TEMPORAL AND SPATIAL VARIATION OF BROADLEAF FOREST FLAMMABILITY IN BOREAL ALASKA

By

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Abstract

The boreal forest is a carbon reservoir containing roughly 40% of the world's reactive soil carbon, which is mainly cycled by wildland fires. Climate warming in boreal Alaska has changed the wildfire regime such that an increase in broadleaf forest relative to conifer forest is likely, which may reduce landscape flammability. However, the current and future flammability of broadleaf forest in a warming climate is not well understood. We used pre-fire and post-fire geospatial data to investigate the flammability of upland boreal forest patches in Interior Alaska in relation to summer weather conditions. Our objectives were to assess burning of broadleaf forest patches during "Normal" vs. "Large Fire Years", by week within a fire season, and by topographic position. Using 30-meter land-cover and fire-severity grids, we estimated the flammability of upland broadleaf forest patches during Large and Normal Fire Years. We then tested for topographic effects using a solar radiation index to eliminate potential deviations within the vegetation. Finally, Moderate Resolution Imaging Spectroradiometer (MODIS) hotspots were used to track the spatial extent of burns during the fire season by examining the periods of fire activity and intensity. Flammability of broadleaf forest patches varied both in time and space. Even during Normal Fire Years, broadleaf forest patches exhibited substantial flammability, with a mean of over 50% patch area burned. Patch flammability was significantly higher during Large Fire Years. Burning of broadleaf patches varied with topographic position and correlated with potential insolation. Broadleaf forest patches burned most frequently in late June-early July. Contrary to "*conventional wisdom*", broadleaf forest patches in boreal Alaska are susceptible to burning even during Normal Fire Years. With climate warming, the flammability of broadleaf forest is likely to increase due to more extreme fire weather events. Thus, although the frequency of broadleaf forest patches on the landscape is likely to increase

with more frequent and severe wildfires, their effectiveness as a fire break may decrease in the future.

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Chapter 1. Introduction

The boreal forest is the largest terrestrial biome, covering 15% of the terrestrial surface, and it acts as a globally substantial carbon reservoir by containing roughly 40% of the world's reactive soil carbon, which is similar to the amount held in the Earth's atmosphere (Melillo et al. 1993; Näsholm et al. 1998; IPCC 2001). Boreal forests have experienced warming in response to the rising levels of atmospheric greenhouse gases (Chapman and Walsh 1993; McGuire et al. 2006). Models predict the most pronounced warming to continue to affect the high northern latitudes, with substantial warming in air temperature occurring there over the next century (IPCC 2001; Kasischke and Stocks 2012).

The potential for an increased release of carbon from the boreal forest has significance for the global carbon cycle and hence for the global climate (IPCC 2001). Wildland fires can increase carbon emissions during burning and can cause decreases in albedo, causing warming of soils and an increase post-fire decomposition (Balshi et al. 2009; Flannigan et al. 2009). With boreal forests warming rapidly, predicted changes in the fire regime can increase the amount of carbon released into the atmosphere, further warming the Earth.

Within the Alaskan boreal forest, the climate and fire regime have changed in recent decades. Because of climate change, Alaska is warming at twice the speed of the contiguous U.S. with the boreal forests increasing the most in mean annual air temperature (Bieniek et al. 2014). The Alaskan fire regime is shifting toward increased fire size and severity, and decreased fire return interval (Calef et al. 2015). For example, in boreal Alaska, three of the four largest annual area burned estimates since 1950 have occurred since 2004 (Barrett and Kasischke 2013).

The Alaskan boreal forest is characterized by few tree species, all of which are adapted for establishment following fire. The most abundant tree species is the highly flammable black spruce (*Picea mariana*), which possesses semi-serotinous cones (Viereck and Schandelmeier 1980). Additionally, upland boreal forest contains the broadleaf species Alaska paper birch (*Betula neoalaskana*) and aspen (*Populus tremuloides*). These species produce light, wind-distributed seeds, and also sucker or sprout vegetatively following fires (Van Cleve et al. 1991). Low severity wildfires in the region tend to favor self-replacement by black spruce and broadleaf trees and shrubs, while high severity fires can allow for broadleaf seedlings to establish on mineral soil within stands that were previously black spruce (Johnstone et al. 2010, Shenoy et al. 2011).

The goal of my research was to investigate the flammability of broadleaf vegetation by examining their spatial and temporal dynamics during the summer fire season. My objectives were: 1) to assess broadleaf forest flammability during Large Fire Years compared to Normal Fire Years (less than 1 million hectares burned within a fire season across the state of Alaska), 2) to assess the effect of landscape position on broadleaf forest flammability, and 3) to assess the temporal effect of changing broadleaf forest flammability within the summer wildfire season. With climate warming, the flammability of broadleaf forest is likely to increase due to more extreme fire weather events. By examining the flammability of broadleaf forest under various spatial and temporal conditions, we can better prepare for the potential increase that is expected.

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Chapter 2. Temporal and spatial variation in the flammability of broadleaf forest in boreal Alaska

Abstract

Context Climate warming has altered the wildfire regime in boreal Alaska. One predicted outcome is a potential reduction in landscape flammability due to an increase in broadleaf forest relative to conifer forest. However, the current and future flammability of broadleaf forest in a warming climate is not well understood.

Objectives To investigative the flammability, likelihood of burn, of upland boreal forest patches in Interior Alaska, we used pre-fire and post-fire geospatial data. Our objectives were to assess burning of broadleaf forest patches during Normal (less than 1 million hectares burned within a fire season across the state of Alaska) vs. Large Fire Years by week within a fire season, and by topographic position.

Methods We estimated the flammability of upland broadleaf forest patches during Large and Normal Fire Years using 30-meter land cover and fire severity grids. We then looked at variation in broadleaf burning base on topographic effects using a solar radiation index to eliminate potential deviations within the vegetation. Finally, Moderate Resolution Imaging Spectroradiometer (MODIS) hotspots were used to track the spatial extent of burns during the fire season by examining the periods of fire activity and intensity.

Results Flammability of broadleaf forest patches varied in both time and space. Normal Fire Years showed a mean patch burned of over 50% patch, while Large Fire Years showed a higher mean patch area burned with over 75%. Burning of broadleaf patches varied with topographic position as indexed by potential insolation. Finally, broadleaf forest patches burned most

frequently in late June-early July with over 90% of the patches having burned by late July. Similarly, conifer forest patches burned most frequently in late June- early July; however, conifers didn’t cumulatively burn over 90% of the patches until early August.

Conclusions Contrary to the belief that broadleaf forest stands act as fire break, broadleaf forest patches in boreal Alaska were susceptible to burning even during Normal Fire Years. With shifting fire regimes, an increase in the flammability of broadleaf forest is likely due to more extreme fire weather events. Thus, broadleaf forest effectiveness as fire breaks during fire-control operations will decrease in the future despite the frequency of broadleaf forest patches on the landscape is likely to increase with more frequent and severe wildfires.

2.1 Introduction

One of the largest sinks of terrestrial carbon, the boreal forest is the largest terrestrial biome on earth (Pan et al. 2011). With climate warming, increased wildfires could result in increased carbon emissions from burning as well as from increased soil respiration from thawing permafrost and warming soils (Flannigan et al. 2009). Several shifts in fire regime of boreal Alaska have occurred over the past 11,000 years in response to a combination of changes in climate and vegetation (Hu et al. 1996).

The fire regime in Interior Alaska is now shifting toward more frequent, larger, and more severe fires (Kasischke and Turetsky 2006; Kasischke et al. 2010; Calef et al. 2015). In boreal Alaska, three of the four largest annual area burned estimates since 1950 have occurred since 2004 (Barrett and Kasischke 2013). Broadleaf forest are considered potential wildfire fuel breaks (Dash et al. 2016) with studies supporting potential for negative feedback, which would eventually decrease fire frequency and size (Johnstone et al. 2011). However, the flammability or likelihood of burning in broadleaf forests (aspen and birch) is likely higher during these larger fire years (Kasischke and Turetsky 2006). Understanding the current and historical flammability of broadleaf forest will aid in our ability to understand the changing role of vegetation on the boreal fire regime.

Forest flammability varies by vegetation type in Alaska's boreal forest and creates complex feedbacks influencing the distribution and abundance of vegetation in boreal forests (Viereck 1973; Foote 1983; Wurtz et al. 2006). Black spruce (*Picea mariana*) is the most common cover type and can be highly flammable due to their high canopy resin content and the ladder fuels they supply from the ground to the upper canopy (Johnstone et al. 2011). Lichens, feathermosses and resinous shrubs in the understory of black spruce stands are also highly flammable (Johnson

1992). In contrast, aspen and birch (*Populus tremuloides, Betula neoalaskana*) stands have lower canopy bulk density, less flammable resins, higher canopy-moisture content, and reduced ground and ladder fuels; all factors that contribute to their lower flammability (Johnstone et al. 2011). For example, in the Jefferson Lake Fire (Pike National Forest, Colorado), fire spread ceased within four meters after entering an aspen stand and stopped without any human control activities (Fechner and Barrows 1976). Because of the lower flammability, aspen and birch stands have been thought of as potential wildfire fuel breaks during the summer season (Fechner and Barrows 1976; Alexander 2010). In the Rocky Mountains, aspen has been described as an "asbestos forest" (DeByle et al. 1987) because it does not commonly exhibit the extreme fire behavior usually characteristic of coniferous forests during the summer fire season (Wright and Bailey 1982). It follows that increased fire severity and fire frequency could lead to an increase in broadleaf forest stands, which could then feedback on the fire regime to decrease overall landscape flammability (Kitzberger et al. 2012; Terrier et al. 2013). However, with climate warming, the flammability of broadleaf forests may increase.

The fire regime of the Alaskan boreal forest could change due to vegetation changes across the landscape. For example, relative to current climate, a warm, dry climate 10,000-8000 years before present (BP) encompassed a decrease in fire frequency associated with a shift from flammable shrub tundra (dominated by *Betula* spp.) to aspen woodland. An increase in flammable black spruce around 5550 years BP triggered an increase in fire frequency despite a cooler and moister climate (Lynch et al. 2002; Higuera et al. 2009; Blarquez et al. 2015). Fire frequency remained similar with a warmer, drier climate during the Medieval Climate Anomaly (~500-1000 years before present), perhaps because black spruce declined while aspen increased on the landscape (Kelly et al. 2013). As the climate continues to warm, fire regime will likely continue to change throughout the 21st century (Balshi et al. 2009; Mann et al. 2012).

With climate warming, the landscape flammability may decrease because an increase in wildfire severity and frequency may lead to a decrease in the ratio of conifer to broadleaf forest (Mann et al. 2012). This reduced flammability may reduce the effects of climate warming on boreal fire regimes. Krawchuk et al. (2006) found that forest vegetation explained more variation in wildfire initiation than weather indices in the mixed wood boreal forest of Canada. However, the relatively low flammability of deciduous forest stands may change under extreme warm, dry climates. For example, De Rose and Leffler (2014) concluded extreme fire weather conditions could negate the "fire proof" nature of aspen stands. Johnstone et al. (2011) projected greater future wildfire activity because the future increase of broadleaf forest in the boreal landscape would not compensate for the effect of severe climate warming in boreal Alaska.

