	5	0

Results

Estimates of WTP across risk groupings are shown in Table 7 estimates by region are shown in Table 8. Positive estimates of WTP reflect the additional private mitigation costs a respondent was willing to incur for a one level change in an attribute. Across all estimated models the presence of a thinned fuel treatment on nearby public lands increases respondent welfare. This outcome suggests that such treatments were associated with increases in the level of private wildfire risk mitigation in the experiment. The same outcome is not observed when the treatment is a cleared fuel break. There are two likely explanations for this occurrence. The first suggests that respondents didn't view the thinned treatment as providing enough protection and were willing to pay for private mitigation. The second suggests that the outcome reflects a preference for preserving amenity values. This outcome has been seen elsewhere (Brenkert-Smith, *et al.* 2012). The number of neighbors mitigating on their own property was statistically significant and shows a preference for some level of neighborhood participation. While neighbor mitigation is beneficial for adjacent landowners from a risk perspective, too much of this activity is estimated to reduce respondent welfare. There is also an important social dimension in the findings. Respondents were willing to pay for private risk reductions knowing that the activity resulted in a reduction in wildfire risk for their neighbors. From a regional perspective, respondents from the FNSB place a lower marginal value on thinning treatments than did respondents from the KPB. Public fuel mitigation options were more valuable to KPB homeowners, with WTP estimates for thinned and 'None' treatments being larger than the baseline.

Table 7. WTP estimates by wildfire risk grouping

	All Respondents	High Risk	Low Risk
No neighbors preparing their property	-	-	-
1-4 neighbors preparing their property	$319.24	$775.97	$111.73
5 or more neighbors preparing their property	$14.78	$431.21	($229.31)
Cleared	-	-	-
Thinned	$1,456.56	$1,586.99	$1,542.45
None	$764.58	$474.99	$1,068.97
Level of risk reduction to property			
No reduction in wildfire risk	-	-	-
25% reduction in risk over 10 years	$1,050.02	$1,502.92	$814.63
50% reduction in risk over 10 years	$1,179.36	$1,659.29	$903.39
Leve of risk reduction to neighbors			
No reduction in wildfire risk	-	-	-
25% reduction in risk over 10 years	$596.27	$1,037.47	$330.02
50% reduction in risk over 10 years	$652.91	$1,186.82	$351.50

Table 8. WTP estimates by study regions

	All respondents	FNSB	KPB
No neighbors preparing their property	-	-	-
1-4 neighbors preparing their property	$319.24	$314.31	$315.23
5 or more neighbors preparing their property	$14.78	$85.88	($162.43)
Cleared	-	-	-
Thinned	$1,456.56	$1,290.49	$1,730.82
None	$764.58	$659.18	$912.40
Level of risk reduction to property:			
No reduction in wildfire risk	-	-	-
25% reduction in risk over 10 years	$1,050.02	$1,133.00	$853.81
50% reduction in risk over 10 years	$1,179.36	$1,296.07	$944.74
Level of risk reduction to neighbors:			
No reduction in wildfire risk	-	-	-
25% reduction in risk over 10 years	$596.27	$667.09	$453.37
50% reduction in risk over 10 years	$652.91	$689.04	$543.56

Discussion

The survey and choice experiment provide useful information to wildfire professionals across Alaska. The findings indicate that respondents were willing to incur additional mitigation costs in the presence of thinned fuel treatments. Additionally, respondents were willing to incur private mitigation costs in the absence of a fuel treatment. Cleared fuel breaks are shown to reduce respondent welfare. The implication of this finding is stark, there is a tradeoff between the potential reduction in wildfire risk achievable through public fuel treatments and the willingness of respondents to pursue beneficial mitigation actions on their own land. If a management objective is to encourage homeowners to pursue mitigation activities on their own property, thinned treatments provide a better means to achieve that objective. A second important finding pertains to the social dimension of shared wildfire risk reductions in the WUI. Clearly, respondents do value private wildfire risk reductions but they also indicated a willingness to incur mitigation costs if they provided a reduction in the wildfire risk level facing their neighbors. Together these outcomes state that thinning treatments should be deployed in collaborative settings in order to preserve amenity values and achieve wildfire reduction objectives in the WUI.

D. Expert Elicitation: Suppression Resource Orders for Wildfire Scenarios

Wildfire Scenarios in the Campbell Tract

Wildfire behavior is the key explanatory factor driving suppression costs. The key to reducing costs should be to find ways to contain wildfires faster and more effectively. Because fuel breaks have been shown to modify wildfire behavior (Carey and Schumann 2003), they often are a central point of discussions about how best to reduce suppression costs. Recent work by Naughton and Burnett (2017) suggests that fuels treatments may increase suppression costs overall, conversely it may also be possible that fuel breaks change the perceived threat of the wildfire, and reduce demand for suppression resources.

To address what role fuel treatments play in suppression resource ordering an expert elicitation was conducted at the Alaska Fire Science Consortium spring fire science workshop on March 29th, 2017. As part of this exercise wildfire management officials were tasked with choosing a package of initial attack suppression resources for a set of wildfire scenarios. The hypothetical resource order, paired with fire characteristics, was analyzed to test the effect of fuel breaks in reducing the size of initial resource orders. Specifically, resource orders were paired with wildfire attributes like risk area classification, climate variables, and a fuel break indicator. An ordered logit model was used to predict the probability of larger initial attack resource packages ordering as a function of scenario attributes including weather conditions and the presence of a cleared fuel break on the landscape.

Expert Pool

The elicitation was conducted during the Alaska Fire Science Consortium spring fire science workshop in March 29, 2017. A total of fifty-one fire managers and other professionals completed the exercise. Each participant evaluated two fire events, producing 102 observations. The respondents were relatively experienced in their professional field, with an average of 19 years working in wildfire suppression. The respondents came from a variety of agencies; the count of each is show in Table 9.

Table 9. Experts by Agency

Agency	Count
Bureau of Land Management (BLM)	18
Alaska Division of Forestry (DOF)	7
United States Forest Service (USFS)	4
Other	22

Wildfire Scenarios

The wildfire scenarios presented to the pool of experts were centered on the Campbell Tract, a high risk WUI location outside Anchorage, Alaska. Fire scenarios were built using the IFTDSS and incorporated field data collected from the Campbell Tract fuel treatment location in 2015. All wildfire scenarios presented the expert pool with information about the ignition source, fire behavior and spread for the first operational time period, and information about surrounding geography, including topography and resources at risk (i.e., structures threatened). Modest increases in wind speed were reflected in increased fire severity and rates of spread as predicted by IFTDSS and presented to participants. Scenarios were broken down by the presence of a fuel break on the landscape. Scenario one included a fuel break, while scenario 2 did not. Each scenario was evaluated by experts twice at wind speeds of 10 and 15 mph. Experts were randomly split into two groups and assigned a scenario. They worked individually during the exercise. Examples of the IFTDSS images shown to the respondent are shown in Figure 15.

Figure 15. IFDTSS images of four different fires at discovery. Starting clockwise from the upper left, 10mph fire with no fuel break, 15mph fire with no fuel break, 10mph fire with a fuel break (shown in blue) and a 15mph fire with fuel break (shown in blue).

Suppression Resource Orders

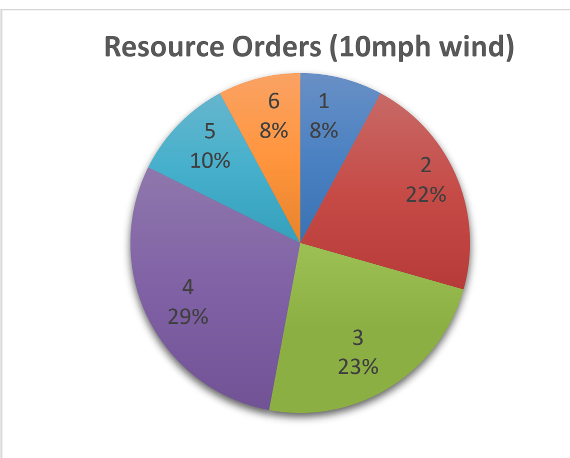
Experts were able to select from one of six discreet initial attack suppression resource packages which ranged from a very light response (a few water drops and a strike team) to a heavier response which included dozens of drops, aerial firing modules, and terra torches. Table 10 describes each resource order option. Our objective was to focus on what resources the expert thought were needed during the first operational period, experts were not shown cost information. While we hesitate to give a specific cost to each package it is sufficient to note that each increase in order size would be associated with a significant expenditure increase. The composition of the resource order packages as well as the scenarios themselves were designed with input from a guided focus group of Alaskan fire managers. Experts accessed and provided their resource orders in real time using a secure online surveying platform. The exercise concluded with a set of questions asking about the need for evacuations, the anticipated level of incident command needed (IC) and anticipated number of structures that could be lost in the scenario.

Table 10. Resource order packages presented to respondents of the expert elicitation survey

Order	Resources
1	10 water drops, 1 engine strike team (task force) and 1 hot shot crew.
2	10 water drops, 1 engine strike team (task force), 1 squad of state protection techs on ATV with drip torches, and 1 hot shot crew.
3	10 water drops, 2 engine strike teams (task forces), 2 hot shot crew, 1 terra torch, 1 bulldozer, and 5 retardant drops
4	10 water drops, 2 engine strike teams (task forces), 2 hot shot crews, 1 squad of state protection techs on ATV with drip torches, 10 retardant drops, 1 bulldozer and 1 helitack crew
5	20 water drops, 3 engine strike teams (task forces), 3 hot shot crews, 10 retardant drops, 2 bulldozer, 2 helitack crews, 2 type-1 structure protection engines, 1 terra torch
6	20 water drops, 4 engine strike teams (task forces), 4 hot shot crews, 10 retardant drops, 3 bulldozer, 3 helitack crews, and 4 Type-1 structure protection engines, 1 terra torch, 1 squad of state protection techs on ATV with drip torches, and an aerial firing module.

Outcomes of the Exercise

The average order size for all scenario 1 fires (regardless of fuel break presence) was 3.81. Differences in scenario winds and fire increase the average resource order. Under scenario 2 the average resource order increased to 4.27 (from 3.35) The distribution of resource orders placed by the respondents are shown in Figure 16, using the levels defined in Table 10, where 1 is the smallest resource order and 6 is the largest.



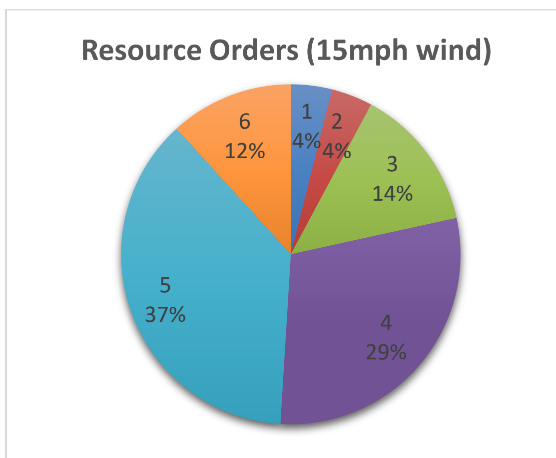


Figure 16. Distribution of resource orders by wind speed

For scenario 1 average resource order is lower in the presence of the fuel break (Table **11**). With 15 mph the magnitude of difference in mean resource order when a fuel break is present, declines. Across both wind levels the average order size for fires with a fuel break was 3.67 and 3.93 when there was no fuel break.

Table 11. Average resource order size for various choice experiment combinations

	10MPH Wind	**15MPH Wind**	**10MPH AND 15MPH**
Fuel Break (Scenario 1)	3.13	4.22	3.67
No Fuel Break (Scenario 2)	3.54	4.32	3.93
All Respondents	3.35	4.27	3.81

The exercise also included a question which asked if the fuel break affected participant resource ordering. Those that did not have a fuel break in their scenario were asked if a fuel break *would have* changed their resource order. In the aggregate, 52.9% of respondents reported that the fuel break did (or would) affect their resource ordering. The responses varied with the severity of the fire conditions. For scenario 1 (low severity), 62.7% of fire managers indicated that the fuel break did (would) affect their resource ordering. But for scenario 2 (high severity) only 43.1% of respondents indicated that the fuel break did (would) affect their order. These outcomes are consistent with the situational effectiveness of fuel breaks in terms of their effectiveness in reducing wildfire spread and resource ordering. It should be expected that fire managers on the ground would understand this and adjust resource orders accordingly.

The survey also asked the respondent if they believed structures would be lost in the fire and which incident command type was needed. A breakdown of responses to key variables is presented in Table 12.

Table 12. Proportion of response to survey questions by group

	Fuel Break 10MPH	Fuel Break 15MPH	No Fuel Break 10MPH	No Fuel Break 15MPH	All Groups
IC Level					
Type 1	8.7%	8.7%	10.7%	17.9%	49.0%
Type 2	26.1%	43.5%	28.6%	32.1%	32.4%
Type 3	56.5%	39.1%	50.0%	50.0%	11.8%
Type 4	8.7%	8.7%	10.7%	0.0%	6.9%
Structures Lost					
None	65.2%	39.1%	60.7%	39.3%	51.0%
1-25	34.8%	56.5%	32.1%	46.4%	42.2%
26-100	0.0%	4.3%	7.1%	7.1%	4.9%
>100	0.0%	0.0%	0.0%	7.1%	2.0%
Fuel Break Binary					
Yes, Affected Order	52.2%	30.4%	71.4%	53.6%	52.9%
No, Did Not Affect	47.8%	69.6%	28.6%	46.4%	47.1%
Resource Order Size					
1	13.0%	0.0%	3.6%	7.1%	5.9%
2	26.1%	4.3%	17.9%	3.6%	12.7%
3	17.4%	21.7%	28.6%	7.1%	18.6%
4	26.1%	30.4%	32.1%	28.6%	29.4%
5	13.0%	34.8%	7.1%	39.3%	23.5%
6	4.3%	8.7%	10.7%	14.3%	9.8%

To control for extraneous variables we modeled the likelihood of each resource order as a function of the wildfire scenario attributes. An ordered logit model was used to estimate the marginal likelihood of the set of resource packages condition upon scenario (Appendix A- 25).

