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NOTE

Quantifying the effect of fuel reduction treatments on fire behavior in boreal forests

B.W. Butler, R.D. Ottmar, T.S. Rupp, R. Jandt, E. Miller, K. Howard, R. Schmoll, S. Theisen, R.E. Vihnanek, and D. Jimenez

Abstract: Mechanical (e.g., shearblading) and manual (e.g., thinning) fuel treatments have become the preferred strategy of many fire managers and agencies for reducing fire hazard in boreal forests. This study attempts to characterize the effectiveness of four fuel treatments through direct measurement of fire intensity and forest floor consumption during a single prescribed burn. The treatments included (1) thinning trees and removing debris (THIN-REMOVE-1 and -2), (2) thinning trees and burning the debris onsite, (3) shearblading and leaving the debris in place (SHEAR), and (4) shearblading and piling the debris in windrows (SHEAR-ROW). Fire burned through treatments 1, 3, and 4 and one control unit. The highest fire intensities (maximum temperature of 1150 °C, maximum heat flux of 227 kW·m^{-2}, and fire cumulative energy release of 4277 J·m^{-2}) were measured in the control. Treatment 1 exhibited a peak temperature of 267 °C, peak heating of 16 kW·m^{-2}, and cumulative energy release of 2600 J·m^{-2}. Treatments 3 and 4 exhibited peak temperatures of 170 and 66 °C, peak heating of 51 and 3 kW·m^{-2}, and cumulative energy release of 2500 and 1800 J·m^{-2}, respectively. The thinned treatment showed the most significant impact in the context of reduced heat release.

Résumé : Les traitements manuels (p. ex. éclaircie) et mécaniques (p. ex. coupe à la cisaille) font maintenant partie de la stratégie préférée des gestionnaires du feu et des agences de protection contre le feu pour réduire le risque d'incendie dans les forêts boréales. Cette étude tente de caractériser l'efficacité de quatre traitements des combustibles en mesurant directement l'intensité du feu et la consommation de la couverture morte lors d'un seul brûlage dirigé. Les traitements incluaient (1) une éclaircie et l'élimination des déchets de coupe (THIN-REMOVE-1 et -2), (2) une éclaircie et le brûlage des déchets de coupe sur place, (3) une coupe à la cisaille en laissant les déchets de coupe sur place (SHEAR) et (4) une coupe à la cisaille et la mise en andains des déchets de coupe (SHEAR-ROW). Le feu est passé dans les traitements 1, 3 et 4 ainsi que dans une parcelle témoin. Les plus fortes intensités du feu (température maximum de 1150 °C, flux de chaleur maximum de 227 kW·m^{-2} et énergie cumulée libérée par le feu de 4277 J·m^{-2}) ont été mesurées dans le traitement témoin. Dans le traitement 1, la température, le flux de chaleur et l'énergie cumulée libérée par le feu ont atteint respectivement 267 °C, 16 kW·m^{-2} et 2600 J·m^{-2}. Dans les traitements 3 et 4, ces valeurs ont atteint respectivement 170 et 66 °C, 51 et 3 kW·m^{-2} et 2500 et 1800 J·m^{-2}. L'éclaircie est le traitement qui a eu le plus d'impact sur la réduction du dégagement de chaleur. [Traduit par la Rédaction]

Introduction

Concerns about a growing wildland-urban interface and the potential for forest fires to burn homes and impact other resources have pushed wildland fire risk mitigation strategies to the forefront of fire management activities (Pyne et al. 1996; Chapin et al. 2006; Noss et al. 2006). Fuel treatment options such as thinning followed by piling and burning, shearblading (mechanical shearing of trees and shrubs), and prescribed fire are used by land management agencies for fire hazard reduction in the boreal forests of Alaska and Canada. Prescribed fire has been shown to be effective in reducing general fire behavior, but broad-scale use as a mitigation strategy has met strong resistance from the public due to concerns about escape, smoke, and aesthetics (Fernandes and Botelho 2003). The effectiveness of various thinning treatments has been analyzed for the most part using fire behavior models (Van Wagtendonk 1996; Graham et al. 1999; Kobziar et al. 2009; Mooney 2010; Schroeder 2010; Knapp et al. 2011), with few empirical observations (Moghaddas and Craggs 2007; Knapp et al. 2011; Cochrane et al. 2012; Estes et al. 2012).