Interaction between climate warming and changing vegetation composition on the landscape can feedback onto the fire regime (Turner and Romme 1994; Mann et al. 2012; Barrett and Kasischke 2013). Change in landscape flammability may occur due to predicted changes in vegetation composition through increased dominance of broadleaf forest, which may affect the fire regime (Krawchuk et al. 2006). For example, Cumming (2001) found preferential burning of conifers in compositional analysis of a boreal mixed-wood area in Alberta, Canada. Dash et al. (2016) focused on land cover interactions with weather conditions and found that land cover significantly influenced Alaska boreal forest burning. This was exhibited by the high flammability of conifers, which had the greatest percentage of area burned over other land cover types. However, Dash et al. (2016) found during warmer and drier summers a significantly greater area burned including vegetation considered to have low flammability like broadleaf forest. A potential negative feedback may occur as the climate warms: increase in fire severity and frequency leading to black spruce replaced by broadleaf forest patches, leading to decreased landscape flammability (Chapin et al. 2000; McGuire et al. 2006). However, this negative feedback may not counteract increased fire activity with climate warming based on modeling of forest dynamics in conjunction with various fire-regime scenarios (Johnstone et al. 2011). Thus, a key question is how flammable are broadleaf forest patches? Our research examines variation in broadleaf forest flammability and seeks to contribute to the assessment of the effects of landscape flammability.

To investigate the following questions, we used pre-fire and post-fire geospatial data in an upland boreal landscape of interior Alaska. How flammable are broadleaf forest patches in the Alaskan boreal forest? What is the spatial and temporal variation in broadleaf flammability? We expected flammability of broadleaf patches to vary, depending on the time of year burned, topography, and a given year's fire season characteristics. In particular, we expected Large Fire Years (years with greater than one million hectares burned within an Alaskan fire season) to experience more broadleaf burning, cooler slopes to be less flammable relative to warmer slopes, and a decrease in broadleaf burning from June to August.

2.2 Methods

Interior Alaska is a region bound by the Alaska Range to the south and by the Brooks Range to the north. A strongly continental climate occurs because of the mountains acting as barriers to maritime air masses, resulting in cold winters and warm, relatively dry summers. Solar input varies seasonally, with more than 21 hours and a solar noon elevation of 49° during the summer solstice in June, and less than 16 hours daylight and a solar elevation of 33° in late August. Mean annual temperature is below freezing, resulting in permafrost in many valley bottoms and north-facing slopes. Temperature ranges from below -40°C in January to over 30°C in July (Stafford et al. 2000). The precipitation ranges from 200 mm to over 400 mm (Stafford et al. 2000). The climate has warmed significantly in the past 100 years (Wendler and Shulski 2009), with the current summer temperature regime the warmest of the past 200 years (Barber et al. 2004).

We chose two ecoregions in boreal Alaska that have the greatest current area of broadleaf forest and relatively high fire frequency: the Ray Mountains and Yukon-Tanana Uplands (Fig. 1). The Ray Mountains ecoregion is dominated by black spruce woodlands with white spruce (*Picea glauca*), birch, and aspen growing on warm, south-facing slopes. Permafrost is present across a majority of the ecoregion in varying levels of thickness and is discontinuous.

The Yukon-Tanana Uplands ecoregion is defined by broad, rounded mountains, which are dominated by black spruce on north-facing slopes and on ridge tops, with tussock and scrub bogs in valley bottoms. White spruce, birch, and aspen dominate on south-facing slopes. The ecoregion had the highest occurrence of lightning strikes in Alaska and the Yukon Territory, leading to frequent forest fires (Dissing and Verbyla 2003). Approximately 15% of the boreal forest (elevation < 500 m) has burned in the last 50 years within these two ecoregions.

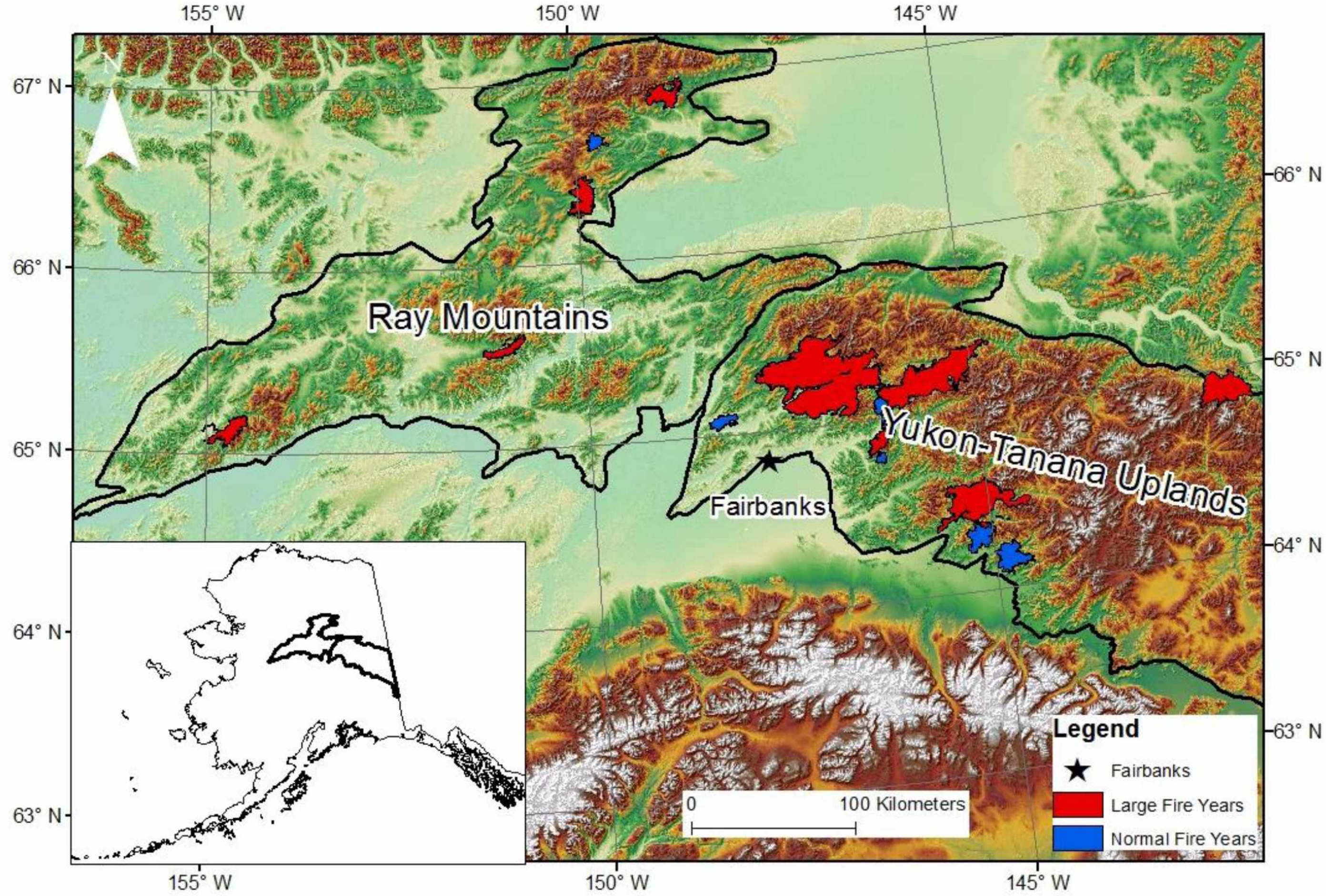


Fig. 1 Ray Mountains and Yukon Tanana Uplands Ecoregion polygons. Years since 2001 with less than one million hectares burned across Alaska in a fire season were classified as Normal Fire Years and those with greater than one million hectares burned classified as Large Fire Years.

To delineate broadleaf forest, we used the 2001 National Land Cover Database (NLCD) (Selkowitz and Stehman 2011) in our study area. The NLCD contains 16 vegetation classes based on 30-m resolution Landsat imagery. We selected broadleaf forest pixels and created broadleaf patches by lumping adjoining pixels within each fire perimeter. Within the ecoregions, the broadleaf forest consisted of about 13% of the total forested pixels. A total of 32,909 pre-fire broadleaf patches were delineated within fire perimeters. For temporal comparison with broadleaf flammability during a fire season, we also delineated conifer forest pixels and created conifer patches from adjoining pixels within each fire perimeter.

To access the accuracy of the NLCD broadleaf forest classification, we used high resolution 2011 Quickbird satellite imagery from unburned areas in the Yukon-Tanana Uplands ecoregion from September when broadleaf forests appeared yellow in color and spruce forest appeared green in the imagery. We generated 900 random locations and visually interpreted as “broadleaf forest” or “not broadleaf forest” at these random points. We then extracted the NLCD pixel class at each random location for accuracy assessment of NLCD broadleaf forest pixels.

Pre-fire broadleaf patches were based on the 1999-2001 Landsat imager (Selkowitz and Stehman 2011), therefore we evaluated wildfires that burned after 2001. We used fire perimeter and burn severity products from the Monitoring Trends in Burn Severity (MTBS) database (http://www.mtbs.gov/data/individualfiredata.html). The MTBS data are developed through analysis of pre- and post-fire Landsat data, applying a standardized and consistent methodology generating products at a 30-m resolution beginning in 1984. We classified “Large Fire Years” as years with greater than one million hectares burned across Alaska’s yearly fire season (Fig. 2). Since 2001, Large Fire Years occurred in 2004, 2005, 2009, and 2015 (Fig. 2). “Normal Fire Years” were classified as years since 2001 with less than 1 million hectares (Fig. 2).

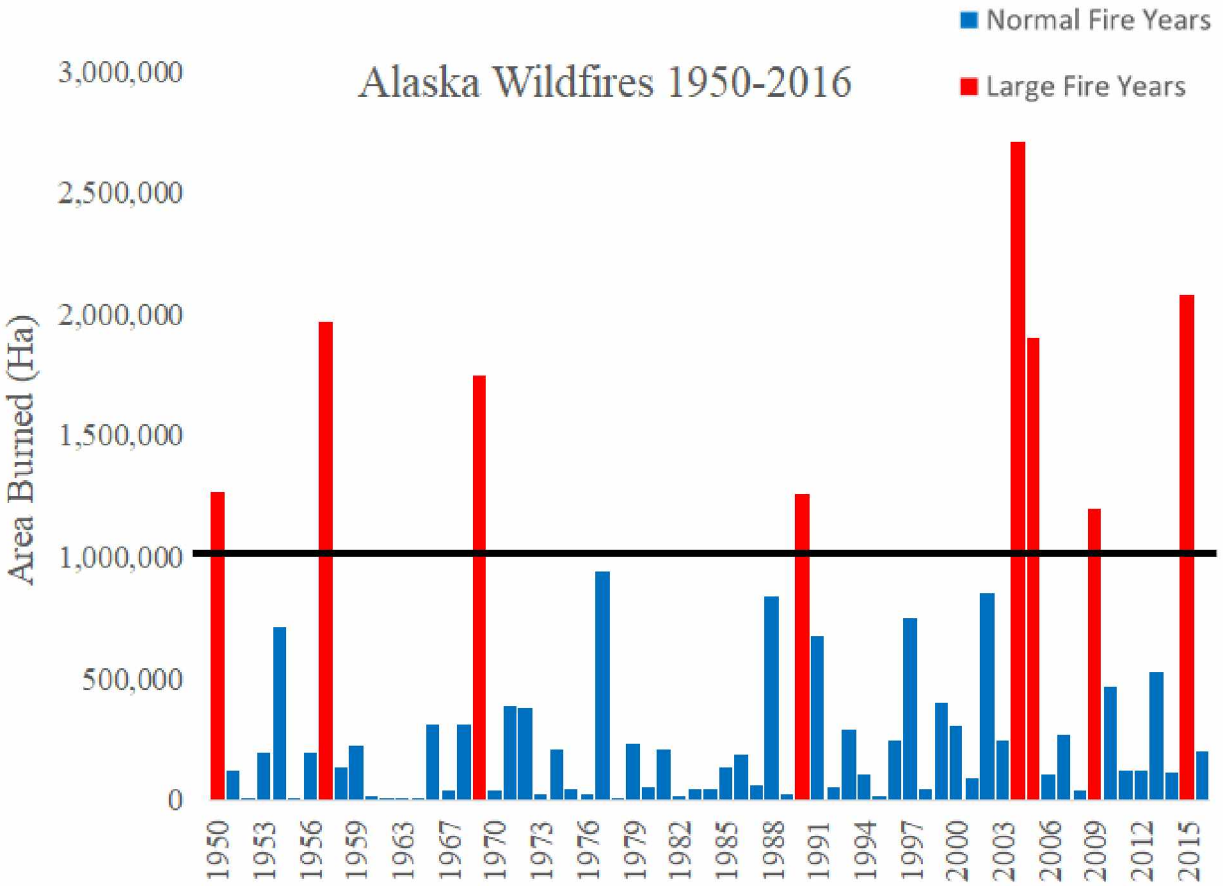


Fig. 2 Annual area burned in Alaska since 1950 according to the Alaska Large Fire Database (https://afsmaps.blm.gov/imf/imf.jsp?site=firehistory). We used a threshold of 1,000,000 hectares to represent Large Fire Years. Large Fire Year burns selected from the study area were fire perimeters from 2004, 2005, 2009, 2015. To represent Normal Fire Year burns, we selected study area fire perimeters from 2002, 2003, 2007, 2010, 2011.