Expert perceptions of the threat presented to structures as well as the expected IC level required are both significant at the 5% level. Estimates of scenario specific effects are interpreted relative to the baseline scenario 1 with winds of 10 mph and a fuel break was present and winds of 10 mph. The coefficients are compared to a baseline group where the fuel break is present with low severity weather conditions (10 mph winds). The results indicate that increasing the severity of weather conditions and removal of the fuel break both increase the likelihood of a larger resource order. The hypothetical effect of the fuel break (post-scenario question to respondents) was also significant in the model.

Estimated marginal effects (Appendix A- 26) of resource orders have been plotted in Figure 17. The estimated marginal effect measures the change in observing a step wise change in the resource order relative to the baseline where there is a fuel break and 10 mph wind. When compared to the baseline, all other scenarios have a decreased likelihood of observing a resource order at levels 1, 2 or 3. Conversely, the likelihood of selecting a level 4, 5 or 6 resource order increases in comparison to the baseline scenario.

In general, scenario specific conditions drive the shape of the probabilistic order function. At winds of 15 mph there is a 12.4% likelihood of observing a one-step increase, from four to five, in resource order when a fuel break was present. In the absence of a fuel break the same step increase is predicted to have a 15.1% chance of occurring.

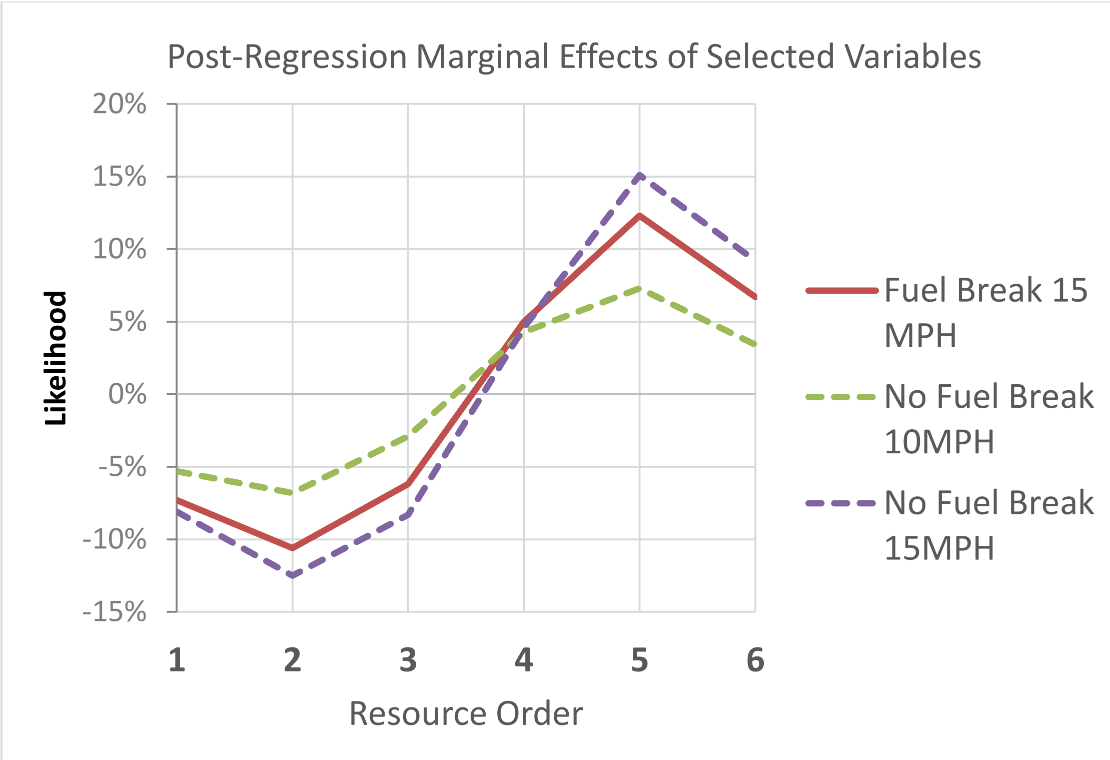


Figure 17. Plot of marginal effects for select variables over resource order size

Appendix A- 26 contains the post-regression estimated distribution of resource orders for each group and the values are plotted in Figure 18. The baseline group "Fuel Break 10MPH Winds" exhibits a positively skewed distribution, with 54% of resource orders equal to or less than 3. Each of the other three groups exhibit a negative skew, with a majority of resource orders equal to or greater than 4. We plot the actual distribution of resource orders in Figure 19.

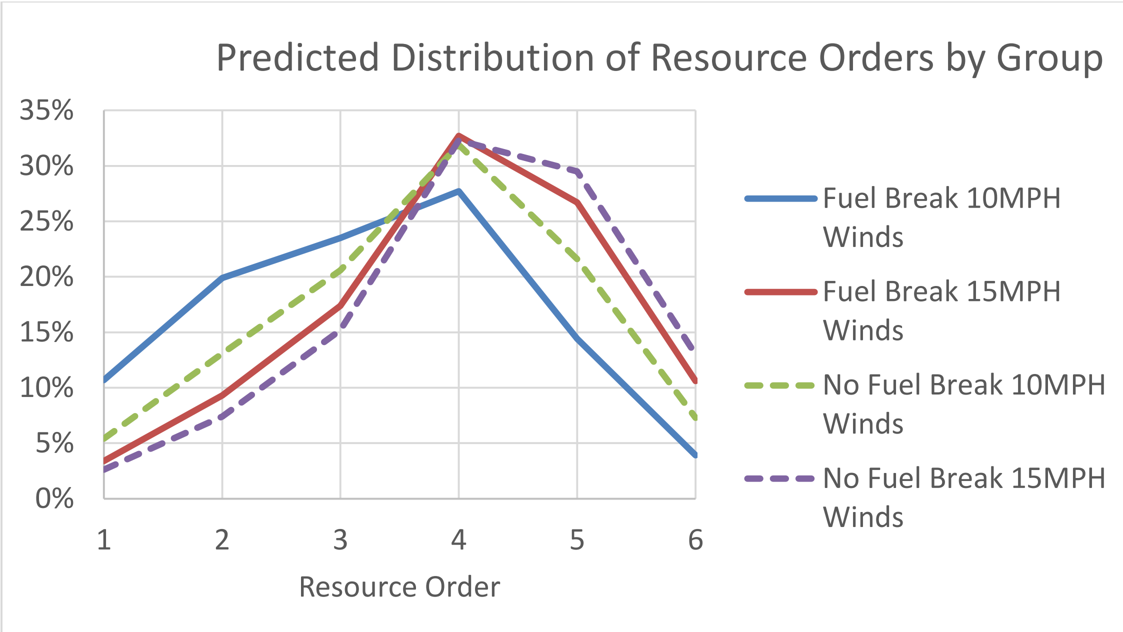


Figure 18. Post-regression probability density function of resource orders by scenario

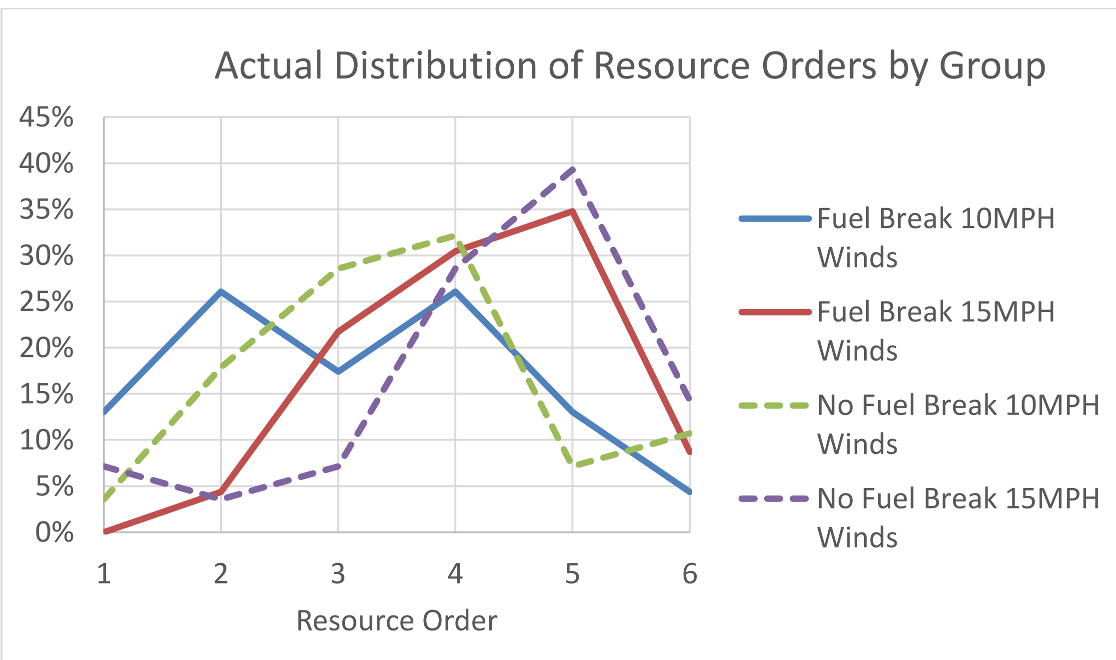


Figure 19. Actual distribution of resource orders by group

The actual and modeled probability density functions (PDF) share some similarities. We observe larger resource orders with 15 mph winds regardless of the presence of a fuel break. If the study was repeated with a much larger sample size, we expect the actual distributions to become smoother and converge with the post-regression model. Generally, we infer that fire managers place smaller resource orders when weather conditions are mild and that the presence of the fuel break had a modest effect in the experiment.

Discussion

The exercise produced interesting results, but further investigation is warranted. Feedback was provided at the workshop via survey comments and informal communication. Several respondents noted that the attributes of the fuel break itself were important in determining its viability. Orientation of the fuel break and road access are both significant factors in the resource order decision. Wildfires are inherently unique, and their behavior changes spontaneously. It is difficult to draw conclusions based on a small set of hypothetical wildfire scenarios. However, the initial findings are consistent with the argument that fuel treatments are leveraged within the context of existing conditions.

Future efforts should be directed towards examining different WUI locations, with different orientations and attributes for the fuel break. Additional research should isolate and compare the effect of fuel breaks and fire conditions on resource ordering. Answers to these questions would inform state agencies on the best methods for pre-suppression fuel treatments.

E. Fire Suppression Cost Analysis

Introduction

Wildland fire has been steadily increasing in frequency and severity for decades (Kasischke & Turetsky 2006). While large fire years are often episodic, climate variables seem to be driving this increase in frequency and scale (Brown *et al*. 2004, Flannigan *et al*. 2009).). Alaska is in a unique position to deal with these climate dynamics, due to its large land area and low population density. While large fires are often left to burn under supervision, any increase in frequency, severity, or proximity to population centers can sharply increase the need for suppression resources. Projections of wildfire costs in Alaska over the next century lie between one and two billion dollars, with an annual average of approximately 60 million per year (Melvin *et al*. 2017). This not only presents a budgetary problem for the state, but a policy issue as well. Since sound policy should be born from quality scientific research, a thorough understanding of the costs of Alaskan wildfire and what drives them will be needed for the coming years. Economic cost modeling will be crucial to examine the variability of expenditures used to suppress Alaskan wildland fires.

Fuel treatments are a complex and divisive topic for wildfire suppression researchers and practitioners. The effectiveness and uses of fuel treatments have been examined extensively in the literature (Reinhardt *et al*. 2009, Amiro *et al*. 2001, Agee *et al*. 2000). Some research suggests that the application of fuel treatments can help mitigate wildland fire costs (Wei *et al*. 2008, Stephens *et al*. 2012), while other research suggests the link between them is weak (Carey and Schumann 2003). Reinhardt *et al*. (2008) further notes that there is significant complexity when analyzing the effectiveness of fuel treatments. As a case study, the fuel treatments associated with the Funny River fire in the Kenai National Wildlife Refuge in 2014 were shown to significantly reduce the spread and, potentially, costs of the fire. However, the cost effectiveness of fuel treatments across the unique Alaskan landscape should be analyzed in the aggregate so that the predicted increase in wildfire frequency and severity can be most effectively mitigated. If certain fuel treatments in certain locations reduce suppression expenditures, then those treatments should be prioritized over less effective resource usage.

From an econometric perspective, wildland fire costs have been examined with many different models (Lankoande & Yoder 2006). If we attempt to find covariates that are directly correlated to our response variable (cost), we must ensure that these predictive covariates are independent from each other, as well as the response variable. Wildfire costs are often modeled with total burn area as an explanatory variable. This presents an issue, since the wildfire area burned is directly correlated to how many suppression resources are ordered (cost).

State of Alaska Wildfire Suppression Cost Data

The data for this analysis was obtained from three sources; The Alaska Interagency Coordination Center (AICC) for the general wildfire information, the Alaska Department of Natural Resources provided suppression cost information for the State of Alaska, and FAM-WEB (Fire and Aviation Management Website) from the USDA Forest Service for the incident reports on individual fires (ICS-209 reports). Other data sources include the United States Geological Survey, the Kenai Peninsula Borough, the Fairbanks North Star Borough, the Western Regional Climate Center, and the National Oceanic and Atmospheric Administration. Much of the data was collected in the spatial database stored by the AICC.

Spatial data was compiled with shape files from different agencies, as well as input by hand using coordinate projections. Using spatial coordinates provided in the fire data, centroids were plotted for each wildfire. These points were then analyzed to apply variable values from other data sources. For example, interactions and distances to fuel treatments were calculated in ArcMap by measuring the distance from fire centroids to the nearest fuel treatment. This process was also used with the climate data (precipitation, temperature, RH) and native allotment data. Raster data was also used to determine the approximate elevation at each wildfire. An elevation raster was drawn, and elevation data was extracted at each fire centroid. The same process was used to estimate values for slope, aspect, and fuel type.