The study described herein was developed based on the recognition of the need for further understanding of fuel treatment effectiveness in boreal forests. The primary objective was to characterize the effectiveness of four different landscape-level fuel treatments in black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) and white spruce (*Picea glauca* (Moench) Voss) forests for reducing crown fire intensity by comparing observations of fuel consumption, burn severity, and fire behavior in treated and untreated forest. Partial success was achieved in June 2009 when three treatment units and one control unit were burned. A substantial quantity of information was acquired from the effort, some of which is intuitive, some that is less obvious but ultimately relevant. Due to formatting restrictions, not all information could be included in this document; additional description of the site, the sensors used, interpretation of the results, and lessons learned can be found as supplementary material on the Journal's website.[1]

Methods

Study site

The study site was located approximately 60 km west of Fairbanks, Alaska, and was selected for its existing road network, large area (~240 ha) of homogenous vegetation, and a current burn plan available for amendment. The site was an even-aged

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B.W. Butler and D. Jimenez. US Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 Hwy. 10 W, Missoula, MT 59802, USA.
R.D. Ottmar and R.E. Vihnanek. US Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 N 34th St., Seattle, WA 98103, USA.
T.S. Rupp. University of Alaska Fairbanks, 3352 College Rd., Fairbanks, AK 99709, USA.
R. Jandt. BLM Alaska Fire Service, 64873 Mawhin Rd., Enterprise, OR 97828, USA.
E. Miller, K. Howard, and S. Theisen. Alaska Fire Service, Ft. Wainwright, AK 99703, USA.
R. Schmoll. Alaska State Division of Forestry, Ft. Wainwright, AK 99703, USA.
Corresponding author: B.W. Butler (e-mail: bwbutler@fs.fed.us).

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stand of black and white spruce with a mix of resin birch (*Betula neoalaskana* Sarg.) and trembling aspen (*Populus tremuloides* Michx.). Understory vegetation was composed primarily of lowbush cranberry (*Vaccinium vitis-idaea* L.), Labrador tea (*Ledum palustre* L.), and some grasses and sedges. Live mosses, primarily feather mosses (*Hylocomium splendens* (Hedw.) Schimp. in B.S.G.) and sphagnum mosses (*Sphagnum* spp. (Sphagnaceae)), were the dominant ground cover with some lichen. Mean tree age was 82 years (n = 47) Total understory seedling density ranged from 3680 to 34 915 stems·ha^{-1} and were composed primarily of black spruce with a component of willow and some birch. All understory stems within treatments were removed during thinning operations.

While three burn blocks were selected, only one was burned and is therefore the focus of this report. Four treatment units were located in the burn block and were spaced so that each was surrounded (minimum of 150 m on all sides) by sufficient control (untreated) vegetation to prevent interaction with fire behavior in neighboring units. The treatments consisted of two thinning methods and two shearblade-based methods selected to replicate actual treatments currently being implemented by Federal and State agencies in Alaska; however, only one thinning treatment and the two shearblade treatments were ultimately burned. The thinning treatment consisted of removing trees to create a 2.4 m × 2.4 m stem separation and pruning the remaining trees to 1.2 m and then hauling the debris away; two of these treatment units (hereafter referred to as THIN-REMOVE-1 and -2) were located in the block that was burned (Figs. 1*a*, 1*b*, and 1*d*). The two shearbladed units consisted of leaving debris in place (hereafter referred to as SHEAR) (Fig. 1*e*) and debris pushed into windrows (hereafter referred to as SHEAR-ROW). Untreated controls where no vegetation treatment was applied were located near each treatment unit (Fig. 1*c*).

Metrics

Vegetation effects and consumption were evaluated by direct measurement (Ottmar et al. 2005). Burn severity was evaluated by visual observations of maximum charring height on tree stems, soil scorch, overall plant mortality, and forest floor biomass consumption. Fire intensity was quantified from measurements of air temperature, maximum energy flux, heating time (time that temperature remains above 50 °C), cumulative fire radiative and total energy (over the heating time), flame length, fire rate of spread (from evaluation of video images), and fireline intensity (Byram 1959; Butler and Jimenez 2009).