We selected 15 fires from Large and Normal Fire Years by using the NLCD broadleaf forest classification and the MTBS fire perimeters that had substantial pre-fire broadleaf forest patches (Table 1). For Large Fire Years, we selected the nine largest fires that exceeded 10,000 hectares. As might be expected, fire perimeters were relatively small during Normal Fire Years, and we selected six fire perimeters exceeding 2,000 hectares (Fig. 2). Of all the forested pixels in both

Large and Normal Fire Years, approximately 11% of the wildfire area was pre-fire broadleaf forest based on the NLCD classification.

Table 1 Listed descriptions of the 15 Normal and Large Fire Years, which included six fire perimeters from Normal Fire Years (shaded in gray) and nine fire perimeters from Large Fire Years.

Fire Name	**Fire Year**	**Discovery Date**	**Elevation Range (m)**	**Area Burned (ha)**	**Percent Broadleaf Forest from Forested Classes**
Normal Fire Years					
West Fork Chena	2002	05/23/2002	252-1068	9058	12
Sand Creek	2003	06/14/2003	329-1176	20148	11
Hodzana River	2007	05/22/2007	360-1024	7416	34
Granite Tors	2010	05/27/2010	284-910	3281	15
East Volkmar	2011	05/26/2011	327-993	19689	11
Hastings	2011	05/30/2011	137-759	10280	18
Large Fire Years					
Wolf Creek	2004	06/08/2004	314-1249	92405	7
Boundary	2004	06/13/2004	198-1223	217789	11
Deer Creek	2004	06/15/2004	291-1407	38478	10

Camp Creek	2004	06/23/2004	326.-1315	70189	8
Tors	2004	07/17/2004	226-1028	12951	15
Crash Creek	2009	07/04/2009	209-932	9994	12
West Fork	2015	06/19/2015	137-966	24989	8
Hardpac Creek	2015	06/21/2015	273-1168	20979	32
Glacier	2015	06/23/2015	149-1318	15335	9

To retroactively quantify the flammability of each broadleaf patch, we estimated the proportion of each patch that was burned. Within each fire perimeter, we delineated all burned pixels based on the MTBS burned classes of low, moderate, and high burn severity according to the Differenced Normalized Burn Ratio (dNBR). Unburned pixels from each broadleaf patch were then delineated as post-fire broadleaf patches. Thus, each broadleaf patch included estimates of the pre-fire and post-fire patch area. These pre-fire and post-fire patches were used to calculate the percentage burn, which we called the flammability of the broadleaf patch.

We restricted our study area to upland landscapes since birch and aspen occur mainly in the uplands. To eliminate tall willow riparian patches along riparian corridors and valley bottoms, we eliminated any pixel with a slope gradient of less than ten percent. We also used a flow accumulation function to eliminate pixels of high flow accumulation that typically were riparian drainages. These eliminations were based on an elevation raster at 30-m pixel size that was downloaded and reprojected from the United States Geological Survey (USGS) (https://nationalmap.gov/elevation.html). The elevation grid was used both to remove from analysis non-upland broadleaf patches and to compute potential solar radiation.

To investigate the potential effect of slope gradient/direction and topographic position on the vulnerability of broadleaf forest to burning, we computed a potential solar radiation index (Rinas et al. 2017). Potential solar radiation was computed for each 30-m pixel on a 0.5-hour interval for the months of May through September with a transmittance of 0.5 (Rinas et al. 2017). For each broadleaf forest patch, the mean potential solar radiation was computed over this period of the year.

To assess the changing flammability of broadleaf stands within a fire season, we analyzed the rate at which broadleaf and conifer pixels burned within weekly time intervals throughout the fire season. The Moderate Resolution Imaging Spectroradiometer (MODIS) thermal anomaly product locates in 1-km pixels that are burning at the time of satellite overpass under relatively cloud-free conditions using a contextual algorithm (Giglio et al. 2003). For each of the nine perimeters from Large Fire Years (Table 1), daily hotspots (centroids of the 1-km fire detections of a composite dataset from Terra and Aqua MODIS fire and thermal anomalies data) within the MTBS perimeters were retrieved from fire MODIS data (https://fsapps.nwcg.gov/afm/gisdata.php?sensor=modis&extent=alaska). We extracted hot spots for individual fires over seven-day periods from June 5th through September 17th during the Large Fire Years of 2004, 2009, and 2015. Weekly burn polygons were created from the weekly hot spot points using a kernel density function based on a search radius of 1000 km and an output cell size of 100 km (Ziel 2016). Kernel densities were then converted into polygons and used to determine broadleaf and conifer flammability and occurrence within the summer fire season.

We compared the difference in broadleaf flammability between Normal and Large Fire Years with the program R-script, which tested whether the difference in patch flammability by broadleaf forest size class with a one-way analysis of variance (ANOVA). To determine which size classes were different, we applied a post-hoc Tukey Honest Significant Difference (HSD) multiple comparison procedure. The null hypothesis was that the mean percentage of the area burned did not differ during the Normal versus Large Fire Years among 13 patch area classes.

To test for topographic effects on broadleaf flammability, we calculated potential isolation (intensity of solar radiation) and constructed a solar radiation index, which was classified into five groups using a natural breaks classification. We tested whether there was an increase in flammability as potential insolation increased. To examine the effect of potential insolation on broadleaf forest on a landscape, we also compared the frequency distribution of broadleaf versus conifer pixels across a gradient of solar radiation to see the range of distribution in the vegetation with different flammability levels.

To determine temporal distribution in broadleaf and conifer flammability within the summer fire season, weekly metrics were computed. These included patch frequency (count of burned broadleaf/conifer patches within each week), percentage of hectares burned (broadleaf forest burned per week divided by the total broadleaf/conifers burned), and cumulative hectares burned for June through August during Large Fire Years. These distributions were compared with a hypothetical weekly uniform distribution throughout the summer fire season.

2.3 Results

Examining the overall broadleaf flammability in the two ecoregions during the chosen fire years, we found that across the ecoregions over 57% of all broadleaf forest pixels burned and within the fire perimeters about 80% of broadleaf patches burned. Broadleaf patches burned substantially more during Large Fire Years across all patch size classes. During Large Fire Years, 58% of broadleaf forest pixels and 82% of broadleaf patches burned while only 46% of broadleaf forest pixels and 70% of broadleaf patches burned during Normal Fire Years. The greatest number of fires occurred within the Yukon Tanana Uplands, an ecoregion known for high lightning strike occurrence.

How accurate was the NLCD broadleaf forest class? Based on 900 random locations, 342 of the 384 broadleaf forest locations were correctly classified (89%) by comparing the NLCD to high resolution imagery (Table 2). The remaining random locations that were not broadleaf forest were correctly classified at 100% accuracy (Table 2).

The percentage of broadleaf forest within a fire perimeter varied substantially (Table 1). Most broadleaf forest patches were in relatively small size classes with a similar frequency distribution for Normal versus Large Fire Years (Fig. 3). Patches created from the adjoining pixels ranged in size from one hectare to 1733 hectares. The greatest percentage of patches occurred in size classes of one and four hectares (Fig. 3). Over 75% of all broadleaf patches were smaller than six hectares in size. Also at larger patch sizes, there is a trend towards a greater percent frequency in

Normal Fire Years than Large Fire Years.

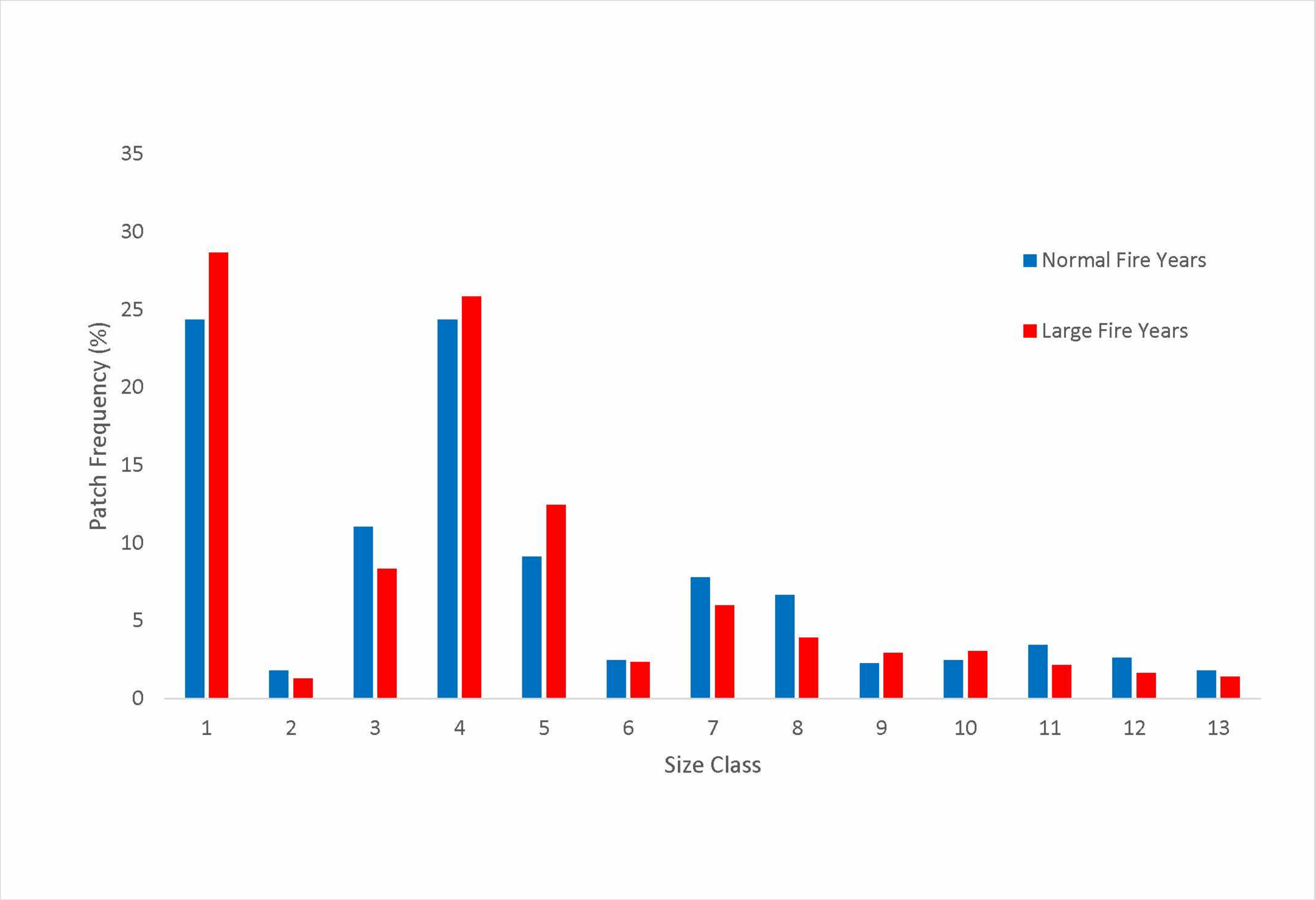


Fig. 3 Frequency (%) of pre-fire broadleaf forest patches across all fire scares examined separated by size class (ha). Size classes (ha): 1: < 1.5ha, 2: 1.5-2.5ha, 3: 2.5-3.5ha, 4: 3.5-4.5ha, 5: 4.5-5.5ha, 6: 5.5-6.5ha, 7: 6.5-7.5ha, 8: 7.5-8.5ha, 9: 8.5-9.5ha, 10: 9.5-10.5ha, 11: 11.5-30.5ha, 12: 30.5-50.5ha, 13: > 50ha