The data set used for this analysis includes 266 wildland fires of greater than 50 acres across eight years (2007-2015) for which the State of Alaska staffed and incurred suppression costs (Appendix A- 29). We do not include AFS costs in this assessment. To date little work has been done on the impact of fuel treatments on state level suppression costs. Additionally, pre-negotiated agreements between the State of Alaska and Federal government ensure for compensatory cross payments when their resources are used. After matching fire locations against fuel treatment we could only identify 14 state fires that were within 5 km of a fuel treatment.

Years 2010 and 2015 (Appendix A- 28) had the largest total state expenditures for wildfires ($23,945,877 and $35,566,768 respectively). These years also had large areas burned on State of Alaska owned lands. For fires in our data set, 2010 saw 745,855 acres burned and 886,697 in 2015. The only year that had more acreage burned in this time frame was in 2009, where over a million acres were burned (1,124,584). The probabilistic nature of wildfire, along with changing climatic variables can create very different fire conditions from year to year which introduces significant variability into a relatively small data set.

As an example, 2015 had total expenditures almost 38 times than of 2008. Figure 20 shows how the inflation adjusted[10] total costs change over time. While Figure 21 illustrates the inflation adjusted average cost per fire. However, we caution making inference about any upward trends because of the limited time frame over which the data are observed.

10 The National Consumer Price Index (CPI) for all goods for all urban consumers was used to calculate inflationary changes, using 2015 as the base year

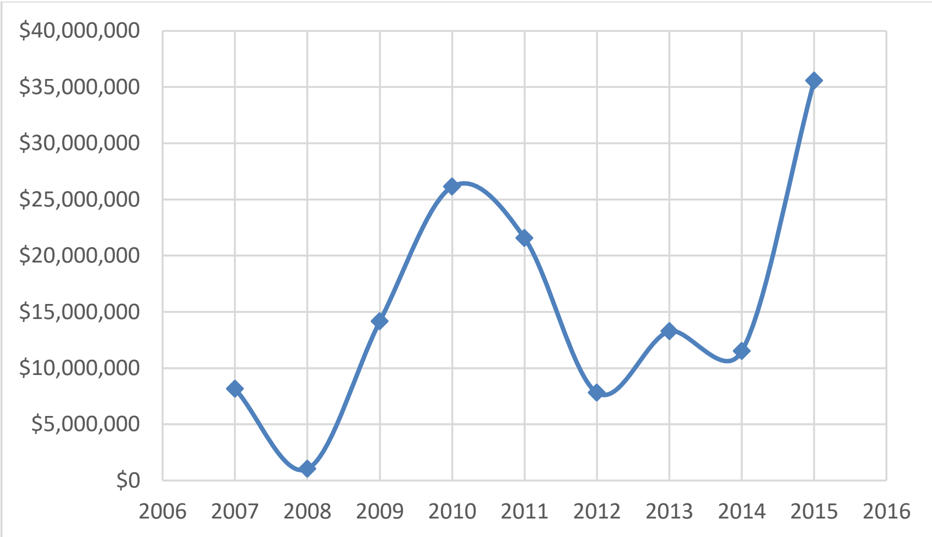


Figure 20. Inflation adjusted total suppression costs for the State of Alaska from 2007-2015

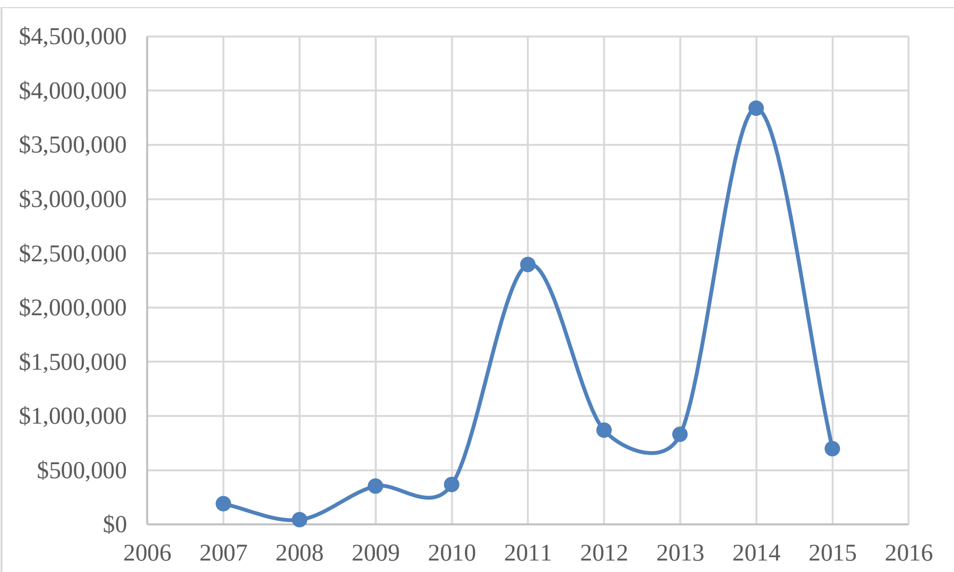


Figure 21. Average suppression cost per wildfire for the State of Alaska from 2007-2015

Appendix A- 33 and Appendix A- 34 show descriptive statistics for the wildfire data in the other factor categories. The largest fire in terms of acreage was the Minto Flats fire in 2009, at over half a million acres. The most destructive in terms of structures threatened and burned was the Caribou hills fire in 2007. Other climate and topographical variable statistics are also provided.

Results

Results from the cross-sectional regression can be seen in Appendix A- 30. Statistically significant variables are indicated at the 10%, 5% and 1% levels. Precipitation, management zone, elevation, tundra fuel types, and five distinct year-binary variables were found to be statistically significant. Since it is a log-log model, the interpretation of the coefficients should be percentage based. This will be true with the exception of binary variables, where the log-level interpretation of the coefficients (multiplying by 100) is necessary. The p-value for the f-test is less than 0.0001 which indicates a model fit. The adjusted R^2 suggests that 28.4% of the variance in *lncostperacre* is explained by our suite of explanatory variables. Standard statistical diagnostic tests were used to test for non-constant variance as well as omitted variable bias (Appendix A- 29). Likewise, variance inflation factors (VIF) (Appendix A- 30) were examined to address serial correlation in our variables. No statistically significant relationship between the fuel treatment variable and cost per acre was identified. This finding does not speak to the effectiveness of fuel treatments in terms of reducing fire behavior but simply suggests that costs per acre are not sensitive to the presence of a treatment. The finding is most likely attributable to the small number of fires occurring near existing fuel treatment locations.

Discussion

Large wildfires burning in Alaska have a wide variety of characteristics, each affecting the suppression costs associated with them. While over 200 Alaskan wildfires were analyzed, only a small fraction had a chance to have any interaction with fuel treatments. At this time no statistically significant relationship between fuel treatments and average wildfire suppression costs per acre could be identified. While this should not suggest the complete ineffectiveness of fuel treatments, it does suggest that suppression costs per acre do not appear to be influenced by the group of treatments. Other factors were found to reduce costs per acre, but they were landscape based (elevation) and do not provide a mechanism to extract these savings. Future research in this area will have to revolve around updating cost data to include more wildfires that interact with fuel treatments. Additionally, it would be worthwhile to examine whether fuel treatments reduce the average duration or likelihood of property damage during wildfire events.

V. Management Implications and Recommendations

A. Fuel Treatment Life Cycle

Preliminary post-treatment monitoring of shaded fuel breaks in Alaska had previously indicated that unintended effects of canopy removal in boreal spruce/feathermoss fuels might include drying of duff layers, an increase in active layer depth, and influencing weather micro-climate toward decreased mean relative humidity and higher mean wind speed (Ott and Jandt 2005, Horschel 2007). These effects might contribute to a reduction in fuelbreak effectiveness by reducing duff fuel moistures, making formerly frozen duff layers available for combustion, and by artificially inducing localized weather conditions that contribute to increased fire behavior.

Fuel moistures were not measured as part of this study, but changes in substrate cover, active layer depths, and species composition all point to how thinning can potentially alter moisture content of surface fuels (moss and duff layers) and therefore alter predicted fire behavior. Hrobak (2004) found duff moisture contents from thinned fuel treatment sites in Delta, Tanacross, and Toghotthele land located in Interior Alaska was significantly drier than control plots. Thinning can alter moisture dynamics in ways that are not consistently illustrated by the current fire prediction models and could critically impact management decisions.

Figure 22. Measuring duff moisture in deep forest floor organic layers in a shaded fuelbreak.

The active layer, which is the layer of soil over permafrost that seasonally thaws, is very sensitive to the current year's summer temperatures and to the insulation effect of winter snowpack. Relative increases in active layer depth, as well as variations in active layer depths, were greater in the fuel reduction treatment blocks than in the control blocks. Average active layer depth and variation increased as the level of fuel reduction (i.e. tree thinning and slash removal) increased. Differences in active layer thickness were still detectable as long as 14 years post-treatment and these differences were profound in cleared and surface-disturbed treatments (although less profound that the comparable effects of burning). Since the moss/duff layers insulate permafrost, this is an important consideration due to the potential of destabilizing infrastructure associated with the fuel breaks. Permafrost across much of Alaska is warming rapidly and, in fact, has recently disappeared from much of the south portion of our study area (Jones *et al.* 2016) leading to profound changes in water storage, drainage and availability to trees (Berg *et al*. 2009).

We also wondered if treatments in boreal black spruce would induce surface layer species composition changes due to moss die-off without exposure of mineral soil, and to destabilization of soils and melting of frozen layers. This study found that thinning treatments in spruce/feathermoss forest initially killed feathermosses—possibly due to increased exposure and drying of the forest floor-but the effect was transient, with the moss layer mostly recovered after 14 years. Initial monitoring identified measurable microclimate differences in thinned vs. control stands during the first few years (Horschel 2007). In southern Alaska fuel treatments, we wondered whether canopy-removal treatments would lead to establishment of flammable grasses or encourage hardwood regeneration. The wide variation in cover changes among sites in shaded fuelbreaks (Tables A-8, A-9, A-10) suggests that localized environmental conditions such as climate may have influenced understory plant dynamics more than generalized treatment effects from tree thinning and slash removal. Treatment effects were more pronounced where there were localized surface disturbances like pile burning. Although mechanical treatments that disturb the organic duff layer might be expected to induce hardwood regeneration, they must be present in the stands pre-treatment for robust colonization post-treatment, as shown by Mercer in his dissertation on birch (2007).

There is also a question as to the level of thinning necessary to achieve goals in Alaskan fuels and how vegetation succession over time since treatment may affect fire risk. Post-treatment tree densities in 11 of 12 demonstration treatment blocks, and at Tanacross, exceeded thinning targets. For this reason, we recommend that tree thinning crews be given conservative tree spacing guidelines to reduce effects like thinning shock, moss die-off, and wind throw. Original treatment specifications were largely based on pre-commercial thinning in more temperate forests. In shallow-rooted stands, and in areas subject to high winds, the potential for wind damage should not be underestimated (since it would also contribute to an increased downed woody fuel load) and it may be wise to consider leaving clumps of trees rather than an evenly spaced opened stand. This approach is now being employed for lodgepole pine stands in the western US for similar reasons, and because it leaves a more natural pattern of forest structure.

B. Fire Behavior Trade-offs

Fuels treatments are not specifically designed to stop the forward advance of a wildfire except in the case where all the canopy and surface fuels are removed such as in firebreaks. Most fuels treatments in Alaska have been installed as firebreaks (strips of bare soil meant to stop or control a fire) or fuels breaks (strips or blocks of vegetation that have been altered to lower fire behavior) around communities (Ott and Jandt 2005). The fuel breaks we investigated in this study are essentially methods for manipulating live and dead vegetation with the intent of reducing the negative consequences of an area burning during a wildfire (Agee and Skinner 2005, Reinhardt *et al*. 2008). Theoretically, fuels treatments that reduce fuel loadings or change fuel characteristics can result in changes in fire behavior such as causing the fire to drop down out of the canopy and burn the landscape as a surface fire (Reinhardt *et al*. 2008). Burning as a lower intensity surface fire may actually result in restoring the ecological benefits of fire to many ecosystems or allow direct attack fire suppression strategies to be used by fire fighters.

Empirical evidence that shaded fuelbreaks can effectively mitigate fire behavior in boreal spruce forest is limited but recent case studies identify successes in the tactical use of fuel breaks during wildfire incidents (Saperstein *et al*. 2015, Perrine 2016, Lojewski 2016) and some of their benefits are related to considerations not easily measured or modeled. For example, in late May 2010, the Eagle Trail fire threatened the eastern Alaska hamlet of Tanacross. Although the Tanacross shaded fuel break was not directly impacted by the head fire, it played a key role in operational decisions and resource allocations (DeFries et al. 2010). By using the opened canopy of the fuelbreak, fire fighters were able to function efficiently. Observers suggested that the fuel break also altered the community's perception of risk, allowing them to react calmly in a potentially stressful and dangerous situation. At the same time, it is important to note how radically the environment around a community can be changed by treatments (see life cycle discussion above) and how the entire ecology should be considered in treatment design.

Our fire behavior modeling effort provides convincing evidence that the fuels treatments do reduce fire behavior potentials especially under a range of weather conditions and lower wind speeds The benefits decrease, sometimes exponentially, at wind speeds greater than 20-mph. However, none of the fuel breaks studied would stop an advancing wildfire on its own. In fact, the more the area is cleared or affected by post-treatment disturbance such as wind throw the more likely the rates of spread will be increased due to increased drying of the surface fuels, conversion of forest to shrub and grass fuel types, and increased wind speeds at the surface when the canopy is removed. Our Tanacross site (Figure 12) illustrates this potential as the site was initially thinned to 12 x 12 spacing then experienced a wind event which toppled additional trees. The additional trees on the ground and the subsequent recovery of shrubs and hardwood regeneration switched the fuel model from a timber understory fuel model TU1 to a grass-shrub fuel model GS3 with the associated increased modeled flame lengths and rates of spread (Figure 13).