Fuel composition, structure, and loading

A point-centered quarter method (Cottam and Curtis 1956) was used to sample the overstory trees (diameter at breast height ≥3.0 cm). Understory trees (diameter at breast height <3.0 cm) were sampled using 2 m radius fixed area plots. Existing shrubs and grasses were characterized (density, composition, height, and cover) by sampling 32 randomly located 1 m × 1 m quadrats throughout the control sites. Shrubs and grasses were characterized for species density, composition, height, and cover. At alternate grid points, a 20 m line was established (Brown 1974) to determine fuel loading for the 1, 10, 100, and 1000 h time lag woody fuel classes. Sixteen forest floor characterization plots were systematically located inside and outside each of the THIN-REMOVE-1 and -2 treatments with those outside the treatment units identified as controls. Sixteen forest floor depth pins (Beaufait et al. 1977) were located at each forest floor plot to determine depth and calculate loading using a bulk density determined from a previous study located nearby (Ottmar and Vihnanek 1998). No forest floor plots were established in the shearbladed units because of the disturbed forest floor layer.

Weather

Remote automatic weather stations were located in clearings (>50 m in diameter) on the northern and southern edge of the burn area to provide hourly observations of air temperature, solar insolation, rainfall, relative humidity, and wind speed and direction from snowmelt through September of each year. Two portable weather stations located in the thinned treatment and the associated control documented in-stand treatment-level differences in 2 min average wind speed (2.6 m above ground), temperature, and relative humidity.

Fuel moisture

Between three and 10 fuel moisture samples were collected at randomly selected sites near the forest floor consumption plots immediately prior to ignition for individual fuelbed categories including the live needles, live grass, dead grass, shrub, live moss, dead moss, upper duff, and lower duff. All samples were weighed, oven dried at 70 °C for 96 h, and reweighed to determine fuel moisture content (see supplementary material for additional information).

Fuel consumption

The forest floor was the only fuelbed category measured for consumption following the prescribed fire. No postfire data on the consumption of the tree crowns, shrub, grass, and woody fuels were collected because very little mass existed for those fuelbed categories as compared with the forest floor. A Fuel Characteristic Classification System boreal forest spruce fuelbed (Ottmar et al. 2007; Riccardi et al. 2007) was customized with measured characteristics and loadings to provide needed inputs to Consume 3.0 (Ottmar et al. 2005) for calculation of fuel consumption (see supplementary material). Forest floor layer depths, burn depth, and fuel moisture content were measured according to established procedures (Beaufait et al. 1977). Consumption of the canopy, shrubs, grasses, and woody fuels was calculated using Consume 3.0 (Ottmar et al. 2005).

Fire behavior

Fire behavior sensors and in-fire video recorders were deployed to sense fire from the expected spread direction based on wind direction and lighting procedures. All sensors and cameras were located nominally 1.0 m above the mineral soil and were oriented to "look" horizontally in the direction they were faced.

Results

Burn timeline

Ignition occurred 17 June 2009 at 1345 h (all times referenced are local time) along the west and east sides of the block using hand-held drip torches. Wind (2 m above ground) was 0.9 m·s^{-1} gusting to 5.5 m·s^{-1} from the southwest, relative humidity was 47%, and temperature was 21 °C 3.5 km northeast of the burn block. Initially, flame lengths were less than 1 m but by 1515 h, active crown fire was observed with flame heights of 30–45 m in individual or groups of torching trees (Fig. 1*f*). Fire spread rate was 0.67 m·s^{-1} as determined from visual inspection of video records of fire in the THIN-REMOVE-1 control.

Fire intensity increased as it burned from south to north, likely due to a higher water table associated with proximity to the river on the southern edge of the block. Crown fire impacted edges of the THIN-REMOVE-1, SHEAR, and SHEAR-ROW units.