Table 2 Accuracy assessment via error matrix comparing the frequency of 2001 NLCD (rows) broadleaf forest and non-broadleaf forest to the frequency of ground truths (columns) from high resolution imagery based on 900 random locations.

	Truth	**Truth**	
NLCD 2001	Non-Broadleaf	Broadleaf Forest	Total 2001 NLCD Pixels
Non-Broadleaf	516	0	516
Broadleaf Forest	0	342	342
Low Intensity Developed	0	1	1
Broadleaf Shrub	0	41	41
Total Random Points	516	384	900
Truth Accuracy (%)	100%	89%	95%

We examined broadleaf flammability across two temporal scales. First, we compared Large Fire Years versus Normal Fire Years, and second we looked at flammability variation across the fire season.

Burning of broadleaf patches was greater during Large Fire Years relative to Normal Fire Years (Fig. 4). Patch percent area burned was significantly greater in size classes of one, three, and four hectares, during Large Fire Years compared to Normal Fire Years (One-Way ANOVA, f-ratio= 44.98, p-value < 0.00001, $p < 0.05$). Normal Fire Years burned on average over 50% of the area in all broadleaf patches, while in Large Fire Years on average over 75% of area burned within all broadleaf patches (Fig. 4). Even in Normal Fire Years, broadleaf forest patches were not resistant to burning.

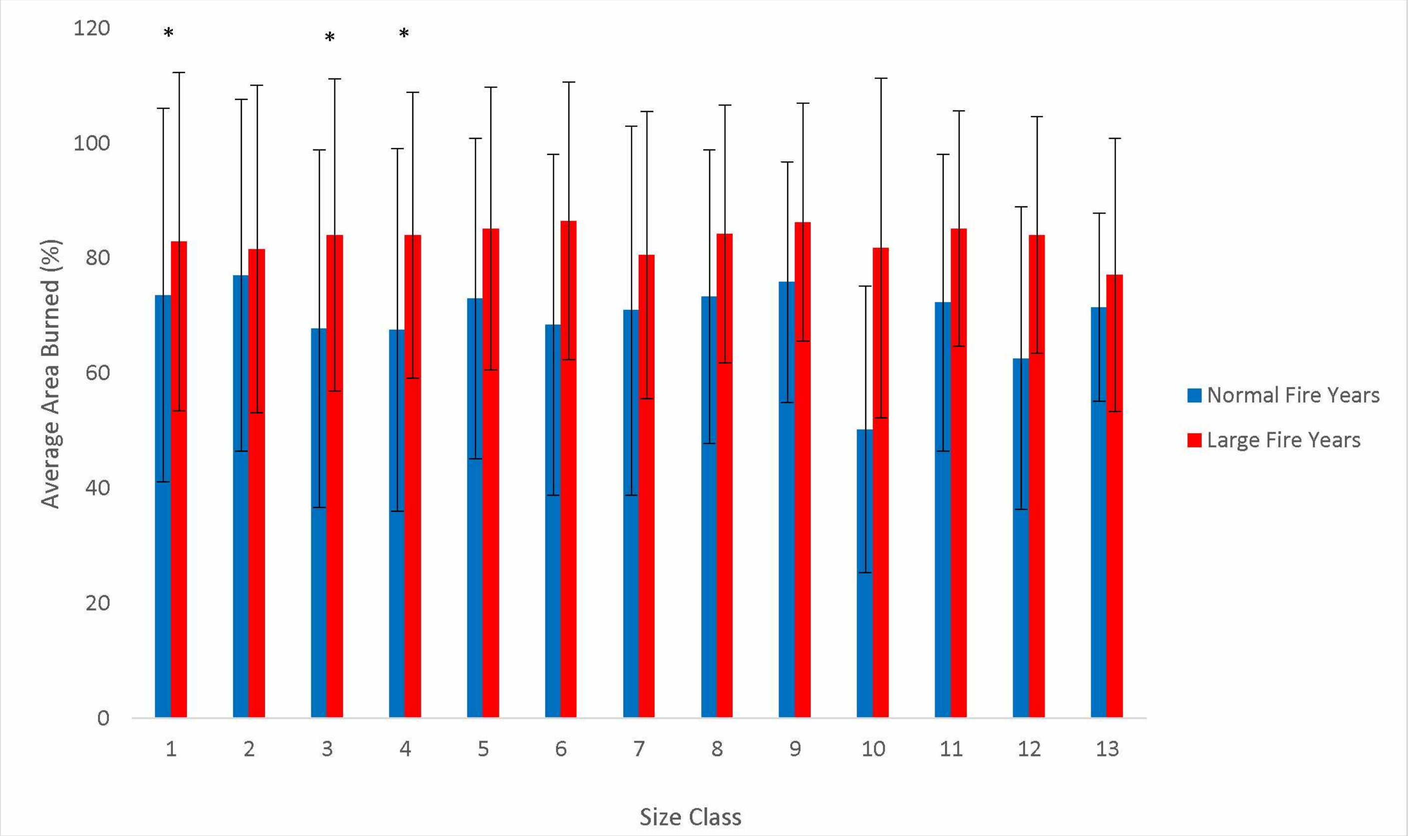


Fig. 4 Percent area burned within broadleaf forest patches by size class during Normal versus Large Fire Years. Mean percent area burned was significantly greater during Large Fire Years compared to Normal Fire Years (One-Way ANOVA, *f*-ratio= 44.98, p-value < 0.05). Asterisks represent significant difference according to a post-hoc Tukey Honest Significant Difference (HSD) multiple comparison procedure. Size classes (ha): 1: < 1.5ha, 2: 1.5-2.5ha, 3: 2.5-3.5ha, 4: 3.5-4.5ha, 5: 4.5-5.5ha, 6: 5.5-6.5ha, 7: 6.5-7.5ha, 8: 7.5-8.5ha, 9: 8.5-9.5ha, 10: 9.5-10.5ha, 11: 11.5-30.5ha, 12: 30.5-50.5ha, 13: > 50ha

The mean area burned was significantly different among the radiation classes. There was a weak, but statistically significant difference in broadleaf forest flammability in relation to solar insolation gain controlled by topographic position (Table 3). Broadleaf patches occurred on warmer sites compared to conifer patches. For example, there was a significant difference in potential insolation between where broadleaf forest patches tended to occur versus conifer forest patches. Over half the broadleaf forest patches occurred at locations with mean potential insolation above 550,000 (WH/m^2/5 months), while less than five percent of conifer patches occurred at locations with higher potential insolation ($R^2 = 0.01$, $p< 0.001$, $n = 3,179$) (Fig. 5). There was a weak positive trend ($R^2 = 0.01$) in broadleaf forest flammability as a function of potential insolation (Fig. 6).

Table 3 Broadleaf forest patches by potential solar radiation class. The mean area burned was significantly different among the radiation classes (One-way ANOVA, $p < 0.001$).

Solar Radiation Index (WH / m2/ 5 months)	Patch Frequency	Average Area Burned (%)	SD
300,000 < x < 450,000	236	79.56	0.30
450,000 < x < 500,000	476	79.18	0.31
500,000 < x < 550,000	953	82.03	0.28
550,000 < x < 600,000	1367	85.37	0.25
x > 600,000	148	86.63	0.27

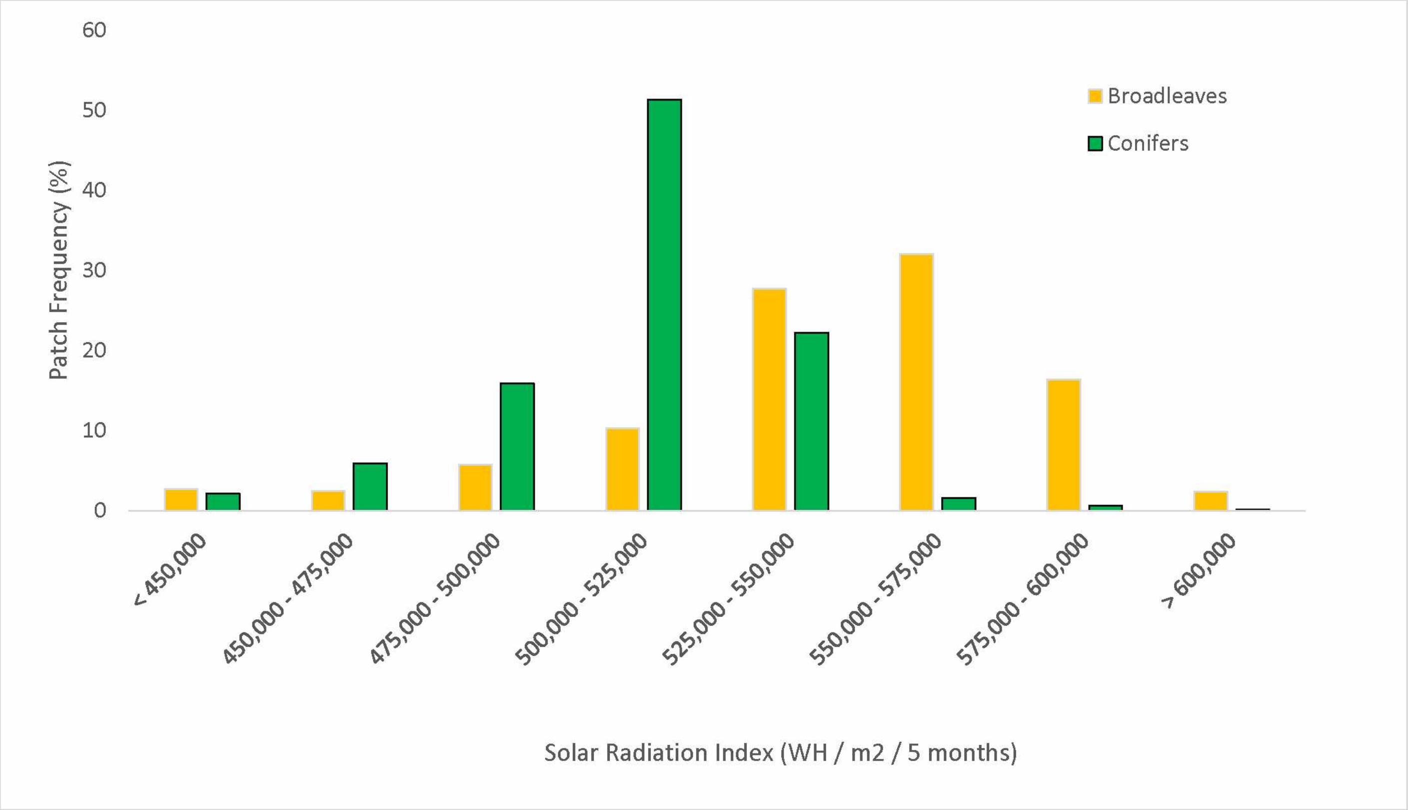


Fig. 5 Frequency distribution of broadleaf forest and non-broadleaf forest pixels within Large Fire Year fire perimeters. The mean potential insolation of broadleaf forest pixels was significantly different than non-broadleaf forest pixels (2-tailed T-test, $p < 0.0001$, n= 83704).

