

Alaska's changing fire regime — implications for the vulnerability of its boreal forests¹

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Abstract: A synthesis was carried out to examine Alaska's boreal forest fire regime. During the 2000s, an average of 767 000 ha-year⁻¹ burned, 50% higher than in any previous decade since the 1940s. Over the past 60 years, there was a decrease in the number of lightning-ignited fires, an increase in extreme lightning-ignited fire events, an increase in human-ignited fires, and a decrease in the number of extreme human-ignited fire events. The fraction of area burned from human-ignited fires fell from 26% for the 1950s and 1960s to 5% for the 1990s and 2000s, a result from the change in fire policy that gave the highest suppression priorities to fire events that occurred near human settlements. The amount of area burned during late-season fires increased over the past two decades. Deeper burning of surface organic layers in black spruce (*Picea mariana* (Mill.) BSP) forests occurred during late-growing-season fires and on more well-drained sites. These trends all point to black spruce forests becoming increasingly vulnerable to the combined changes of key characteristics of Alaska's fire regime, except on poorly drained sites, which are resistant to deep burning. The implications of these fire regime changes to the vulnerability and resilience of Alaska's boreal forests and land and fire management are discussed.

Résumé : Une synthèse a été effectuée pour étudier le régime des feux de la forêt boréale en Alaska. Durant les années 2000, le feu a détruit en moyenne 767 000 ha·an⁻¹, soit une superficie 50 % plus grande qu'au cours de n'importe quelle décennie précédente depuis les années 1940. Au cours des 60 dernières années, le nombre de feux de foudre a diminué, les feux de foudre majeurs ont augmenté, les feux d'origine humaine ont augmenté et le nombre de feux majeurs d'origine humaine a diminué. La proportion de la superficie brûlée par des feux d'origine humaine a chuté de 26 % au cours des années 1950 et 1960 à 5 % au cours des années 1990 et 2000 à cause d'un changement de politique de gestion du feu qui accordait la plus haute priorité à la suppression des feux qui surviennent près des établissements humains. La superficie brûlée par les feux de fin de saison a augmenté au cours des deux dernières décennies. Les horizons organiques de surface ont été brûlés plus en profondeur dans les forêts d'épinette noire (*Picea mariana* (Mill.) BSP) par les feux de fin de saison et sur les stations les mieux drainées. Toutes ces tendances contribuent à rendre les forêts d'épinette noire plus vulnérables aux changements combinés des caractéristiques clés du régime des feux en Alaska, à l'exception des stations mal drainées qui sont résistantes aux feux de profondeur. La discussion porte sur les conséquences de ces changements des caractéristiques du régime des feux sur la vulnérabilité et la résilience des forêts boréales de l'Alaska et sur la gestion des feux de forêt.

[Traduit par la Rédaction]

Introduction

Wildland fire is one of the most widespread and important disturbances affecting Alaska's boreal forests. Its role in regulating ecosystem processes across the North American bor-

real forest has long been recognized (Viereck 1973; Wein and MacLean 1983). Since 2000, research carried out by the Bonanza Creek LTER program and projects funded by other agencies have focused on developing a clearer understanding of how variations in the fire regime impact forest

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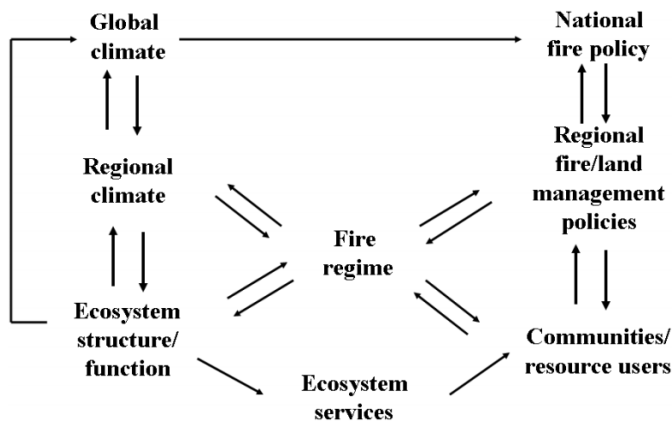
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Fig. 1. Conceptual model of the interactions among climate, ecosystems, fire, human communities, and fire policy in the Alaskan boreal forest (modified from Chapin et al. 2003, 2008).



ecosystems and the services they provide (Euskirchen et al. 2010; Johnstone et al. 2010; Jorgenson et al. 2010; Kofinas et al. 2010; Turetsky et al. 2010).

Alaska's fire regime is not only regulated by regional climate and landscape variations in physiography and ecosystem structure but also by human ignitions, regional fire and land management suppression policies, and local community actions (Fig. 1). What remains unclear is whether the net effect of these interactions will tend to maintain a constant level of fire activity in the face of global climate change or whether shifts in characteristics of the fire regime will occur. If there are no responses, then the fire regime is resilient to climate change; however, if there are, then the fire regime is vulnerable to climate change and the challenge becomes identifying which characteristics are likely to influence the vulnerability of forest ecosystems and the services they provide.

For this paper, we reviewed our current understanding of Alaska's fire regime based on new insights derived from research conducted since a previous synthesis that was based on data through the 2000 fire season (Kasischke et al. 2006). There were four areas that provided for an extension of this previous synthesis effort. First, there were four large fire years during the 2000s that burned some 6.6×10^6 ha (or 15% of the boreal forest region of interior Alaska below treeline) and their occurrence has changed many of the metrics used to quantify the fire regime. Second, more detailed information on fire events from the 1950s and data on lightning strikes have recently become available through efforts of the Alaska Fire Service to update their databases. Third, a number of field-based studies that quantified fire severity have recently taken place. And fourth, the development of fire information products from satellite remote sensing data has created new tools for the study of spatial characteristics of the fire regime.