Composition, structure, and fuel loading

Immediate (1–3 years) post-treatment response of understory vegetation to thinning was minimal. However, substantial changes in understory species composition in the shearblade treatments were identified. Post-shearblade, the mosses declined by approximately 50% and grasses and sedges increased by approximately 4000%. Total pre-fire fuel loading was similar for both the THIN-REMOVE-1 control (217.2 Mg·ha^{-1}) and the THIN-REMOVE-1 treated unit (224.8 Mg·ha^{-1}) (Table 1; see supplementary material). Aver-

Fig. 1. Images of burn units. (*a*) Aerial photograph of the burn area looking from south to north. Locations of various treatments are labeled; THIN-REMOVE-2 is not readily apparent from aerial images. (*b*) Photograph of the THIN-REMOVE-1 unit after the burn taken at the northeast corner of the unit looking south along the unit edge. (*c*) Photograph of the THIN-REMOVE-1 control unit post-burn with fire behavior sensor. (*d*) Photograph of the THIN-REMOVE-2 unit post-burn. (*e*) Photograph of the SHEAR unit post-burn. (*f*) Photograph of a crown fire burning in the center of the A block.

age tree spacing in the control units ranged from 1.15 to 1.61 m and from 2.06 m to 2.78 m for the treatment units. Average stem density in the control units ranged from 3849 to 7531 stems·ha^{-1} and from 2359 to 1290 stems·ha^{-1} for treatment units THIN-REMOVE-1 and THIN-REMOVE-2, respectively. Average basal area ranged from 11.83 to 31.53 m^2·ha^{-1} and from 10.76 to 16.32 m^2·ha^{-1} for the THIN-REMOVE-1 and THIN-REMOVE-2 control units, respectively. Black spruce trees comprised at least 95% of stems in both control and treatments. Overstory canopy cover ranged from 29% to 50% in the control units, while the thinning resulted in canopy cover of 11% and 41% for THIN-REMOVE-1 and THIN-REMOVE-2, respectively.

Table 1. Measured pre-fire loading and post-fire consumption of the forest floor.

Unit	Pins placed (no.)	Pins analyzed (no.)	Pins burned (no.)	Pre-burn load ($Mg \cdot ha^{-1}$)	Pre-burn load SE ($Mg \cdot ha^{-1}$)	Post-burn load ($Mg \cdot ha^{-1}$)	Post-burn load SE ($Mg \cdot ha^{-1}$)	Consumption ($Mg \cdot ha^{-1}$)
THIN-REMOVE-1[a]	256	60	60	219.80	7.62	186.38	8.54	33.40
THIN-REMOVE-1 control[a,b]	256	249	256	209.3	3.86	179.8	3.41	29.1

[a]Only pins that had a chance to burn were analyzed.
[b]Seven pins were lost or stepped on and were eliminated from the analysis.

Fuel moisture and fuel consumption

Pre-fire forest floor moisture content for the THIN-REMOVE-1 treatment area averaged 37% for the live moss, 105% for the dead moss, 183% for the upper duff, and 247% for the lower duff (see supplementary material). The moisture content of the dead grass was 9.3%, live grass 293%, and shrubs 93%. Black spruce live needle fuel moisture content was 151%. Pre-fire forest floor moisture content for the THIN-REMOVE-1 control unit averaged 92% for the live moss, 193% for the dead moss, 132% for the upper duff, and 163% for the lower duff. Shrub moisture content was 161%, while the live black spruce needles were 95% (see supplementary material). No moisture samples were collected for the live and dead grass.

Of the 256 forest floor pins located in the THIN-REMOVE-1 treatment units, 60 burned with a pre-burn mass of 219.8 $Mg \cdot ha^{-1}$ with a forest floor consumption of 33.4 $Mg \cdot ha^{-1}$ (see supplementary material). Of the 256 forest floor pins located in the THIN-REMOVE-1 unit control, 249 burned with a pre-burn mass of 209.4 $Mg \cdot ha^{-1}$ and a forest floor consumption of 29.1 $Mg \cdot ha^{-1}$. Using only the pins that burned, Consume 3.0 underpredicted the measured forest floor consumption by 20% for the control and by 38% for the treatment block (supplementary material).