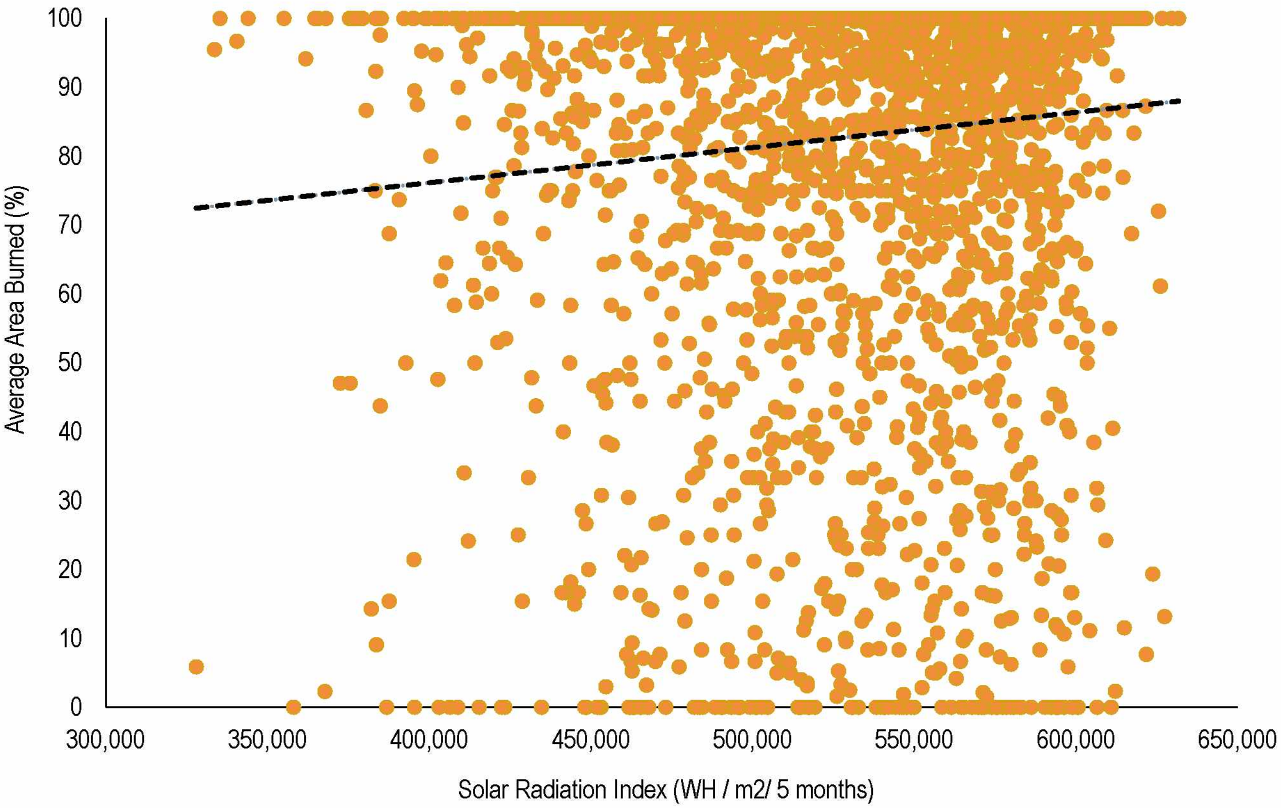


Fig. 6 Trend in broadleaf patch flammability as a function of potential insolation ($R^2 = 0.01$, $p < 0.001$, n = 3,180 broadleaf forest patches).

Weekly burn polygons were derived from the MODIS hotspot locations within each fire perimeter from the Large Fire Years (Fig. 7). If a fire progressed at a constant rate, as the fire grew the areal extent of burning would increase. The majority of burning occurred in late June/early July across the Large Fire Years combined, with both the greatest frequency of broadleaf and conifer patches and the greatest area of broadleaf and conifer forest burning during the same interval. However, some Large Fire Years started later in the season and caused, later peaks of greatest burn of broadleaf forest that deviated from the average trend (Table 4). By mid-July, over 90% of the summer's broadleaf forest burning was completed (Fig. 8). However, the summer's conifers forest burning only reached 90% completion in early August.

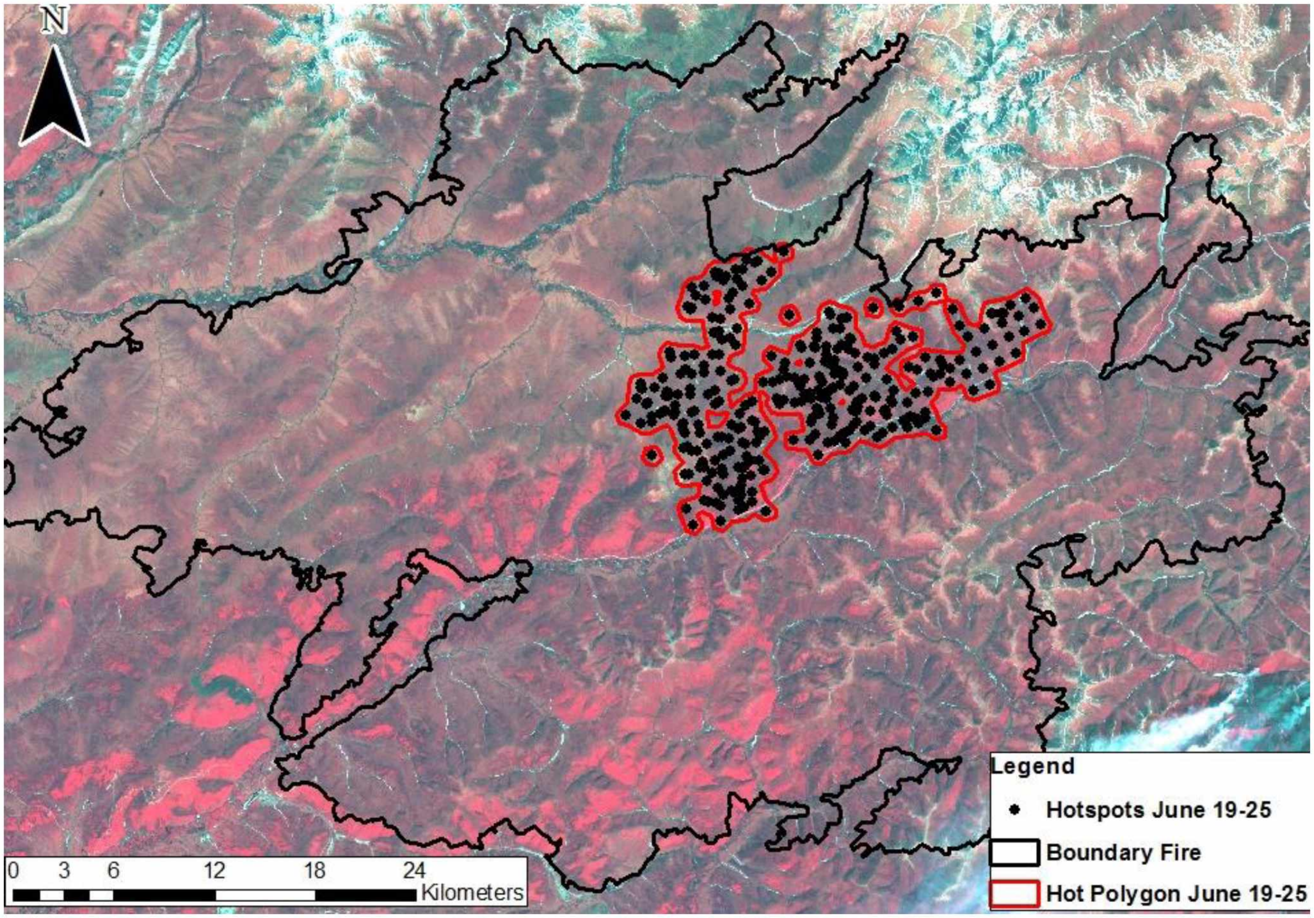


Fig. 7 Hot polygon, representing one week, created from MODIS hotspot locations within portion of 2004 Boundary Fire, Northeast of Fairbanks. Background image is the near-infrared band from Landsat TM where the bright red patches are high in near-infrared reflectance due to broadleaf canopy.

Table 4 The weekly interval of fire perimeters from Large Fire Years where over 90% of the cumulative broadleaf patches burned. Week of fire seasons by fire perimeter when over 90 percent of broadleaf patches were cumulatively burned. Each fire was from a Large Fire year because a relatively large fire perimeter was more appropriate with 1km MODIS hot spot data.

Fire Name	**Week of Fire Season**
Boundary	07/17/04 - 07/23/04
Camp Creek	08/07/04 – 08/13/04
Crash Creek	07/31/09 – 08/06/09
Deer Creek	07/03/04 – 07/09/04
Glacier	06/26/15 – 07/02/15
Hardpac Creek	07/03/15 – 07/09/15
Tors	08/21/04 – 08/27/04
West Fork	07/10/15 – 07/16/15
Wolf Creek	08/07/04 – 08/13/04