Our modeling results strengthen the point that fuels treatments meant to reduce fire hazard, particularly around communities, should not be expected to stop a fire without human intervention. Rather they should be planned and installed within a cohesive fire suppression plan or community wildfire protection plan that specifies how the treated area will be used strategically to support fire suppression tactics. Plans for how the treatments will be entered and what strategies such as burning out or further removal of vegetation with heavy equipment before the advancing wildfire will be used should be in place before the fuels are treated.

Unintended effects of canopy removal Alaskan forests should also be considered. Removing canopy trees does change the ecology of the treated landscape visually and ecologically. Unintended consequences of fuels treatments such as thawing of the permafrost layer, encouraging the growth of shrubs and grasses, and creating conditions conducive to increased canopy disturbance by winds and insects should be considered. Shaded fuels treatments should be planned and maintained to retain as much canopy cover as possible to shade the surface fuels, decrease in stand wind speeds as much as possible, and lower the potential growth of shrubs and grasses within treated areas. Our results indicated that a maximum of 8 x 8 spacing with pruning from below in interior Alaskan black spruce forests could lower the potential negative ecological effects of fuels treatments while retaining the positive benefits of lowering canopy fire potential and increasing the ability for fire fighters to enter the stand and conduct fire suppression actions. In our study most shaded fuel breaks in white spruce/hardwood stands were thinned to 12 by 12 spacing. However, these fuel breaks appear to make the stand more susceptible to blowdown which reduces the overall effectiveness of the treatment. Retaining more canopy trees on site may decrease blowdown potentials. We suggest that canopy trees by thinned to a maximum of 10 by 10 spacing when installing fuel breaks in white/spruce hardwoods. This will retain more of the canopy structure will maintaining access to the stand by fire suppression forces.

C. Fuel treatment Maintenance Schedule Recommendations

We recommend that existing fuels treatments be maintained on a 10 to 15 year schedule, however slow growing interior black spruce stands may warrant longer maintenance intervals. Our modeling results indicate that fuels treatments still retain benefits for reducing wildfire potential as much as 14 years post-treatment. However, over time the recovery of treated mosses and shrubs potentially decreases these benefits for reducing fire hazard, especially when the canopy is completely removed. Maintaining fuel breaks on a 10 to 15 year schedule will retain the fire hazard reduction benefits and reduce re-entry costs as removing the shrubs and tree seedlings when they are still relatively small will require less resources, have a lower ecological impact especially if done with hand tools, and likely cause less ecological harm.

Treatments should be planned and maintained within a comprehensive plan that outlines how the treated areas will be used by fire suppression forces when the area is threatened by advancing wildfire and how often those treatments need to be maintained. Planning and practicing how the treated area will be used beforehand will eliminate confusion and greatly increase the effectiveness of the fuels treatment as shown in the Funny River and Tanacross examples. Maintaining the treatments on a regular schedule will ensure that the treatments retain the conditions necessary for success.

VIII. Deliverables

A. Data Tables and Inputs into Findings Database (available from www.firescience.gov)
B. Digital Photo Library (Photos available at https://www.frames.gov/partner-sites/afsc/projects/)
C. Completed Deliverables (available on CD and entered into citation database at www.firescience.gov)
D. Forest Treatments to Reduce Fire Hazard in Alaska: A compilation of case studies (Available at https://www.frames.gov/partner-sites/afsc/projects/): this product, in preparation, will present all of this project's study areas as case studies with photos and the individualized results.

Final Project Report (JFSP Project Number: 14-5-01-27).

E. List of Deliverables

1) Research Project JFS Project 14-5-01-27 website: Duration and cost effectiveness of fuel treatments in the Alaska boreal region

2) Knowledge Transfer

Fuel Treatment Effectiveness: JFSP Workshop for Current Research, Preliminary Results and Implications 2016. "Duration and Cost Effectiveness of Fuel Treatments in the Alaska Boreal Region: Assessing the Continued Longevity and Duration of Existing Projects."

Alaska Fire Science Consortium Fire Science Workshop 2017 "Fuel Treatment Effectiveness and Suppression Cost Update and Exercise."

3) Professional Presentations

Society of American Foresters (Alaska Chapter) Annual Meeting 2016 "Duration and Cost Effectiveness of Fuel Treatments in the Alaska Boreal Region: Assessing the Continued Longevity and Duration of Existing Projects."

Alaska Interagency Fall Fire Review 2017 "Examining Homeowner Preferences for Fuel Treatments."

Fire Continuum Conference 2018 "Fire on the Frontier: Understanding Alaskan Homeowner Wildfire Risk Mitigation Preferences."

4) Graduate Education:

Allen Molina, PhD Candidate, University of Alaska Fairbanks, Natural Resources and Sustainability program.

Brock Lane, University of Alaska Fairbanks MS Resource and Applied Economics

5) Publications in print or preparation :

Drury, S.A., (2018) Fire behavior model assessments – A case study at the Magitchlie Creek Fire Alaska. (*In Preparation)*

Drury, S.A., Jandt, R., and Little, JM (2018) Fuel treatment longevity in Alaska: A modeling approach. *(In Preparation)*

Molina, A. C., Little, J. M., Drury, S. A., Jandt, R., and Lane, B. (2018). Homeowner Preferences of Wildfire Risk Mitigation in the Alaskan Wildland Urban Interface. *(In Preparation)*

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Appendices

Appendix A- 1. Average overstory cover changes over time in JFS demonstration sites (DBH, TOG, FWW).

Treatment	Time period	Overstory Cover %	Change Cover*
8X8	Pre-Treatment	53.3	
	0 Yr. Post-Treatment	20.0	-23.3
	2 Yr. Post-Treatment	18.7	-1.3
	14 yrs Post-Treatment	23.1	+4.3
8X8P	Pre-Treatment	42.0	
	0 Yr. Post-Treatment	24.0	-18
	2 Yr. Post-Treatment	20.7	-3.3
	14 yrs Post-Treatment	24.7	+4
10X10	Pre-Treatment	51.3	
	0 Yr. Post-Treatment	12.0	-39.3
	2 Yr. Post-Treatment	12.0	-
	14 yrs Post-Treatment	17.2	+5.2
10X10P	Pre-Treatment	40.0	
	0 Yr. Post-Treatment	20.7	-19.3
	2 Yr. Post-Treatment	18.0	-2.7
	14 yrs Post-Treatment	24.7	+6.7
Control	Pre-Treatment	46.0	
	2 Yrs	47.3	+1.3
	14 yrs	46.7	-0.6

*****Change from one observation period to the next.

Appendix A- 2. Canopy and stocking rate measures used for fuel loading calculations.

TREE MEASURES: **All treatments :**	**DBH (in.) PIGL**	**PIMA**	**POTR**	**BEPA**	**Tree Ht. Avg (m)**	**Crown Radius Avg (m)**	**Crown Base Ht. (m)**	**Crown Mass[1] (kg)**	**2015 Stems/ acre**	**Pre-Rx Stems/ acre**	**2015 Can Fuel* (T/ac)**	**Pre-Rx Can Fuel* (T/ac)**	**CBD* kg/m^3**	**plot area (m^2)**
NORTH BEAN														
Fuel treatment	4.4	4.0		1.5	6.7	1.1	1.1							300
CAMPBELL TRACT	**7.5**	**2.9**		**8.0**	**11.2**	**2.2**	**3.6**							
Fuel Break		2.9			4.1	0.8	0.8							240
Thinned treatment	7.5			8.0	13.0	2.6	4.3							300
DELTA BISON R		**3.4**			**6.9**	**0.5**	**1.6**	DBR						
10x10 non-pruned		3.5			6.7	0.6	1.1	15.5	573.3	7520.7	4.1	53.8	0.163	120
10x10 pruned		3.8			7.3	0.5	1.8	18.2	539.6	7385.8	4.5	62.1	0.183	120
8x8 non-pruned		3.4			7.0	0.6	1.5	15.2	505.9	7588.1	3.6	53.5	0.145	120
8x8 pruned		3.5			7.2	0.6	2.2	15.9	640.8	6003.1	4.7	44.2	0.209	120
Control		2.7			6.4	0.4	1.6	9.9	3541.1	3541.1	16.2	16.2	0.756	120
DOT LAKE	**8.0**		**7.5**		**14.2**	**1.7**	**8.6**							
12x12	8.0		7.5		14.2	1.7	8.6							150
Untreated	9.0		5.2		10.3	1.7	4.3							30
FUNNY RIVER	**5.5**	**2.0**		**11.3**	**13.7**	**1.3**	**3.8**							
Burned area	6.3			11.6	13.8	0.6	4.6							240
Thinned treatment	4.7	2.0		11.2	13.6	1.9	3.2							360
FT. WAINWRIGHT	**3.7**	**2.6**		**6.9**	**5.6**	**0.6**	**0.8**	FWW						
10x10 non-pruned	3.0	2.4			5.4	0.5	0.2	9.4	640.8	2698.0	2.8	11.8	0.122	120
10x10 pruned	4.7	2.5		6.9	6.1	0.7	1.3	13.0	269.8	2832.9	1.6	17.1	0.075	120
8x8 non-pruned		2.7			5.4	0.6	0.1	9.7	607.1	2967.8	2.7	13.3	0.114	120
8x8 pruned	3.0	2.0			4.4	0.5	1.0	6.9	944.3	3338.8	3.0	10.6	0.199	120
Control		1.5			3.8	0.3	0.1	3.8	3035.3	3035.3	5.3	5.3	0.313	120
HOPE GATE														
Thinned treatment				6.4	18.8	2.2	13.1							300
NENANA RIDGE		**2.9**		**6.8**	**6.5**	**0.5**	**1.5**	NR						

8x8 thin (B4)		2.9	6.8	7.2	0.5	1.4	12.4	620.5	4397.7	3.6	25.2	0.139	150
8x8 thin (B3)		3.0		6.3	0.5	1.5	12.2	998.3	2563.1	5.6	14.4	0.263	150
Control		1.9		4.3	0.4	2.1	5.4	3372.5	3372.5	8.4	8.4	0.887	30
TOGHOTTHELE		**3.5**		**7.4**	**0.6**	**1.6**	TOG						
10x10 non-pruned		3.7		7.4	0.7	2.0	17.2	371.0	1686.3	3.0	13.4	0.124	120
10x10 pruned		4.3		8.6	0.7	1.8	22.4	708.2	2023.5	7.3	21.0	0.243	120
8x8 non-pruned		3.5		7.0	0.8	1.3	15.8	640.8	2360.8	4.7	17.3	0.185	120
8x8 pruned		3.8		7.9	0.7	2.2	18.3	674.5	1753.7	5.7	14.9	0.226	120
Control		2.3		5.6	0.5	0.8	7.7	1618.8	1618.8	5.7	5.7	0.268	120
TANACROSS	**8.3**			**14.8**	**1.3**	**1.6**							
Thinned treatment	8.3			14.8	1.3	1.6							150
Untreated	4.8			10.6	0.6	0.9							30

**Combustible fraction of canopy--foliage & twigs < 1/4"; 42.1/46.8% of total crown mass for upland/lowland black spruce (Barney 1978).*

[1]TOT Crown Mass = 358.352*dbh+158.166*dbh^2, for black spruce (Yarie 2007)

Appendix A- 3. Canopy cover by species, 2015, all treatment blocks.

SITE	Points (n)	% Open	% Canopy	% BEPA	% PIMA	% PIGL	% SALIX	% TSME	% POTR	% POBA	% LALA
BC											
Fuel Treatment	300	84.3	15.7	3.3	3.3	6.3	1.0	1.7			
CT											
Fuelbreak	240	95.8	4.2	4.2							
Shaded FT	300	52.3	47.7	44.0		3.0	0.7				
DBR											
10x10	120	78.3	21.7		21.7						
10x10P	120	78.3	21.7		21.7						
8x8	120	81.7	18.3		18.3						
8x8P	120	75.8	24.2		24.2						
Control	120	35.8	64.2		62.5		1.7				
DL											
12x12	150	52.7	47.3	0.7		7.3			39.3		
Control	30	46.7	53.3			20.0			33.3		
FR											
Shaded	360	73.3	26.7	14.2		9.2				3.1	
Burned	240	91.3	8.8	2.1		5.8				0.8	
Masticated	300	100.0	0.0								
FWW											
10x10	120	90.0	10.0	0.8	8.3	0.8					
10x10P	120	78.3	21.7	2.5	10.8	3.3	5.0				
8x8	120	78.3	21.7		19.2		2.5				
8x8P	120	80.8	19.2		16.7	2.5					
Control	120	69.2	30.8		29.2	0.8	0.8				
HG											
Fuel Treatment	300	37.7	62.3	61.7				0.7			
NR											
Shearblade	300	100.0	0.0								
B3 (8x8P)	150	87.3	12.7		12.7						
B4 (8x8P)	150	67.3	32.7	2.00	30.0						0.7
Control	30	50.0	50.0		50.0						
TOG											
10x10	120	80.0	20.0		20.0						
10x10P	120	69.2	30.8		30.8						
8x8	120	70.8	29.2	0.83	28.3						
8x8P	120	69.2	30.8		30.8						
Control	120	55.0	45.0		45.0						
TX											
14x14	150	94.0	6.0			4.0			2.0		

Untreated	30	56.7	43.3	43.3

Appendix A- 4. Average seedling-small tree (<4.5’) density (per acre) at JFS demonstation sites (FWW, DBR & TOG).