Burn severity

Burn severity on the southern half of the block was relatively low, as demonstrated by zero consumption of forest floor, surface vegetation, and tree canopies. However, the northern half of the block where the THIN-REMOVE-1, SHEAR, and SHEAR-ROW treatment units were located burned with high-intensity crown fire in the untreated forest, likely due to drier fuel conditions caused by slightly higher elevation and decreased stem density that facilitated increased exposure to wind and solar drying.

The highest fire intensity occurred on the south-southeast corner of the THIN-REMOVE-1 unit. Flame height (maximum stem scorch height) was nominally 5 m in the southeast corner of the THIN-REMOVE-1 unit. High-intensity crown fire occurred along the south, west, and east boundaries of this unit (Fig. 1*b*) and in the control plots along the south boundary. Flame height reached 20 m in the untreated forest along the south and west of the THIN-REMOVE-1 unit as indicated by stem scorch with 100% consumption of crown foliage and small stems (Fig. 1*c*). As fire burned across the south-central and southwest boundaries of the THIN-REMOVE-1 unit, scorch height dropped to 1–2 m. Burn severity in this area could be characterized as moderate substrate severity (50% duff consumption) and high vegetation severity (100% vegetation mortality). Fire burned less than 4 m into the west side of the THIN-REMOVE-1 unit. Surface fire spread approximately one third of the distance across the unit from south to north. Stem scorch height in the interior was generally less than 1 m.

The THIN-REMOVE-2 treatment experienced little fire, likely due to the higher surface fuel moisture contents in the southern portion of the burn block (Fig. 1*d*). Vegetation along the southern edge of the unit was characterized by taller trees with substantial understory vegetation that appeared well hydrated.

The SHEAR unit included significantly more unburned slash remaining from the treatment and winter burn than the SHEAR-ROW unit. Consequently, post-fire inspection revealed much higher burn severity as indicated by oxidized soil over a larger portion of the treatment area (Fig. 1*e*). The SHEAR-ROW unit burned primarily where unburned slash remained; some limited consumption of the grassy areas between windrows was observed. The untreated forested areas along the southern boundary of the SHEAR and SHEAR-ROW units burned with high intensity (Fig. 1*f*).

Fire behavior

Sensors in the THIN-REMOVE-1 unit recorded a maximum heat flux of 2.2 $kW \cdot m^{-2}$ and maximum temperature of 71 °C (Table 2). The heating time was 1100 s with a cumulative total energy of 600 $J \cdot m^{-2}$. Video images indicated that the fire burned up to the edge of the treatment as a crown fire but dropped out of the crowns and burned with decreasing intensity about 30 m into the treated unit. Flame lengths (derived from video images) were less than 1 m at the edge of the unit and fire rate of spread into the treatment was very slow (<0.01 $m \cdot s^{-1}$). Fireline intensity calculated from the product of rate of spread, heat content, and fuel consumed was 0.16 $MW \cdot m^{-1}$.

The highest measured fire intensities occurred in the untreated control south of the THIN-REMOVE-1 unit. This location recorded maximum flame temperatures of 1150 °C and peak total energy fluxes of 227 $kW \cdot m^{-2}$. The heating time was relatively short (approximately 400 s) and the cumulative total energy release averaged 4277 $J \cdot m^{-2}$ between the two sensors. Flame heights were 8–45 m and fire rate of spread was nominally 0.67 $m \cdot s^{-1}$. Fireline intensity was 38.99 $MW \cdot m^{-1}$.

Sensors in the THIN-REMOVE-2 unit indicate that a flanking fire burned through a portion of the unit. Heating time was 510 s, cumulative total energy release was 2600 $J \cdot m^{-2}$, peak air temperature was 267 °C, and peak total heat flux was 16 $kW \cdot m^{-2}$. Flame length was 0.3 m and fire rate of spread was 0.025 $m \cdot s^{-1}$ or less over limited distance until the fire self-extinguished.