a

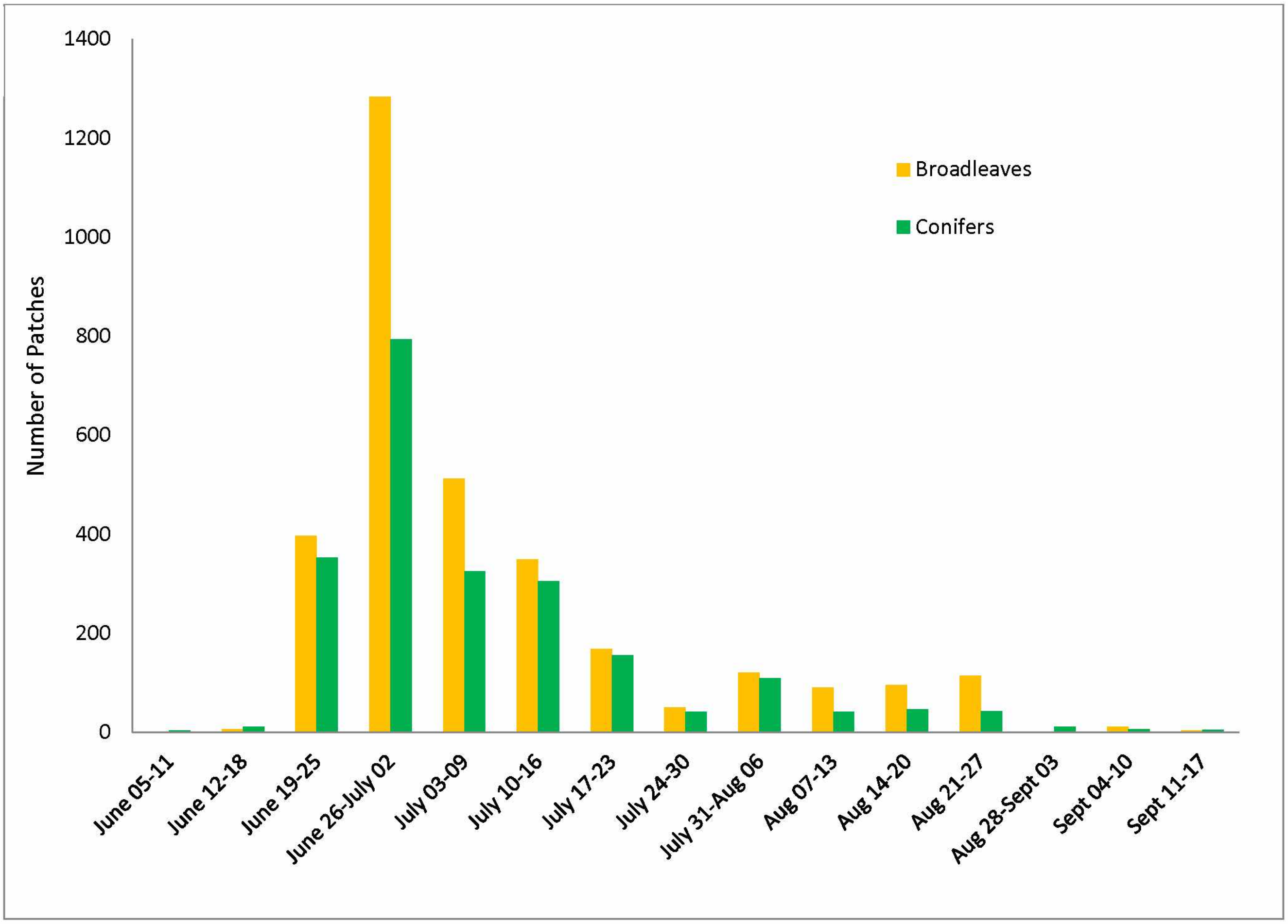
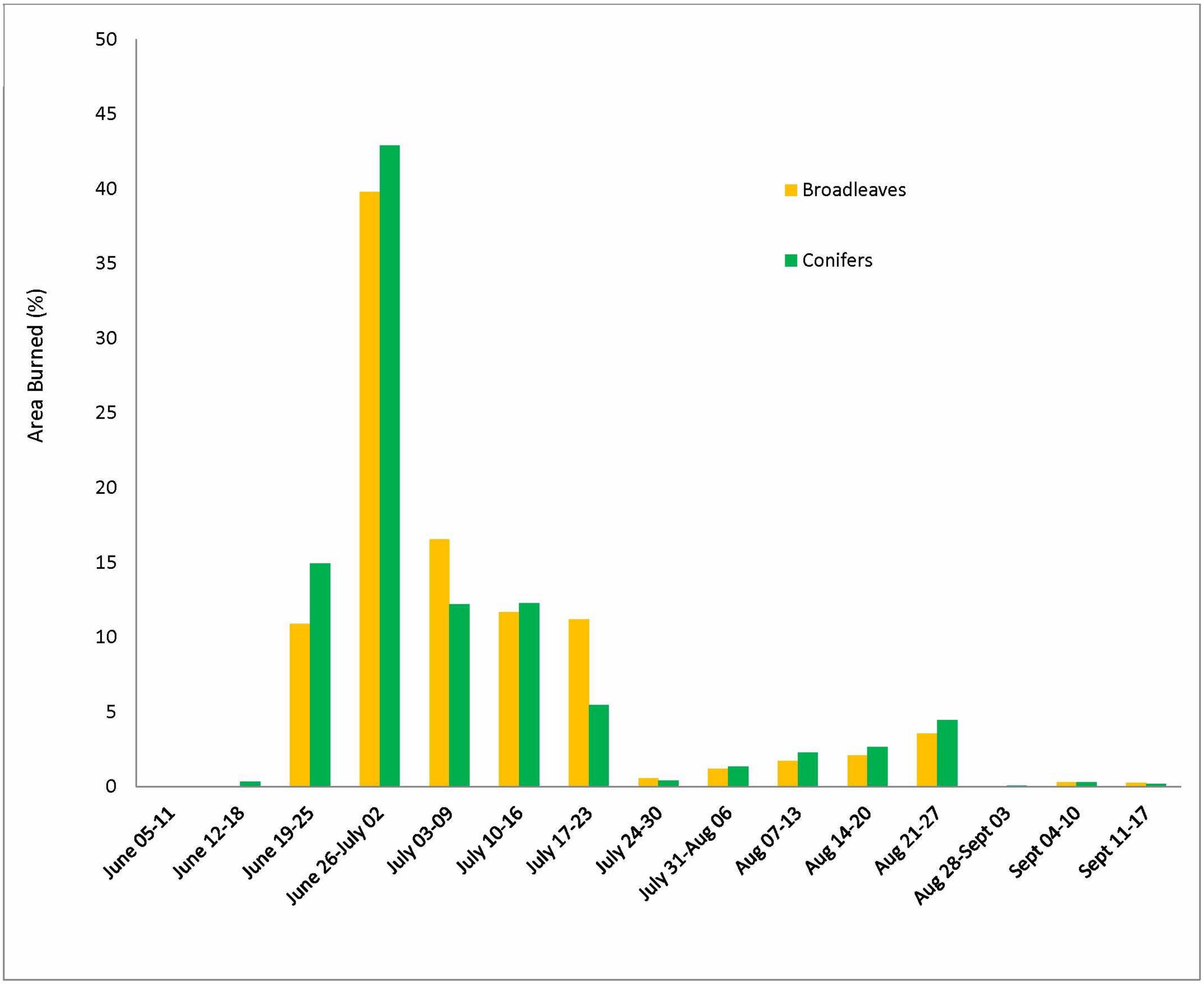


Fig. 8 a Frequency of broadleaf and conifer patches burned from the Large Fire Years over the fire season of June 5th through September 17th. The greatest frequency of burned broadleaf and conifers patches per week and the greatest percentage of broadleaf and conifer patches burned happened during June 26-July 02 (a, b). **b** Fractional area of broadleaf and conifer patches burned during Large Fire Years over the fire season. **c** Cumulative percentage of broadleaf and conifer patches burned in Large Fire Years over the fire season. The cumulative percentage of broadleaf hectares per week summed all previous weeks and increased between June 19-25 (10.94%) to June 26- July 02 (50.75%). By July 17- July 23, over 90% of the broadleaf total area burned across the fire seasons. Over 90% of the conifer total area burned across the fire seasons by July 31- August 06.

b



Area Burned (%)
50
45
40
35
30
25
20
15
10
5
0
Broadleaves
Conifers
June 05-11
June 12-18
June 19-25
June 26-July 02
July 03-09
July 10-16
July 17-23
July 24-30
July 31-Aug 06
Aug 07-13
Aug 14-20
Aug 21-27
Aug 28-Sept 03
Sept 04-10
Sept 11-17

Fig. 8 (cont.)

c

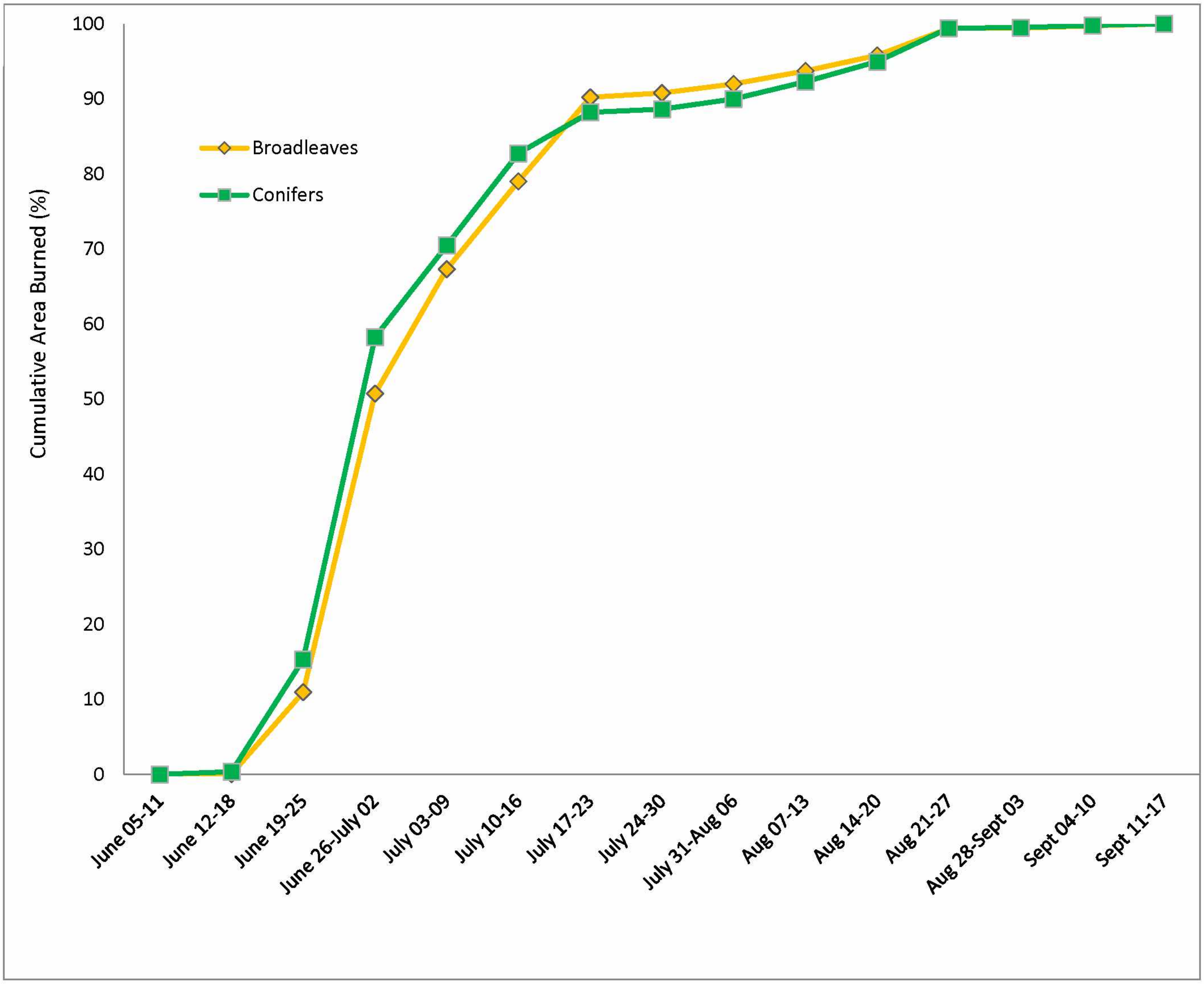


Fig. 8 (cont.)

2.4 Discussion

The summer climate regime of boreal Alaska is now the warmest over the past 200 years (Barber et al. 2004). As the climate continues to warm, the fire regime is also changing. These changes include increases in fire frequency (Kelly et al. 2013) and larger, more severe fires (Kasischke and Turetsky 2006; Kasischke et al. 2010; Calef et al. 2015). As a result of the changing fire regime, an increase in broadleaf stands on the landscape is predicted (Mann et al. 2012). Our goal was to examine how broadleaf forest variability varies among years, within a summer fire season, and by topographic position. We found that broadleaf stands, in general, are more flammable than earlier predicted.