		Picea mariana		*Picea glauca*		*Larix laricina*		*Betula papyrifera*	
Treatment	**Time period**	**Live**	**Dead**	**Live**	**Dead**	**Live**	**Dead**	**Live**	**Dead**
8X8	Pre-Treatment	4900	633	0	0	0	0	183	0
	0 Yr. Post-Treatment	3717	183	0	0	0	0	0	0
	2 Yr. Post-Treatment	2567	667	0	0	0	0	750	17
	14 Yr. Post-Treatment*	2111							
8X8P	Pre-Treatment	6400	250	0	0	17	0	0	0
	0 Yr. Post-Treatment	5017	33	17	0	0	0	0	0
	2 Yr. Post-Treatment	4117	767	0	0	0	0	0	0
	14 Yr. Post-Treatment*	5621							
10X10	Pre-Treatment	7050	567	0	0	0	0	0	0
	0 Yr. Post-Treatment	4000	233	0	0	0	0	0	0
	2 Yr. Post-Treatment	4222	617	0	0	17	0	0	0
	14 Yr. Post-Treatment*	3716							
10X10P	Pre-Treatment	5350	300	0	0	0	0	0	0
	0 Yr. Post-Treatment	3733	117	0	0	0	0	0	0
	2 Yr. Post-Treatment	2933	483	17	0	0	0	0	0
	14 Yr. Post-Treatment*	1942							
Control	Pre-Treatment	7600	467	0	0	0	0	0	0
	0 Yr. Post-Treatment	7600	467	0	0	0	0	0	0
	2 Yr. Post-Treatment	8617	617	0	0	0	0	0	0
	14 Yr. Post-Treatment	(10,118)							

*combined species: correction factor (0.751) applied *assuming control unchanged*, because 2015 counts included trees < 1” dbh at 4.5’ in these tallies.

Appendix A- 5 (a). Life-cycle changes in fuel loading—Crown mass, including foliage and twigs < ¼" (tons/ac) from JFS demonstration fuel treatments. 2001-2002 values from Ott and Jandt, **2005**

Crown Mass	**Ft. Wainwright**			**Delta Bison Range**			**Toghotthele**		
	Tons/acre			**Tons/acre**			**Tons/acre**		
Treatment	**2001**	**2015**	**Diff.**	**2002**	**2015**	**Diff.**	**2001**	**2015**	**Diff.**
8X8	2.44	2.73	+0.29	3.99	3.56	-0.43	2.70	4.70	+2.0
8X8P	1.79	2.99	+1.2	5.50	4.72	-0.78	4.36	5.72	+1.36
10X10	1.86	2.79	+0.93	1.44	4.10	+2.66	3.54	2.96	-0.58
10X10P	2.01	1.63	-0.38	3.46	4.53	+1.07	6.36	7.35	+0.99
Control	7.05	5.28	-1.77	13.01	16.22	+3.21	6.18	5.74	-0.44

Appendix A-5(b). Crown bulk density (foliage and twig < 1/4") kg/m^3, Ott and Jandt 2005.

Crown Mass	**Ft. Wainwright**			**Delta Bison Range**			**Toghotthele**		
	kg/m^3			kg/m^3			kg/m^3		
Treatment	**2001**	**2015**	**Diff.**	**2002**	**2015**	**Diff.**	**2001**	**2015**	**Diff.**
8X8	0.09	0.11	+0.02	0.13	0.14	+0.01	0.08	0.18	+0.10
8X8P	0.10	0.20	+0.1	0.21	0.21		0.15	0.23	+0.08
10X10	0.07	0.12	+0.05	0.06	0.16	+0.1	0.10	0.12	+0.02
10X10P	0.08	0.08		0.13	0.18	+0.05	0.17	0.24	+0.07
Control	0.36	0.31	-0.05	0.46	0.76	+0.3	0.23	0.27	+0.04

Appendix A- 6. Response of trees in JFS demonstration fuel treatments measured by mean dbh change in two periods: (1) 4-5 years after treatment and (2) subsequent 10 years.

SITE Treatment	**DBH Diff 2001-2006**	**N**	**DBH Diff 2006-2015**	**N**	**DBH Diff 2001-2015**	**N**
DBR	**0.12**	84	**0.47**	35	**0.67**	35
10x10	0.31	8	0.51	8	0.81	8
10x10P	0.18	10	0.47	10	0.65	10
8x8	0.19	6	0.47	6	0.67	6
8x8P	0.13	11	0.45	11	0.58	11
Control	0.06	49		0		
FWW	**0.02**	78	**0.21**	37	**0.28**	36
10x10	0.12	8	0.14	8	0.25	8
10x10P	0.08	8	0.28	8	0.36	8
8x8	0.10	8	0.24	9	0.34	8
8x8P	0.02	9	0.19	9	0.22	9
Control	-0.02	45	0.14	3	0.12	3
TOG	**0.14**	92	**0.21**	36	**0.40**	36
10x10	0.17	8	0.23	8	0.40	8
10x10P	0.18	8	0.20	8	0.37	8
8x8	0.23	9	0.28	9	0.52	9
8x8P	0.15	8	0.13	8	0.28	8
Control	0.12	59	0.18	3	0.39	3
All Site Total	0.09	254	0.89	108	0.44	107

Appendix A- 7. Response of trees in JFS demonstration fuel treatments measured by height change (ft.) in two periods: (1) 4-5 years after treatment and (2) subsequent 10 years.

SITE Treatment	**Height Diff 2001-2006**	**N**	**Height Diff 2006-2015**	**N**	**Height Diff 2001-2015**	**N**
DBR	0.0	74	1.4	35	2.0	35
10x10	1.0	7	2.0	8	2.9	8
10x10P	0.2	9	0.9	10	1.2	10
8x8	1.0	5	2.8	6	3.7	6
8x8P	0.9	10	0.5	11	1.3	11
Control	0.0	43				
FWW	0.8	79	0.8	37	1.9	37
10x10	0.7	8	1.0	8	1.7	8
10x10P	1.8	8	0.5	8	2.2	8
8x8	1.0	9	1.2	9	2.2	9
8x8P	1.3	9	0.1	9	1.4	9
Control	0.6	45	1.7	3	2.8	3
TOG	1.3	87	1.5	36	3.1	36
10x10	1.7	6	1.3	8	2.6	8
10x10P	2.0	6	1.7	8	3.5	8
8x8	1.7	9	1.4	9	3.1	9
8x8P	1.4	7	1.8	8	3.0	8
Control	1.1	59	0.8	3	3.8	3
All Site Total	0.7	246	1.2	108	2.4	108

Appendix A- 8. Common vegetation cover by species and lifeform at southern Alaska fuel treatment sites (2015). Cover values are based on "all hits" using point-intercept method so represent absolute cover including canopy and can exceed 100%.

SITE	**North Bean**	**Hope Gate**	**Campbell Tract**	**Campbell Tract**	**Funny River**	**Funny River**	**Funny River**
Cover %	fuel treatment	fuel treatment	Fuel Break	Shaded fuel treatment	Burned area	Masticated Break	Shaded fuel treatment
Fern Total	**4.0**	**8.3**		**9.7**	**17.1**	**3.0**	**18.6**
Forb Total	**31.0**	**13.3**	**7.1**	**48.3**	**78.3**	**37.3**	**47.5**
Fireweed	9.7		0.8	1.3	60.0	31.7	33.1
Dw. Dogwood	4.0	8.7	2.9	31.3	8.3	5.0	10.0
Horsetail	16.3	2.3	1.3	2.0	1.3	0.7	3.3
Clubmoss		2.0		2.7			0.6
Graminoid Tot.	**5.7**	**6.7**	**18.3**	**23.7**	**60.8**	**15.7**	**25.3**
Bluejoint gr.	2.3	6.7	8.8	22.3	20.8	6.0	10.3
GRASS	2.7		0.8	0.3			
SEDGE	0.7		8.8	1.0	40.0	9.7	15.0
Shrub Total	**11.3**	**6.7**	**43.3**	**20.3**	**10.8**	**6.3**	**27.5**
Crowberry	6.7			0.7			
Labrador tea	0.7		4.2	6.3	0.8	1.0	8.1
Menziesia	1.3	1.7		3.3			
Devilsclub		2.3					
Willow	1.3		12.1	1.0	7.1	1.3	7.2
Blueberry		0.3	4.2	0.3			3.3
Lingonberry	1.3		4.2	4.7	0.8		5.0
Tree Total	**20.0**	**72.0**	**8.3**	**48.0**	**18.3**	**0.3**	**30.3**
Birch	4.7	62.0	7.5	44.3	2.1		14.2
White spruce	8.7			3.7	5.8		10.6
Black spruce	5.0						
Aspen					10.4	0.3	5.0
Douglas fir	1.7	9.7					0.3

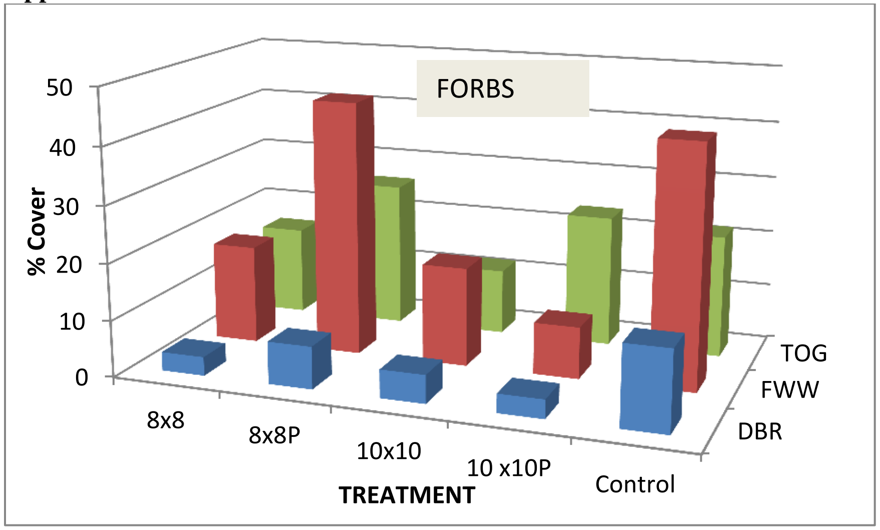
Appendix A- 9. Common vegetation cover by species and lifeform at Nenana Ridge, Tanacross, and Dot Lake study sites (2015). Cover values are based on "all hits" using point-intercept method so represent absolute cover including canopy (and can exceed 100%).

	NR	**NR**	**NR**	**NR**	**TX**	**TX**	**DL**	**DL**
	8x8P (B4)	8x8P (B3)	Control	Shearblade	14x14P	Untreated	12x12	Untreated
Forb	**25.3**	**25.3**	**20.0**	**40.0**	**16.7**	**-**	**17.8**	**22.4**
ARUV					1.3		6.0	23.3
CHAN9		3.3		4.0	4.7		2.7	6.7
COCA				4.7			1.3	
EQUIS	16.0	19.4	10.0	27.3	0.7		0.7	
GABO					2.0		0.7	
GELI	8.7	0.7		0.7	0.7		4.0	6.7
LIBO					4.7	16.7	2.0	3.3
LUAR2					0.7		2.0	6.7
MEPA	0.7			3.3	1.3		1.3	
Graminoid	**12.0**	**35.3**	**13.3**	**78.0**	**21.7**	**-**	**27.8**	**66.7**
CACA4	6.7	30.7	13.3	50.0	26.0		12.7	66.7
CAREX	5.3	4.7		28.0			7.3	
Lichen			6.7					
Shrub	**70.7**	**79.3**	**66.7**	**59.3**	**33.3**	**70.1**	**35.0**	**49.9**
ARUV					1.3		6.0	23.3
EMNI	0.7	2.7		1.3	4.0	10.0		6.7
LEPA11	21.3	22.7	20.0	12.0	0.7	10.0		
ROAC		0.7	3.3	4.0	1.3		6.7	3.3
SALIX	0.7	1.3		8.0	2.0		0.7	
SHCA					3.3	6.7	1.3	
VAUL	13.3	17.3	20.0	14.7				
VAVI	34.7	34.7	23.3	19.3	16.7	26.7	18.0	13.3
Tree	**34.7**	**15.3**	**56.7**	**21.3**	**16.1**	**50.0**	**57.2**	**66.7**
BEPA	2.0			8.7			1.3	
LALA	0.7							
PIGL				2.7	5.3	50.0	8.0	30.0
PIMA	32.0	15.3	56.7					
POTR5				10.0	4.0		46.0	36.7

Appendix A- 10. Common vegetation cover by species in JFS demonstration fuel treatments (2015). Cover values are based on "all hits" using point-intercept method so represent absolute cover including canopy (and can exceed 100%). Forb cover by site/treatment shown at bottom.