Sensors in the SHEAR unit recorded fire in the area for 4100 s with a cumulative total energy release of 2500 $J \cdot m^{-2}$. The peak measured air temperature was 170 °C and the peak total heat flux was 51 $kW \cdot m^{-2}$. Flame lengths were 0.3–0.6 m. No clear fire rate of spread was detected, as the fuels were disbursed and did not burn as a uniform front. Post-fire inspection indicates that a crown fire burned up to the southern boundary followed by nearly complete broad-scale low-intensity burning of the debris remaining in the treatment area.

Sensors near the center of the SHEAR-ROW unit detected the presence of fire for 5300 s and a total cumulative energy load of 1800 $J \cdot m^{-2}$, an air temperature that remained below 66 °C, and a total energy flux of less than 3 $kW \cdot m^{-2}$. No clear flame length or rate of spread was detected. Post-burn inspection indicates that the windrows in the unit burned partially with relatively low intensity.

Weather

A total of 13 807 pooled data pairs (control and treatment) were collected from two portable weather stations (one in the THIN-REMOVE treatment and one in the associated control) over the period 2007–2010 to document in-stand microclimatic changes at the plot level. The average difference between the thinned treatments and control for all samples was a 0.25 $m \cdot s^{-1}$ increase in average wind speed, a 1 $m \cdot s^{-1}$ increase in wind gust, a 0.1 °C increase in air temperature, and a 1% decrease in relative humidity. The average wind speed was higher for all cases and peaked more

Table 2. Summary of fire intensity metrics by unit.

Unit	Heating time (s) above 50 °C	Cumulative total energy load at completion of heating time ($J\cdot m^{-2}$)	Maximum temperature (°C)	Peak total heating flux ($kW\cdot m^{-2}$)	Flame length (video record) (m)	Flame length (stem scorch) (m)	Fire rate of spread (video record) ($m\cdot s^{-1}$)	Fireline intensity ($MW\cdot m^{-1}$)[b]
THIN-REMOVE-1	1100	600	71	2.2	0.30	1.0	<0.01	0.16
THIN-REMOVE-1 control[a]	380, 450	5105, 3450	1150, 780	227, 50	8–30	20	0.67	38.99
THIN-REMOVE-2[a]	510	2600	267	16	0.30		0.02–0.30	
SHEAR[a]	4100	2500	170	51	0.30–0.60			
SHEAR-ROW	5300	1800	66	3				

[a]Where two values are presented, they represent individual values or observations from sensors in the burn.
[b]Calculated using a nominal heat content of 20 $MJ\cdot kg^{-1}$ for all vegetation components.

than 2.2 $m\cdot s^{-1}$ above the control, the maximum gust speed was higher for 92% of the samples in the treatment with a maximum difference of 6 $m\cdot s^{-1}$, the air temperature was higher in the treatment for approximately 70% of the time with a maximum increase of 5 °C, and the relative humidity was lower for approximately 56% of the time and reached a value more than 30% lower but was 15% higher for 44% of the time (on a relative basis).

Discussion

Fuel consumption

Although the magnitude of biomass is similar for the THIN-REMOVE-1 and THIN-REMOVE-1 control, the open canopy of the THIN-REMOVE-1 provided increased drying to the upper forest floor layers causing slightly higher forest floor consumption. The open canopy and higher live needle moisture content (probably due to less competition) also reduced crown consumption, as confirmed by visual observations of significant reduction in fire spread and intensity in the THIN-REMOVE-1 treatment.

Burn severity

The thinned treatment appeared to be most effective in stopping fire spread and effectively limiting thermally induced mortality in plants. Very little impact was observed beyond 10–20 m of the treatment edge, as the fire did not progress farther into the unit.

Results indicate that the top moss and duff layers were drier in the thinned unit than in the control, probably due to increased exposure to solar irradiation and wind, slightly increasing the forest floor biomass consumption.