Our ecoregions were upland sites that had high occurrence of fire and broadleaf patches; however, on lowland sites broadleaf forest patches winds are not driving factors in fire behavior. Lowland sites may have more cold, wet drainages or substantial water bodies that act as fire barriers. The flammability variations in broadleaf forest could be different in these lowland sites compared to the upland sites of our ecoregions.

How accurate was the broadleaf forest class? Based on 900 random locations on high resolution autumn imagery, all NLCD 2001 broadleaf forest pixels were correctly classified (Table 2). Some random locations in 2001 broadleaf forest class were misclassified as broadleaf shrub, which is likely due to the temporal difference between the NLCD 2001 source and the high resolution imagery obtained more than a decade later. In comparison, Selkowitz and Stehman (2011) had a broadleaf producer's classification accuracy of only 60% for their statewide assessment of Alaska. Our higher percentage of accuracy was likely due to most broadleaf forest stands occurring as relatively large stands of aspen or birch in the boreal uplands, while Selkowitz and Stehman (2011) assessed the accuracy of broadleaf forest throughout all of Alaska, which includes lowland areas.

In comparing Normal and Large Fire Years, ignition dates of Normal Fire Years were earlier in the fire season than during Large Fire Years (Table 1), which was likely related to our selecting of the largest fires during Normal Fire Years. Due to normal climate conditions, the fires during the Normal Fire Years spread slowly throughout the summer fire season and thus needed a long period of fire growth to attain their final area of greater than 2,000 hectares. Our fire perimeters from Normal Fire Years had ignition dates mostly in May, while fire perimeters from Large Fire Years had ignition dates from June and July.

We found a trend of broadleaf forest patches burning to increase with the changing fire regime, which if it continues would likely increase broadleaf flammability during the extreme fire seasons that are associated with Large Fire Years (DeRose and Leffler 2014; Johnstone et al. 2011). To examine the trend, we looked at relative rates of burning, ignition dates, and differences in fire between Normal Fire Years (representing the historic fire regime) and Large Fire Years (representing potential future fire regime with an increase frequency and severity of Large Fire Years (Rupp et al. 2002)). Broadleaf forest patches burned more during Large Fire Years relative to Normal Fire Years consistently across all patch size classes (Fig. 4).

Landscape flammability is likely to change with a warming climate, changing fire regime, and changing vegetation mosaic. Decreased landscape flammability may occur as climate warming and increased wildfire severity and frequency leads to a reduction of highly flammable black spruce in future boreal landscapes (Mann et al. 2012; Johnstone et al. 2011). At some sites, high fire frequency can also maintain broadleaf stands over many decades (Mann and Plug 1999). However, our analysis suggests that the flammability of broadleaf forest may increase as the climate continues to warm due to more frequent, intense, and severe fires, and extreme fire weather increasing broadleaf flammability. Similarly, Johnstone et al. (2011) concluded that landscape vegetation is unlikely to fully compensate for changes in the fire regime due to climate warming. In the presence of Large Fire Years, fire-induced changes in the vegetation cannot have negative feedbacks on the fire regime.

We expected large broadleaf patches to burn less in terms of areal percentage due to less edge in large stands (Fechner and Barrows 1976). However, the flammability of broadleaf forest did not decrease as patch size increased. For example, the broadleaf patch in the largest size class that had the greatest area/perimeter ratio burned at a similar rate as smaller patches (Fig. 9). Despite “conventional wisdom” (Dash et al. 2016), numerous broadleaf patches burned during Normal Fire Years (Fig. 4). This result is important because some landscape-level models assume broadleaf forest patches are low in flammability (Terrier et al. 2013; Rupp et al. 2002).

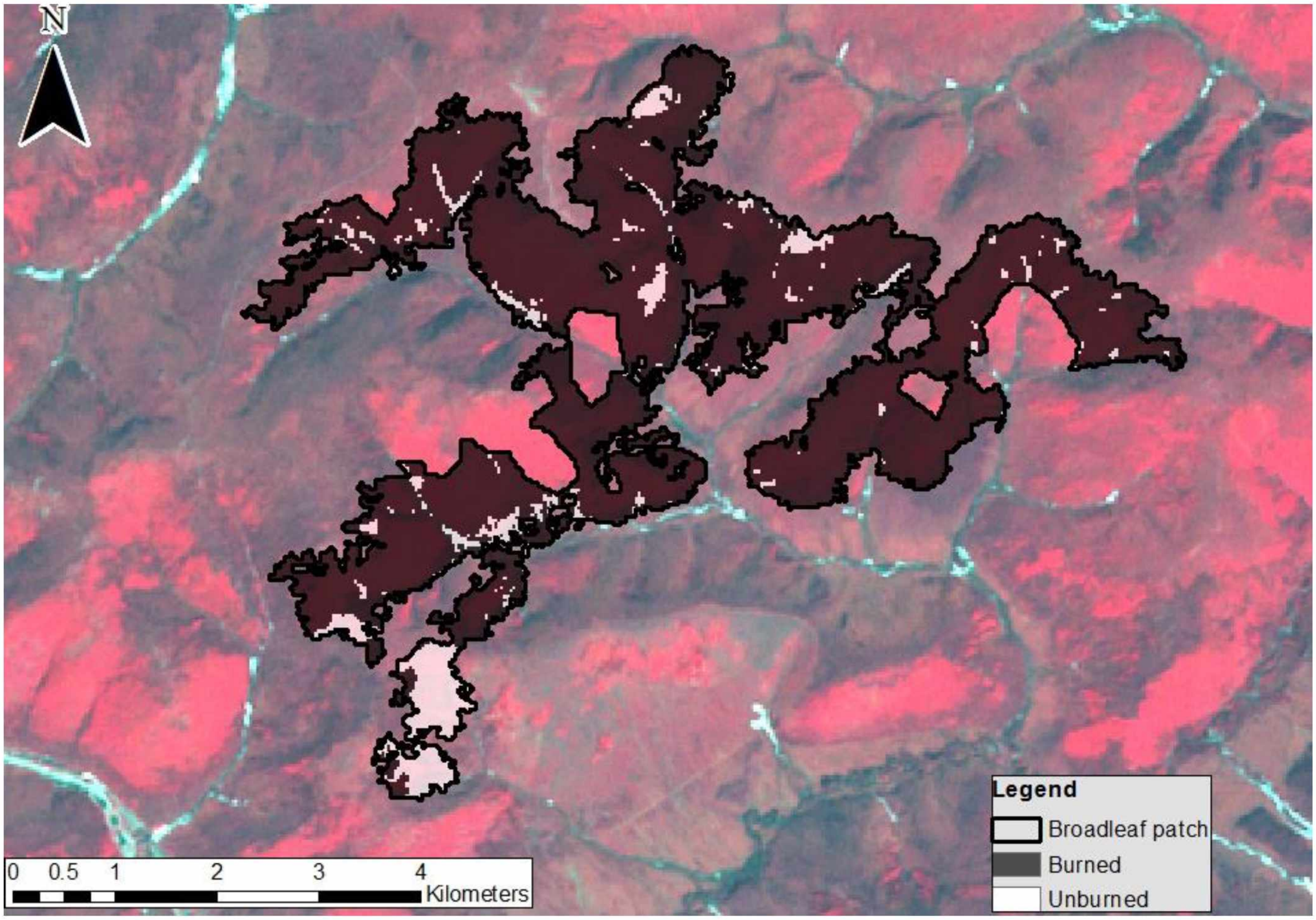


Fig. 9 Broadleaf patch from adjoining broadleaf forest pixels in Boundary Fire with burned and unburned pixels utilized to quantify flammability. Example of a large broadleaf patch (1,733 ha) that had 90% of area burned. Background image is the near-infrared band from Landsat TM where the bright red patches are high in near-infrared reflectance due to broadleaf canopy.

As climate warming continues, the effectiveness of broadleaf vegetation as a fire break may be reduced. Our results support Barrett and Kasischke (2013) that, in boreal Alaska, broadleaf forest are less flammable than spruce, but not completely fire resistant. Even during Normal Fire Years, broadleaf flammability exceeded 50% (Fig. 4). This contrasted previous studies suggesting that broadleaf forest are fire resistant (Pu et al. 2007; Kasischke and Hoy 2012). Pu et al. (2007) found that deciduous and mixed stands are more resistant to burning relative to conifers when examining North American wildfires through mapping of fire perimeters across the boreal and temperate forest of US and Canada. Examining the influence of vegetation type of the interior Alaska fire regime, Kasischke and Hoy (2012) found stands dominated by broadleaf forest were generally more fire resistant. However, we found broadleaf flammability was consistently greater during Large Fire Years compared to Normal Fire Years. The flammability of broadleaf forest might increase substantially if the climate continues to warm past a threshold. Alexander (2010) suggested that a threshold in fuel conditions and fire weather was exceeded enabling fire spread in broadleaf forest stands in Alaska and Canada. Based on lake sediment records, boreal deciduous forests burned at high intensities under a warm, dry climate in the Early Holocene (Hudspith et al. 2014).

We expected greater flammability of broadleaf forest patches with higher potential insolation which were likely warmer and drier sites as potential insolation varies with slope direction, slope gradient, and slope position (topographic shading). Broadleaf patches did occur on sites with higher potential insolation relative to spruce patches (Fig. 6). The higher insolation sites also were likely to have a less flammable understory of feathermosses that are common on cool sites. Broadleaf flammability consistently increased among potential insolation classes (Table 3). This may be due to a reduction in vegetation flammability, a warmer and drier microclimate, and/or changes in fire behavior associated with slope position as potential insolation increased. There was a weak positive trend in flammability and potential insolation among all broadleaf patches (Fig. 5). This may have been due to confounding temporal factors related to fire weather such as hour of burning; for example, afternoon burning with low humidity, high winds, high temperature compared to early morning burning with high humidity, no wind, cooler temperature. A broadleaf site also likely had a lower flammability late in the fire season when solar heating, low humidity, high winds, and extreme fire weather were less likely.

As wildfires continue to burn throughout the summer, the weekly area burned will increase. For example, Johnson (1992) reconstructed the 1950 Chinchaga River fire which burned the whole fire season with rapid growth periods during September. The Chinchaga River fire reconstruction examined the potential cause of large fires in the boreal forest being an early spring ignition followed by a whole season burning.

We expected a time period of greatest burning over the fire season (Ziel 2016). The majority of broadleaf and conifer forest burning occurred in late June/early July and over 90% of the total broadleaf forest area burned occurred before the end of July (Fig. 8). In contrast, the total conifer forest area burned had not reached over 90% until early August. Thus, overall, broadleaf forest and conifers were most flammable during a narrow window of time relative to the summer fire season. Rapid fire growth over a few days during Large Fire Years such as 2004 has been documented (Ziel 2016), probably due to high solar heating, low relative humidity, and high winds during the extreme fire events. For example, during the summer of 2015 was a Large Fire Year, ranking second to 2004 in terms of total annual area burned since 1950. In 2015, rapid fire growth followed a week-long lightning event that began on June 19th, including three consecutive days with over 12,000 strikes daily in Alaska. This seven day period gave rise to nearly 300 fire starts, with wildfires burning over 1.4 million hectares in 20 days. By July 15th, cooler and damper conditions prevailed and most of the annual area burned had occurred (Strader and Alden 2015).