spp	ARRU	BENA	BEPA	CACA	CAREX	COCA	EMNI	EQUIS	LEPA	PEFR	PIGL	PIMA	ROAC	RUCH	SALIX	VAUL	VAVI
DBR																	
10x10	0.8	0.0	0.0	1.7	1.7	0.0	2.5	5.0	14.2	0.0	0.0	24.2	8.3	0.0	2.5	5.0	25.8
10x10 P	0.0	0.0	0.0	0.8	3.3	0.0	2.5	2.5	15.8	0.0	0.0	24.2	6.7	0.0	0.0	1.7	33.3
8x8	0.0	0.0	0.0	9.2	0.8	1.7	3.3	1.7	20.0	0.0	0.0	21.7	6.7	0.0	8.3	5.0	40.0
8x8 P	0.0	0.0	0.0	0.0	3.3	4.2	2.5	2.5	0.8	0.0	0.0	25.8	3.3	0.0	1.7	1.7	32.5
Control	0.0	0.0	0.0	4.2	16.7	0.0	4.2	14.2	5.8	0.0	0.0	67.5	8.3	0.0	3.3	0.0	35.0
FWW																	
10x10	0.0	1.7	0.8	23.3	10.8	0.0	0.0	15.8	26.7	0.0	0.8	9.2	0.0	0.0	5.8	11.7	38.3
10x10 P	0.0	1.7	3.3	0.0	5.8	0.0	0.0	6.7	32.5	0.0	3.3	13.3	0.8	0.0	8.3	9.2	46.7
8x8	0.8	1.7	0.0	0.0	8.3	0.0	0.8	10.8	40.8	0.0	0.0	21.7	0.0	0.8	8.3	15.8	46.7
8x8 P	0.8	0.8	0.0	1.7	14.2	0.0	0.8	41.7	39.2	0.0	2.5	20.8	0.0	0.0	5.0	14.2	40.8
Control	0.0	0.0	0.0	5.0	3.3	0.8	0.0	35.0	29.2	2.5	0.8	30.8	0.8	2.5	3.3	10.0	49.2
TOG																	
10x10	0.0	5.8	0.0	40.8	3.3	0.0	0.0	0.0	41.7	0.8	0.0	25.0	5.8	10.0	2.5	5.0	25.0
10x10 P	0.0	6.7	0.0	45.0	0.0	0.0	0.0	0.0	37.5	0.8	0.0	38.3	1.7	22.5	0.8	4.2	28.3
8x8	0.0	0.0	1.7	20.8	0.0	0.8	0.0	1.7	47.5	3.3	0.0	35.8	8.3	8.3	0.8	2.5	25.8
8x8 P	0.0	5.0	0.0	36.7	1.7	0.0	0.0	11.7	45.0	0.8	0.0	38.3	0.8	13.3	3.3	3.3	25.8
Control	0.0	5.0	0.0	10.0	50.0	0.0	0.0	5.0	31.7	1.7	0.0	74.2	1.7	12.5	2.5	5.0	21.7

Appendix A- 10. Continued



SITE	Treatment	Forb	Graminoid	Shrub	Tree
DBR	10x10	5.0	3.3	59.2	24.2
DBR	10 x10P	3.3	4.2	60.0	24.2
DBR	8x8	3.3	10.0	83.3	21.7
DBR	8x8P	7.5	3.3	42.5	25.8
DBR	Control	14.2	20.8	56.7	67.5
FWW	10x10	17.5	34.2	85.0	10.8
FWW	10 x10P	9.2	5.8	99.2	20.0
FWW	8x8	17.5	9.2	115.0	21.7
FWW	8x8P	45.0	15.8	101.7	24.2
FWW	Control	42.5	8.3	93.3	31.7
TOG	10x10	11.7	44.2	103.3	25.0
TOG	10 x10P	23.3	45.0	79.2	38.3
TOG	8x8	15.8	20.8	85.0	37.5
TOG	8x8P	25.8	38.3	84.2	38.3
TOG	Control	21.7	60.0	67.5	74.2

Appendix A- 11. Average cover values (%) for the most common understory plants over time on JFS demonstration fuelbreaks in interior Alaska. Change is from one observation period to the next.

Treatment	Time period	*Lingonberry*	*Labrador tea*	*Blueberry*	Willow	*Calamagrostis*	Sedge
8X8	**Pre-Treatment**	39.2	32.7	7.7	5.5	8.7	0.8
	2 Yr. Post-Treatment	34.1	29.6	6.8	4.8	0.5	12.5
	Change	-5.1	-3.1	-0.9		-8.1	11.7
	14 yrs post-treatment	37.5	36.1	7.8	5.8	10.0	3.1
	Change	**+3.4**	**+6.5**	**+1.0**	**+1.0**	**+9.5**	**-8.6**
8X8P	**Pre-Treatment**	42.9	35.2	5.9	4.5	10.5	11.9
	2 Yr. Post-Treatment	37.5	28.0	5.1	1.2	5.2	6.9
	Change	-5.5	-7.2			-5.3	-4.9
	14 yrs post-treatment	33.1	28.3	6.4	3.3	12.8	6.4
	Change	**-4.4**	**+0.3**	**+1.3**	**+2.4**	**+7.6**	**-0.5**
10X10	**Pre-Treatment**	41.3	26.9	3.3	5.7	12.4	13.5
	2 Yr. Post-Treatment	28.9	22.7	3.5	2.5	1.7	12.9
	Change	-12.4	-4.3	+0.2	-3.2	-10.7	-0.5
	14 yrs post-treatment	29.7	27.5	7.2	3.6	21.9	5.3
	Change	**+0.8**	**+4.8**	**+3.7**	**+1.5**	**+20.2**	**-7.6**
10X10P	**Pre-Treatment**	46.7	32.7	6.4	5.1	6.3	2.1
	2 Yr. Post-Treatment	35.9	25.9	6.0	2.4	1.1	11.2
	Change	-10.8	-6.8			-5.2	9.1
	14 yrs post-treatment	36.1	28.6	5.0	3.1	15.3	3.1
	Change	**+0.2**	**+2.7**	**-1.0**	**+0.6**	**+14.2**	**-6.0**
Control	**Pre-Treatment**	43.2	29.9	3.7	5.5	6.3	16.7
	2 Yr. Post-Treatment	32.5	23.7	4.0	4.0	3.3	4.3
	Change	-10.7	-6.1	+0.7	-1.5	-2.9	-12.4
	14 yrs post-treatment	35.3	22.2	5.0	3.1	6.4	23.3
	Change	**+2.8**	**-1.5**	**+1.0**	**-0.9**	**+3.1**	**+19.0**

Appendix A- 12. Average cover values (%) for selected substrates (ground cover types) over time on JFS demonstration fuelbreaks in interior Alaska. Change is from one observation period to the next.

Treatment	Time period	Exposed duff layer	Dead moss	Live moss	Litter	Lichens
8X8	**Pre-Treatment**	0.8	0.0	65.1	28.5	10.0
	2 Yr. Post-Treatment	1.5	21.1	41.1	30.7	6.6
	Change	0.7	21.1	-24.0	2.1	-3.4
	14 yrs post-treatment	0	0	63.1	25.3	10.6
	Change	-1.5	-21.1	+22.0	-5.4	+4.0
8X8P	**Pre-Treatment**	0.5	0.0	56.6	27.9	14.9
	2 Yr. Post-Treatment	0.7	27.5	24.3	40.7	9.4
	Change	+0.2	27.5	-32.3	12.8	-5.5
	14 yrs post-treatment	0	0	58.1	26.4	15.3
	Change	-0.7	-27.5	+33.8	-14.3	+5.9
10X10	**Pre-Treatment**	0.5	0.0	64.9	28.1	12.0
	2 Yr. Post-Treatment	3.3	24.7	35.9	30.0	8.9
	Change	2.8	24.7	-29.0	1.9	-3.1
	14 yrs post-treatment	0	0	60.3	26.4	13.3
	Change	-3.3	-24.7	+24.4	-3.6	+4.2
10X10P	**Pre-Treatment**	0.1	0.0	66.8	21.5	12.4
	2 Yr. Post-Treatment	1.1	24.9	36.0	32.1	9.9
	Change	0.9	24.9	-30.8	10.7	-2.5
	14 yrs post-treatment	0	0	55.3	26.9	17.8
	Change	-1.1	-24.9	+19.3	-5.2	+7.9
Control	**Pre-Treatment**	0.8	0.0	65.9	16.9	12.3
	2 Yr. Post-Treatment	0.0	0.0	46.8	31.3	20.1
	Change	-0.8	0.0	-19.1	14.4	+7.9
	14 yrs post-treatment	0	0	76.1	10.0	13.9
	Change			+29.3	-21.3	-6.2

Appendix A- 13. Comparison of pre-treatment (Ott and Jandt 2005) and 14-year-post-treatment forest floor (moss, litter and duff) layer thickness for all three JFS demonstration sites in central Alaska (inches).

DBR, FWW, and TOG: **Treatment**	**Litter**	**Lichen**	**Live moss**	**Dead moss**	**Upper duff**	**Lower duff**	**Pre-Rx Total**	**2015 Total**
8X8	0.4	0.2	2.3	2.6	4.1	2.8	12.4	10.9
8X8P	0.1	0.1	2.0	2.3	3.5	3.2	11.2	8.8
10x10	0.4	0.1	2.4	2.5	3.4	2.8	11.5	11.0
10X10P	0.1	0.4	1.8	2.5	3.2	2.3	10.2	9.8
Control	0.1	0.3	1.6	3.2	3.3	2.9	11.3	12.0

Appendix A- 14. Average litter and duff layer thickness from all treatment blocks (cm) in 2015.

Site	Block	Lichen	Litter	Live moss	Dead moss	Upper duff	Lower duff
BC	Shaded		4.2	4.6	5.0	5.2	6.2
CT	Campbell Tract Fuel Break		1.1	3.8	5.4	7.6	12.4
CT	Campbell Tract Shaded		4.9	2.7	3.0	4.9	6.5
DBR	10		1.0	2.9	4.1	9.5	8.4
DBR	10P		1.6	3.3	4.2	7.3	7.9
DBR	8		1.7	2.6	2.4	7.0	8.1
DBR	8P		2.0	2.8	2.7	4.8	4.8
DBR	C			5.1	6.4	10.9	10.0
DL	HFR Unit-C		2.0	2.0	2.0	4.0	4.5
DL	HFR Unit		3.2	2.4	1.3	3.2	2.8
FR	FRSH		3.0	4.5	3.5	3.9	6.4
FR	FRSH-Burn		3.0	4.0	3.3	4.4	6.5
FR	MB		1.6		2.0	4.5	8.1
FWW	10	6.0		6.3	6.5	5.4	6.0
FWW	10P	3.2	1.0	2.0	3.0	7.5	7.4
FWW	8	3.0	1.0	2.4	4.9	7.9	9.0
FWW	8P			4.3	5.0	5.6	7.4
FWW	C		1.0	4.0	4.5	8.1	10.9
HG	Hope Gate		3.3	3.0	5.0	3.7	6.2
NR	B1	1.0	1.7	3.5	3.0	2.1	2.5
NR	B2		0.8	3.5	5.4	5.3	5.1
NR	B3		4.0	3.1	4.3	7.5	7.5
NR	B4		2.0	2.7	3.8	8.6	7.4
NR	C		1.0	2.0	3.5	14.0	2.5
TOG	10		5.0	4.2	4.2	10.3	4.4
TOG	10P	1.5	1.9	3.5	4.3	11.8	3.4
TOG	8	6.0	2.0	6.0	3.6	11.6	3.6
TOG	8P		3.0	4.9	4.4	11.5	3.7
TOG	C			3.9	5.0	10.3	11.1
TX	HFR Unit-C			3.0	5.0	6.5	7.0
TX	HFR Unit		2.0			3.0	3.0

Appendix A- 15. Change in down woody fuel load (tons/acre) by treatment for all three JFS demonstration sites in central Alaska (DBR, FWW, TOG) before treatment, after 2 years and after 14 years (2015).

Treatment	1-hr			10-hr			100-hr			1000-hr		
	Pre	2 yr	14 yr	Pre	2 yr	14 yr	Pre	2 yr	14 yr	Pre	2 yr	14 yr
8X8	0.25	0.34	0.00	0.97	0.90	0.44	0.70	0.23	0.18	2.77	0.37	1.31
8X8P	0.16	0.50	0.01	0.43	0.63	0.15	0.80	0.23	0.46	0.80	0.00	0.46
10X10	0.23	0.42	0.01	0.47	0.50	0.23	0.00	0.07	0.37	2.00	0.00	0.51
10X10P	0.13	0.42	0.00	0.47	0.43	0.15	0.40	0.07	0.28	0.53	0.07	0.56
Control	0.13	-	0.00	0.80	-	0.50	0.70	-	1.29	0.60	-	1.32

Appendix A- 16 (a). Down woody fuel load (tons/acre) by size class for central Alaska study sites in 2015.

Site	Treatment Block	1-hr *<1/4 in.*	10-hr *1/4-1 in.*	100-hr *1-3 in.*	1000-hr *>3 in.*	Total Woody Fuel *(T/ac)*
DBR	10x10	0.01	0.37	0.28	0.00	0.65
DBR	10x10P	0.01	0.18	0.83	1.00	2.02
DBR	8x8	0.00	0.55	0.55	0.80	1.90
DBR	8x8P	0.01	0.27	1.39	0.74	2.41
DBR	Control	0.01	0.82	2.49	2.52	5.84
DL	12x12	0.13	0.65	1.45	2.42	4.65
DL	Untreated	0.02	0.00	0.00	2.60	2.61
FWW	10x10	0.01	0.05	0.56	0.00	0.61
FWW	10x10P	0.00	0.22	0.00	0.00	0.23
FWW	8x8	0.01	0.64	0.00	0.00	0.65
FWW	8x8P	0.00	0.05	0.00	0.00	0.05
FWW	Control	0.00	0.46	0.28	0.00	0.73
NR	Shearblade (B1)	0.00	0.25	2.59	1.50	4.34
NR	Shearblade (B2)	0.00	0.11	2.37	2.04	4.52
NR	8x8P (B3)	0.00	0.07	0.44	1.31	1.82
NR	8x8P (B4)	0.04	0.11	0.00	0.59	0.74
NR	Control	0.00	0.00	0.00	0.00	0.00
TOG	10x10	0.00	0.27	0.28	1.53	2.09
TOG	10x10P	0.00	0.05	0.00	0.68	0.73
TOG	8x8	0.00	0.14	0.00	3.12	3.26
TOG	8x8P	0.00	0.14	0.00	0.65	0.80
TOG	Control	0.00	0.23	1.11	1.44	2.78
TX	14x14P	0.02	0.82	0.43	6.29	7.55
TX	Untreated	0.02	0.53	0.00	8.76	9.31

Appendix A-16(b). Down woody fuel load (tons/acre) by size class for southern Alaska study sites in 2015.