Fire behavior

Fire intensity in the untreated forest on the northern half of the burn could be considered to be moderate to high in terms of maximum air temperatures and heating rates when compared against similar measurements in other studies (Butler et al. 2004; Frankman et al. 2012). All treatments resulted in significant reductions in fire intensity. Very little of the crown foliage was consumed in the THIN-REMOVE-1 treatment unit, indicating that this treatment was highly effective in reducing crown fire under these burn conditions. The THIN-REMOVE-1 and THIN-REMOVE-2 units resulted in lower heating time and cumulative energy load than the SHEAR and SHEAR-ROW units. Air temperatures and incident peak energy fluxes were substantially below the ignition threshold of 300 °C and 20 $kW\cdot m^{-2}$ (Babrauskas 2002) for all treatments except the SHEAR unit where the measured peak total heating reached 50 $kW\cdot m^{-2}$. Heating time was longest in the shearblade treatment as a result of long-duration burning of the residual slash albeit at relatively low intensities. The SHEAR unit exhibited broad-scale burning as indicated by the charring and scorching of the soil. The residual slash in the windrows in the SHEAR-ROW unit did not burn intensely and very little scorching of soil was observed. The low air temperatures associated with this unit suggest that flames were dispersed and much shorter than the 1.0 m height of the sensors.

It is possible that in a dry season, significantly higher fire intensity could occur in the thin and burn units. However, it can be postulated that in years subsequent to the treatment, the effectiveness of the thinned treatment could supersede that of the shearblade treatments due to the fire risk associated with the higher fine fuel (grass) loading in the shearblade that would be susceptible to fire versus the potential for higher fine fuel moisture levels in the lower moss layers in the thinned unit that could act to reduce fire intensity. Clearly, a desired additional treatment to the shearblade treatments would be to burn the residual slash remaining after the winter broadcast burn to remove the potential for ignition of the remnant slash under high fire risk conditions.

Active crown fire stopped after burning less than 30 m into the THIN-REMOVE-1 treatment, likely because tree canopy density was not sufficient to support crown fire as well as the removal of ladder fuels. Smoldering continued in the ground fuels for several days after the event, but eventually stopped within 65 m of the treatment edge. Slash and duff in the SHEAR-ROW unit were consumed after several days of smoldering combustion. Clearly, the shearblade treatments will modify a crown fire, but their effect on forest succession and conversion from conifers to hardwoods remains a question for consideration.

Weather

Consistent multiyear differences in weather observations and duff layer moisture measurements indicate that the thinned treatments experienced windier (average and gust), warmer (air temperature), and dryer (relative humidity) conditions than the control, at least over the period sampled. The dryer live and dead moss likely contributed to the increase in forest floor consumption as compared with the THIN-REMOVE-1 control.

Lessons learned

Several lessons can be identified. (1) Project managers underestimated the time and subsequent cost required for the treatments (see supplementary material). Future similar efforts should carefully consider labor and equipment costs required to apply the specified treatments. (2) The ground fuels consisted primarily of moss and duff layers that were susceptible to compression from personnel entering the units. Efforts were made during entry to the units to walk as dispersed groups rather than along lines or paths; however, in some cases, paths developed. Although it appears that these paths did not affect crown fire spread and intensity, they possibly affected surface fire spread in the thinning treatments. (3) The placement of Remote Automatic Weather Stations (RAWS) at the site provided researchers with the capability to monitor current and past weather from their respective locations. This timely information facilitated communications and travel planning. (4) Location of the study site near Fairbanks reduced travel times from the sites to staging and lodging facilities. (5) Images gathered from an infrared camera placed in a helicopter assisted interpretation of the fire behavior. (6) More than 1500 digital photographs of the treatments pre- and post-fire were collected. A repository of data, images, and video footage is maintained at the Alaska Fire Science Consortium (http://www.akfireconsortium.uaf.edu). (7) Additional research and discussion is warranted on the impacts of the different treatment options on forest succession.

Conclusions

This study is the first of its kind testing the effect of four fuel treatments on fire intensity in the boreal forests of Alaska. The anecdotal ($n = 1$) evidence suggests that all treatments significantly reduced fire intensity. The thinning treatment modified fire behavior while maintaining an aesthetical appearance that closely matches the original forest stand; it also led to the lowest peak heating rates and was the most effective in stopping fire spread. The shearblade treatments produced the lowest air temperatures with some indication that grass loads that could develop in years subsequent to the treatment could facilitate fire spread across the entire treatment area.

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