Our analyses show that broadleaf flammability is greatest during late June/early July, which we compared closely with (Ziel 2016) and contrasted with (Barrett and Kasischke 2013) similar previous examination of hotspot data. Ziel (2016) concluded there was a narrow window during which most burning occurs during a fire season based upon examination of the correlation between fire danger indices and MODIS fire. Our analyses of broadleaf forest support the notion that there is a distinct interval for greatest burn. Barrett and Kasischke (2013) examined MODIS fire detections, incorporating residual burning, between what they classified as small and large fire years with a focus on the fire intensity based upon the Fire Radiative Power (FRP) or boreal wildfire intensity. They found that there was a difference in seasonality, with large fire years having about 63% of broadleaf fire activity occurring after July 19th (Barrett and Kasischke 2013). In contrast, over 60% of broadleaf forest burned by early July in Large Fire Years in our analysis. This is potentially due to how Barrett and Kasischke (2013) classified percent burned and Large Fire Years versus how we did. For example, Barrett and Kasischke (2013) classified large fire years as having one percent (~ 48,000 hectares) of the boreal forest area burn while we classified it as greater than one million hectares burned across all of Alaska during a fire season.

The seasonal timing of burning can influence the post-fire vegetation composition. It affects whether a black spruce site might be converted to an aspen/birch site because depth to mineral soil is a strong control on post-fire seedling establishment (Johnstone et al. 2010). Typically, during August burning, the depth of the unfrozen organic horizon is maximized allowing for “deep burning” with a higher likelihood of burning the organic horizon to mineral soil, allowing for potential aspen/birch seedling establishment. The August 4, 2004 Boundary Fire had 95% of the broadleaf forest burned prior to July 24th, 2004 (Fig. 10) avoiding the deeper burn.

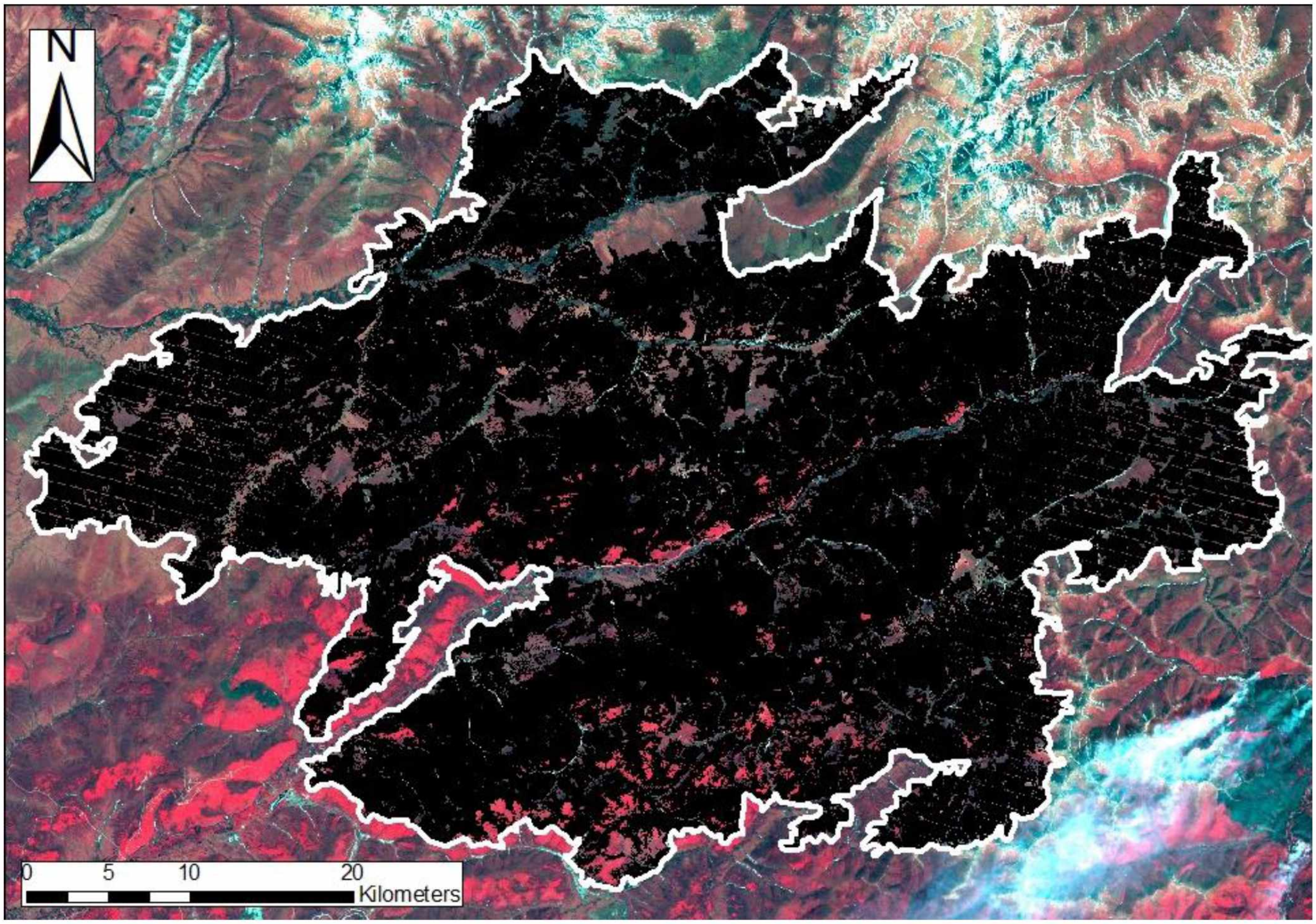


Fig. 10 Normalized Burn Ratio (NBR) from post-fire Landsat imagery within the Boundary Fire where 95% of the broadleaf forest burned prior to July 24th, 2004 when a partially frozen active layer was possible on cooler black spruce sites. Background image is the near-infrared band from Landsat TM where the bright red patches are high in near-infrared reflectance due to broadleaf canopy.

Our research began to examine the facets of broadleaf flammability both temporally and spatially. By understanding broadleaf flammability, predictions of vegetation composition and potential changes in the fire regime linked to it can be more accurate. This has implications for the shift of the fire regime, associated with climate change, and related distribution and types of vegetation. We found that warming climate and consequent changes in the fire regime can affect broadleaf flammability. The continued trend of increased frequency and severity in fires could result in greater flammability of broadleaf forest. Our research is important as many models still have flammability of broadleaf forest relatively low making their predictions inaccurate, which will not allow those who use the knowledge, such as fire managers, to be prepared for the future. Contrary to conventional wisdom, broadleaf forest patches in boreal Alaska are susceptible to burning even during Normal Fire Years. However, Normal Fire Years had a lower probability of broadleaf flammability more consistently than Large Fire Years. With climate warming, the flammability of broadleaf forest is likely to increase due to more extreme fire weather events. Thus, although the frequency of broadleaf forest patches on the landscape is likely to increase with more frequency and severe fires, their effectiveness as a fire break will probably decrease in the future. Examining the spatial components, the consistent increase of solar radiation on the landscape suggests vegetation, environmental, or fire weather changes occurring. Finally, we found broadleaf forest were most flammable during a narrow window of time relative to the summer fire season.

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Chapter 3. Conclusion

Boreal forest covers about 31% of the Alaska's interior region (Van Cleve et al. 1991). The boreal forest is experiencing a rapid period of warming, with the current summer climate the warmest in the past 200 years (Barber et al. 2004). Climate warming is predicted to affect the fire regime, which has a strong relationship with the vegetation composition and distribution. In return, vegetation changes across the landscape interact with and change the fire regime in a feedback loop. Both sides of the interacting relationship between vegetation and fire regime, though is changing with climate warming (Fig. 11).

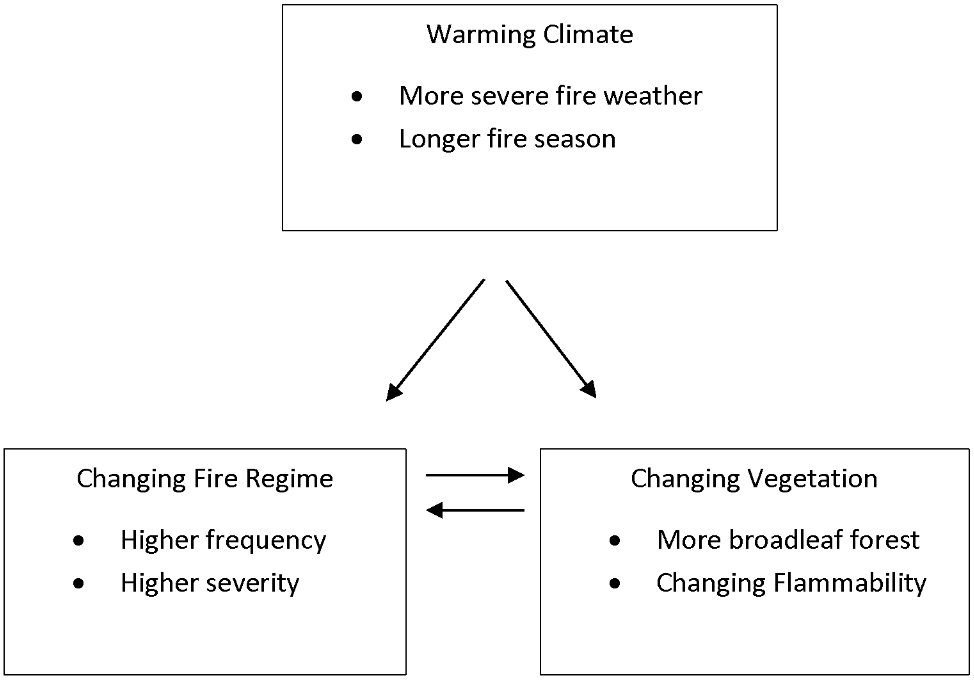

Fig. 11 Diagram of the interactions between the warming climate, the changing fire regime, and the changing vegetation.

The goal of our research was to investigate the flammability of broadleaf forest in response to spatial and temporal dynamics. We examined Large and Normal Fire Years, timeframe of burn, and the influence of solar radiation on burning of broadleaf patches in the boreal forest, which suggested an increase of broadleaf flammability due to a changing climate and fire regime. Broadleaf flammability is expected to change with the shift in the fire regime to more frequent (Kelly et al. 2013), intense, and severe fires (Kasischke and Turetsky 2006; Kasischke et al. 2010; Calef et al. 2015). With climate warming, changes in fire regime and broadleaf forest flammability are likely in the future (Johnstone et al. 2011).

The ratio of broadleaf forest to spruce forest may have already increased on Alaska's boreal landscape (Mann et al. 2012), shifting the ratio between them and conifers. Because the flammability of broadleaf forest can affect the spread of wildfire across the landscape (Johnstone et al. 2011), understanding broadleaf flammability can help with predicting vegetation composition and potential changes in the fire regime linked to it. This has implications for the shift of the fire regime, associated with climate change, and related distribution and types of vegetation. With the increased abilities of remote sensing and data available, the potential for generating models of future flammability of vegetation across different types is possible.

In conclusion, contrary to "conventional wisdom" broadleaf forest patches in boreal Alaska were susceptible to burning even during Normal Fire Years. With climate warming, the flammability of broadleaf forest is likely to increase due to more extreme fire weather events. Thus, although the frequency of broadleaf forest patches on the landscape is likely to increase with more frequency and severe fires, their effectiveness as a fire break may decrease in the future. With climate warming, the flammability of broadleaf forest is likely to increase due to more extreme fire weather events. Examining the spatial components, the consistent increase of solar radiation on the landscape suggests vegetation, environmental, or fire weather changes occurring. Finally, we found broadleaf forest were most flammable during a narrow window of time relative to the summer fire season.

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