Site	**Treatment Block**	**1-hr *<1/4 in.***	**10-hr *1/4-1 in.***	**100-hr *1-3 in.***	**1000-hr *>3 in.***	**Total Woody Fuel *(T/ac)***
BC	Fuel Treatment	0.02	0.64	1.63	4.76	7.04
HG	Fuel Treatment	0.04	0.39	5.47	5.09	10.98
CT	Fuel Break	0.01	0.13	0.54	1.91	2.59
CT	Shaded Fuel Break	0.08	0.18	1.07	6.59	7.92
FR	Shaded Fuel Break	0.00	0.43	2.16	3.05	5.64
FR	Shaded/burned	0.00	0.67	6.21	8.39	15.27
FR	Masticated	0.00	0.82	3.78	1.41	6.01

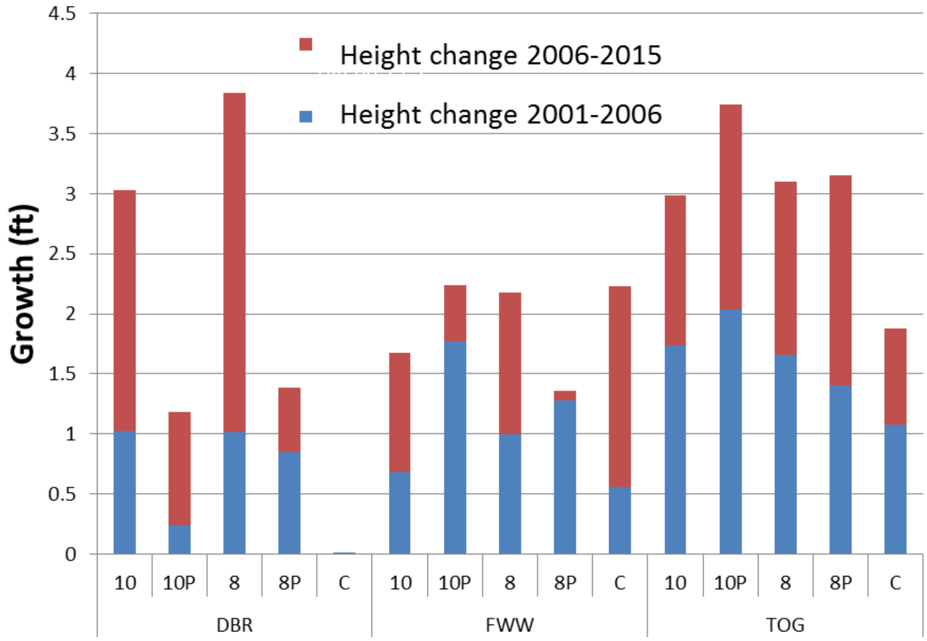
Appendix A- 17. Active layer measurements at all treatments with reference sites (2015).

Site	**Block**	**treatment**	**Date**	**Mean AL (cm)**	**Std.Dev (cm)**	**Points N**
DBR	10	10x10 non-pruned	21-Jul-15	66.5	16.0	40
DBR	10P	10x10 pruned	23-Jul-15	68.8	9.3	40
DBR	8	8x8 non-pruned	21-Jul-15	68.3	13.8	40
DBR	8P	8x8 pruned	22-Jul-15	73.1	11.0	40
DBR	C	Control	23-Jul-15	49.4	8.5	40
DL	12 x 12	Shaded fuel break	08-Jul-15	37.2	11.9	50
DL	C	Untreated	10-Jul-15	28.8	8.3	10
FWW	10	10x10 non-pruned	18-Jun-15	39.2	13.5	40
FWW	10P	10x10 pruned	11-Jun-15	38.6	8.5	40
FWW	8	8x8 non-pruned	10-Jun-15	33.7	9.5	40
FWW	8P	8x8 pruned	23-Jun-15	36.0	3.5	40
FWW	C	Control	24-Jun-15	36.8	5.8	40
NR	B1	Shearblade	16-Jul-15	115.1	36.9	50
NR	B2	Shearblade	17-Jul-15	104.6	53.5	50
NR	B3	8x8 pruned	18-Jul-15	82.7	34.2	50
NR	B4	8x8 pruned	11-Aug-15	138.6	29.2	50
NR	C	Control	21-Aug-15	52.2	9.2	10
TOG	10	10x10 non-pruned	18-Aug-15	43.0	7.5	40
TOG	10P	10x10 pruned	14-Aug-15	45.2	5.0	40
TOG	8	8x8 non-pruned	19-Aug-15	44.9	13.2	40
TOG	8P	8x8 pruned	17-Aug-15	45.0	8.5	40
TOG	C	Control	12-Aug-15	40.7	6.9	40
TX	14x14P	Shaded Fuel Break	09-Jul-15	33.1	25.6	49
TX	C	Untreated	09-Jul-15	47.4	9.7	10

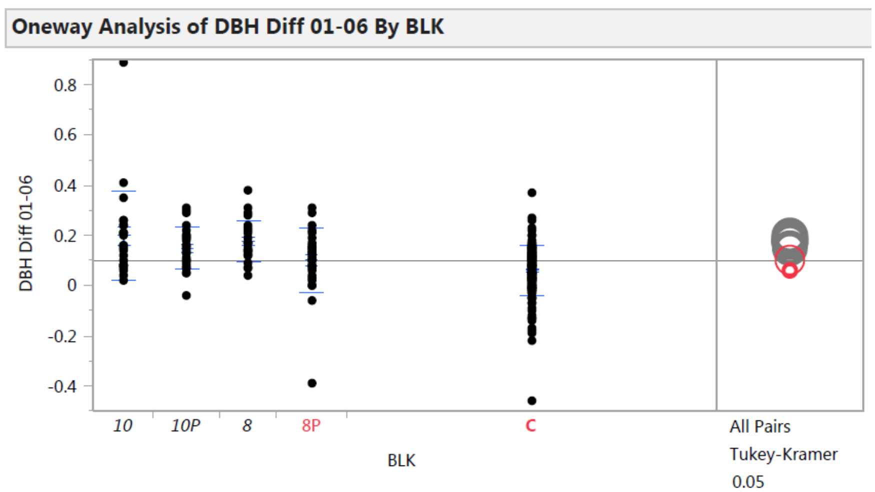
Appendix A- 18. Active layer measurements (cm) at JFS demonstration treatments 1-2 years and 7 years after treatment (unpublished BLM Alaska Fire Service data).

Site	Block	treatment	Sample Date	Mean AL (cm)	StDev AL (cm)	AL depth N
DBR	10	10x10 non-pruned	02-Sept-02	57.66	8.0	50
DBR	10P	10x10 pruned	02-Sept-02	62.62	13.7	50
DBR	8	8x8 non-pruned	02-Sept-02	70.5	13.2	50
DBR	8P	8x8 pruned	02-Sept-02	73.02	12.0	50
DBR	C	Control	02-Sept-02	66.3	13.5	50
DBR	10	10x10 non-pruned	04-Sept-08	72.44	10.7	50
DBR	10P	10x10 pruned	04-Sept-08	74.04	10.8	50
DBR	8	8x8 non-pruned	04-Sept-08	78.84	8.9	50
DBR	8P	8x8 pruned	04-Sept-08	77.08	6.5	50
DBR	C	Control	04-Sept-08	59.94	13.5	50
FWW	10	10x10 non-pruned	01-Sep-01	61.6	15.9	50
FWW	10P	10x10 pruned	01-Sep-01	70.8	11.8	50
FWW	8	8x8 non-pruned	01-Sep-01	67.7	18.3	50
FWW	8P	8x8 pruned	01-Sep-01	58.4	12.1	50
FWW	C	Control	01-Sep-01	58.1	9.9	50
FWW	10	10x10 non-pruned	05-Sep-08	126.7	36.8	50
FWW	10P	10x10 pruned	10-Sep-08	133.3	22.7	50
FWW	8	8x8 non-pruned	05-Sep-08	116.6	30.6	40
FWW	8P	8x8 pruned	05-Sep-08	97.7	24.1	50
FWW	C	Control	05-Sep-08	70.7	11.3	50
TOG	10	10x10 non-pruned	03-Sep-03	44.6	7.2	50
TOG	10P	10x10 pruned	03-Sep-03	48.1	6.1	50
TOG	8	8x8 non-pruned	03-Sep-03	48.4	8.1	50
TOG	8P	8x8 pruned	03-Sep-03	45.1	6.2	50
TOG	C	Control	03-Sep-03	44.6	6.1	50
TOG	10	10x10 non-pruned	03-Sep-08	47.0	4.9	50
TOG	10P	10x10 pruned	03-Sep-08	52.7	5.2	50
TOG	8	8x8 non-pruned	03-Sep-08	55.0	6.1	50
TOG	8P	8x8 pruned	03-Sep-08	46.8	5.7	50
TOG	C	Control	03-Sep-08	43.3	6.0	50

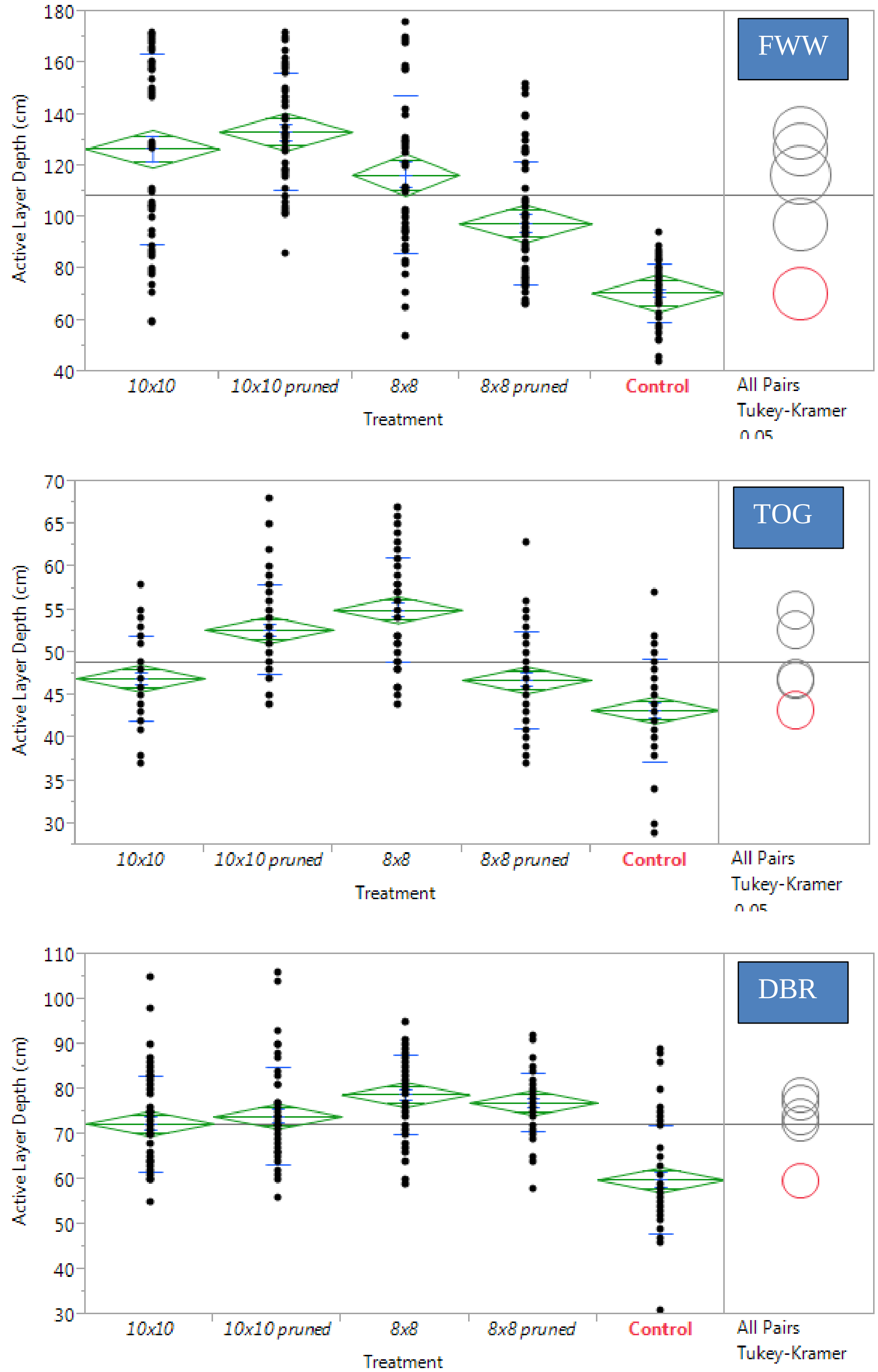
Appendix A- 19. Graph of changes in height of tagged trees in JFS Demonstration Units (Figure 4, sites b-d).



Appendix A- 20. Oneway ANOVA of change in DBH from 248 tagged trees between JFS Demonstration fuel treatments blocks/control from 2001-2006. Means (in.) 10x10'- 0.20, 10x10'P- 0.15, 8x8'- 0.18, 8x8'P- 0.10, Control – 0.06. Red is significantly different than black.



Appendix A- 21. Oneway ANOVAs of active layer thaw depth on three JFS Demonstration fuel treatments blocks/control sampled in September 2008. Red control circle indicates it is significantly different than black treatment circles.



Appendix A-21. Continued

Site	Treatment					Mean
FWW	10x10 pruned	A				133.28
	10x10	A	B			126.66
	8x8		B			116.60
	8x8 pruned			C		97.66
	Control				D	70.66
TOG	8x8	A				55.02
	10x10 pruned	A				52.70
	10x10		B			47.02
	8x8 pruned		B			46.82
	Control			C		43.30
DBR	8x8	A				78.84
	8x8 pruned	A	B			77.08
	10x10 pruned	A	B			74.04
	10x10		B			72.44
	Control			C		59.94

Levels not connected by same letter are significantly different.

Appendix A- 22. Survey sample respondent demographics (proportions)

	High Risk	Very High Risk	Extreme Risk	All Risk Levels
Younger than 30 years old	3.50%	0.80%	2.80%	2.10%
30-49	29.90%	29.00%	39.40%	32.70%
50-70	56.30%	56.50%	49.60%	54.10%
Older than 70	10.30%	13.70%	8.20%	11.10%
High school diploma or less	6.97%	6.52%	10.09%	7.81%
Some College/ Non-Bachelor's Degree	27.91%	34.06%	41.29%	34.84%
Bachelor's Degree or Higher	65.11%	59.42%	48.62%	57.36%
Less than $50,000	10.84%	17.03%	21.14%	16.77%
$50,000-$99,999	38.55%	48.16%	42.32%	43.78%
$100,000-$150,000	36.15%	21.48%	26.92%	27.03%
Greater than $150,000	14.46%	13.33%	9.62%	12.42%

Appendix A- 23. Question asking respondents what activities they have taken that reduce surrounding flammable fuels

Section II: Activities You Take to Reduce Wildfire Risk

Which of the following activities have you completed (or have paid to be completed) on your home or surrounding property?
(Please select all that apply. If none apply, do not select any.)

- whichactions_1 installed fire resistant siding
- whichactions_2 installed fire resistant roofing
- whichactions_3 installed screening over roof vents
- whichactions_4 installed a chimney spark arrester
- whichactions_5 widened the road leading to property
- whichactions_6 regularly cleared leaves from roof to reduce wildfire risk
- whichactions_7 regularly cleared leaves from roof for appearance purposes
- whichactions_8 regularly cleared first 10 feet of land around your home of light brush
- whichactions_9 regularly cleared first 50 feet of land around your home of light brush
- whichactions_10 regularly cleared first 100 feet of land around your home of light brush
- whichactions_11 regularly cleared leaves from yard for appearance purposes
- whichactions_12 pruned and trimmed trees and bushes
- whichactions_13 cut down dead or decaying trees
- whichactions_14 thinned dense areas of vegetation
- whichactions_15 mowed long grasses to reduce wildfire risk
- whichactions_16 mowed long grasses for appearance purposes
- whichactions_17 whichactions_17_other other:

Appendix A- 24. Risk mitigation actions taken by homeowners

Risk Mitigation Activity	Selected (Count)	Selected (Proportion)	Total Respondents (Proportion)
Installed fire resistant siding	26	8.25%	6.93%
Installed fire resistant roofing	120	38.10%	32.00%
Installed screening over roof vents	44	13.97%	11.73%
Installed a chimney spark arrester	49	15.56%	13.07%
Widened the road leading to property	83	26.35%	22.13%
Regularly cleared leaves from roof to reduce wildfire risk	122	38.73%	32.53%
Regularly cleared leaves from roof for appearance purposes	70	22.22%	18.67%
Regularly cleared first 10 feet of land around your home of light brush	193	61.27%	51.47%
Regularly cleared first 50 feet of land around your home of light brush	152	48.25%	40.53%
Regularly cleared first 100 feet of land around your home of light brush	59	18.73%	15.73%
Regularly cleared leaves from yard for appearance purposes	129	40.95%	34.40%
Pruned and trimmed trees and bushes	227	72.06%	60.53%
Cut down dead or decaying trees	269	85.40%	71.73%
Thinned dense areas of vegetation	187	59.37%	49.87%
Mowed long grasses to reduce wildfire risk	158	50.16%	42.13%
Mowed long grasses for appearance purposes	166	52.70%	44.27%
other: [Respondent Specify]	40	12.70%	10.67%

Appendix A- 25. Coefficient estimates for ordered logistic regression.

Ordered Logistic Regression Log Likelihood = -144.92	N = 102
Resource Order	**Coefficient**
Structures* **	1.191 (.335)
Crew Type**	-.529 (.256)
Interactions	
Fuel Break 15MPH**	1.289 (.554)
No Fuel Break 10MPH	.786 (.537)
No Fuel Break 15MPH***	1.580 (.583)
Fuel Break Binary**	.914 (.422)
Pseudo R^2 = 0.1494 LR $chi^2(6)$ = 50.92 Prob > chi^2 = 0.00	
Significance: *** >1%, ** >5%, * >10%	

Appendix A- 26. Marginal likelihood of suppression package orders

Resource order	1	2	3	4	5	6
Fuel Break 15MPH	-.073	-.106	-.062	.050	.123	.067
No Fuel Break 10MPH	-.053	-.068	-.029	.043	.073	.034
No Fuel Break 15MPH	-.081	-.125	-.083	.046	.151	.092
Fuel Break 10MPH	-.046	-.066	-.044	.016	.079	.061

Appendix A- 27. Variable Definitions

Variable	Definition
SF	South Facing Aspect
Precip	Sum of the precipitation on the discovery month
Temp	Average temperature in the discovery month
Temp_1	1 month lag of Avg_Temp variable
Precip_1	1 month lag of Sum_Precip variable
native	distance to nearest native allotment
FT	Fuel Treatment
Zone	Management zone
RH	Average relative humidity in discovery month
slope	Slope at start of fire location
dem	Elevation (m)
tundra	primary fuel was tundra forest
shrub	primary fuel was shrub
mixed	primary fuel was mixed forest
totaldays	Total Days fire burned
StrThreat	Structures Threatened
StrBurned	Structures Burned

Appendix A- 28. Total yearly DOF expenditures per cost category per year.

	Overhead & Crews	Aircraft	Engines	Supplies	Total
2007	$2,837,987	$1,512,572	$33,267	$2,716,610	$7,100,436
2008	$436,093	$226,385	$7,256	$268,568	$938,302
2009	$8,386,025	$815,573	$3,346	$3,541,937	$12,746,881
2010	$8,857,569	$4,395,789	$222,164	$10,470,355	$23,945,877
2011	$7,222,191	$3,785,072	$133,654	$9,266,704	$20,407,621
2012	$2,261,607	$914,861	$45,259	$4,329,408	$7,551,134
2013	$3,964,109	$2,246,714	$223,975	$6,605,000	$13,039,797
2014	$3,456,586	$2,447,778	$57,830	$5,531,961	$11,494,155
2015	$8,343,933	$7,741,475	$211,209	$19,270,150	$35,566,768

Appendix A- 29. Expenditure by year and suppression zone for DOF wildfires larger than 50 acres

	Sum of OH__Crews	Sum of Aircraft	Sum of Engines	Sum of Supplies
2007	**$2,837,987**	**$1,512,572**	**$33,267**	**$2,716,610**
FULL	$2,658,894	$1,436,569	$26,035	$2,629,526
LIMITED	$159,692	$70,205	$1,532	$86,113
MODIFIED	$19,401	$5,798	$5,699	$971
2008	**$436,093**	**$226,385**	**$7,256**	**$268,568**
CRITICAL	$244,107	$106,017	$3,906	$146,224
FULL	$158,540	$103,854	$3,290	$113,581
LIMITED	$31,432	$12,182	$60	$8,738
MODIFIED	$2,015	$4,331	$0	$25
2009	**$8,386,025**	**$815,573**	**$3,346**	**$3,541,937**
CRITICAL	$932,635	$0	$0	$33,166
FULL	$4,209,442	$815,573	$3,346	$926,736
LIMITED	$2,943,918	$0	$0	$2,582,035
MODIFIED	$300,030	$0	$0	$0
2010	**$8,857,569**	**$4,395,789**	**$222,164**	**$10,470,355**
CRITICAL	$114,697	$71,132	$87	$23,750
FULL	$2,112,946	$1,017,521	$50,824	$3,442,350
LIMITED	$611,494	$713,034	$4,129	$410,090
MODIFIED	$6,018,433	$2,594,102	$167,124	$6,594,165
2011	**$7,222,191**	**$3,785,072**	**$133,654**	**$9,266,704**
CRITICAL	$5,362,259	$2,130,614	$93,907	$6,063,544
FULL	$1,859,933	$1,654,458	$39,747	$3,203,160
2012	**$2,261,607**	**$914,861**	**$45,259**	**$4,329,408**
CRITICAL	$33,784	$34,034	$1,963	$8,591
FULL	$2,227,823	$880,826	$43,296	$4,320,817
2013	**$3,964,109**	**$2,246,714**	**$223,975**	**$6,605,000**
CRITICAL	$879,846	$236,877	$56,127	$1,146,282
FULL	$3,084,263	$2,009,837	$167,848	$5,458,718
2014	**$3,456,586**	**$2,447,778**	**$57,830**	**$5,531,961**
FULL	$3,456,586	$2,447,778	$57,830	$5,531,961
2015	**$8,343,933**	**$7,741,475**	**$211,209**	**$19,270,150**
CRITICAL	$869,231	$1,025,708	$30,851	$4,865,330
FULL	$7,474,702	$6,715,767	$180,358	$14,404,820
Grand Total	**$45,766,100**	**$24,086,218**	**$937,960**	**$62,000,693**

Appendix A- 30. Parameter estimates of explanatory factors in cost per acre.

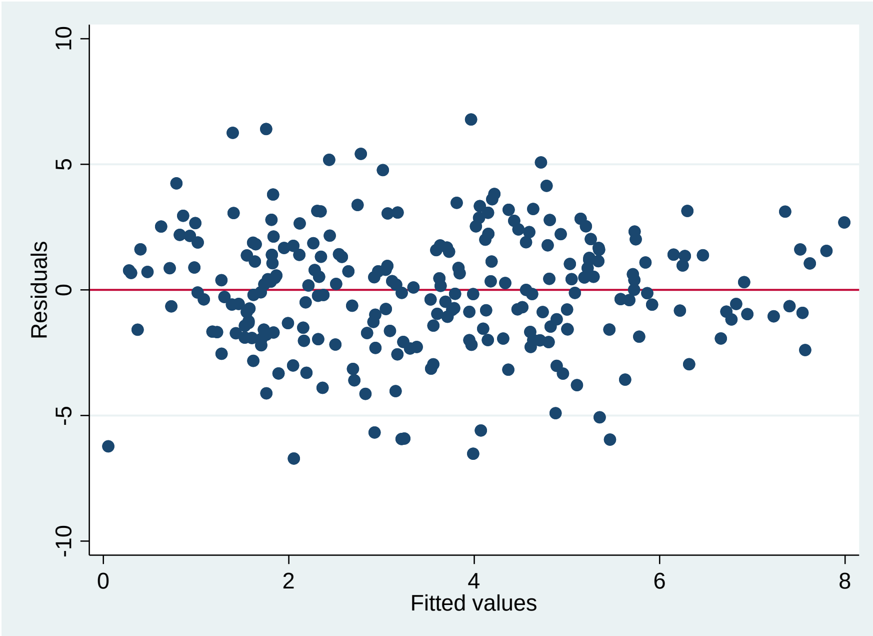
Variable	Coefficient
SF	-0.158
lnsumprecip	0.353**
lnavgtemp	-0.486
lnsumprecip_1	-0.226
lnavgtemp_1	0.214
lnnative	0.139
FT	0.817
zone	1.641***
lnRH	1.307
lnslope	0.001
lnelevation	-0.549**
tundra	-1.262*
shrub	-0.468
mixed	0.031
lndays	-0.113
StrThreat	0.002
StrBurned	-0.036
y2007	0.436
y2008	0.253
y2009	1.901***
y2010	1.762***
y2011	1.959*
y2012	1.963**
y2013	2.341***
y2014	0.946
_cons	-3.358
R^2	0.357
Adjusted R^2	0.284
p-value (F-Test)	0.000
N	245

Note: *,, and *** denote statistical significance at the 10%, 5% and 1% respectively. Also includes R^2 and adjusted R^2 values.**

Appendix A- 31. Variance Inflation Factors

Variable	VIF	1/VIF
StrBurned	4.09	0.244705
StrThreat	3.93	0.254282
y2010	2.51	0.398848
lnelevation	2.32	0.431008
y2007	2.06	0.484662
y2009	2	0.500488
zone	1.98	0.505912
tundra	1.91	0.524699
y2008	1.74	0.57628
lnslope	1.71	0.584475
lnsumprecip	1.56	0.639577
shrub	1.53	0.65345
lndays	1.44	0.693289
y2013	1.44	0.69425
y2011	1.43	0.698893
lnavgtemp	1.42	0.704159
lnsumpreci~1	1.36	0.735595
lnRH	1.34	0.745332
FT	1.34	0.74645
lnnative	1.32	0.754949
y2012	1.31	0.762309
mixed	1.26	0.795918
lnavgtemp_1	1.21	0.82766
y2014	1.17	0.852061
SF	1.12	0.896157
Mean VIF	1.78	

Appendix A- 32. Scatter plot of regression residuals versus fitted values.



Appendix A- 33. Total large wildfires counts for six non-cost variables.

Year	Count	Fuel	Count	Management Zone	Count	Discovery Month	Count
2007	43	tundra	42	Limited	104	March	2
2008	24	shrub	35	Modified	29	April	4
2009	40	mixed	69	Full	115	May	73
2010	71	spruce	120	Critical	18	June	106
2011	9					July	68
2012	9					August	8
Year	**Count**	**Aspect**	**Count**	**Fuel Treatment**	**Count**	**Discovery Month**	**Count**
2013	16	NF	144	FT	14	September	3
2014	3	SF	122	Non-FT	252	November	2
2015	51						

Appendix A- 34. Descriptive statistics large wildfires for nine non-cost variables.

	Min	Max	Average	Std. Dev
Total days	0	204	50	41
Area (acres)	50	517,078	13,608	43,321
Structures Threatened	0	1603	18	158
Structures Burned	0	72	1	6
Elevation (m)	1	999	269	222
Slope (degrees)	0	17	2	3
Avg Temp (F)	0	65	48	11
Precipitation (inches)	0	10	2	2
Relative Humidity	1	89	62	11

Source: Western Regional Climate Center (WRCC) Web, 2018