This paper is based on a review of the scientific literature as well as new data analyses. The methods used in these additional analyses are summarized in online supplemental materials³, and the information from them is presented in

Tables 1 and 2 and Figs. 2–6. For the synthesis, we further examined the longer-term patterns of burned area in Alaska (1860–2009), reviewed a number of fire regime characteristics and factors influencing fire during the modern era (1950–2009), and assessed information generated through analysis of satellite remote sensing data. We evaluated the possible causes for variations in burned area over the past 70 years, focusing on the relative roles of changes in climate versus changes in fire management policies. We then assessed the implications of the changing fire regime in Alaska, both in terms of vulnerability and resilience of Alaska's boreal forest and in terms of ecosystem services and fire management options, and identified priorities for future research.

Longer-term trends in burned area

Combining burned area derived from climate reconstructions (1860–1939) with estimates from fire management records (1940–2009) provided for an assessment of longer-term trends in Alaskan wildfire activity (Fig. 2). Average area burned at a decadal scale was regulated by the frequency of large fire years (>470 000 ha burned), which represented 17% of all years and accounted for 68% of burned area. There was a change in Alaska's fire regime beginning early in the 20th century. Since the 1920s, there has been at least one large fire year each decade, an average of 2.3 large fire years per decade, and an average area burned of 399 700 ha·year⁻¹. The highest average annual burned area (767 000 ha·year⁻¹) occurred in the 2000s. Between 1860 and 1919, there were three decades without a large fire year, an average of 0.8 large fire years per decade, and an average burned area of 420 400 ha·year⁻¹. The highest average burned area of 264 900 ha·year⁻¹ occurred during the 1870s. The fire return interval was 159 years for 1860–1919 and 105 years for 1920–2009.

Data from the 1940s to 2000s show that the number of large fire years during the 1940s and 1950s was the same as during the 1990s and 2000s (seven), with less frequent large fire years during the intervening 30 years (4) (Fig. 3). The number of extreme fire events (>50 000 ha) was high during the 1950s, low in the 1960s through 1980s, and then rose during the 1990s and 2000s (Table 1). As a result of changes in the frequency of large fire years and extreme fire events, there was a decrease in decadal average area burned from the 1940s and 1950s through the 1980s and a rise in the 1990s and 2000s. The 2000s experienced the highest burned area and number of extreme fire events during the modern record period (Table 1; Fig. 3).

The relationship between burned area and the number of large fire years has been observed across all Canadian boreal forest ecoregions (Kasischke and Turetsky 2006). The burned area trend in Alaska over the past 70 years differs from that observed in Canada, where average burned area increased continuously from the 1940s (816 500 ha·year⁻¹) through the 1990s (3 170 700 ha·year⁻¹) (Gillett et al. 2004) before sharply decreasing in the 2000s (1 654 300 ha·year⁻¹).

³Supplementary material for this article is available on the journal Web site (<http://cjfr.nrc.ca>).

Fig. 2. Estimates of annual burned area for Alaska from 1860 to 2009. The backcast was constructed using a modified version of the regression model presented in Duffy et al. (2005), while the data from 1940–2009 are based on fire management records (see supplementary online materials for a discussion on the sources for these data).

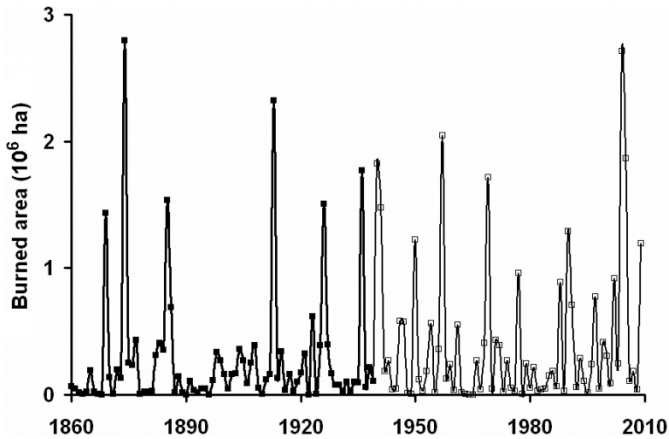
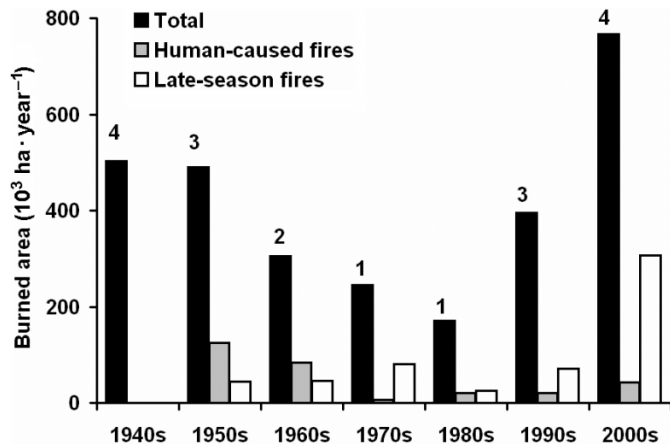


Fig. 3. Average burned areas for each decade from the 1940s through the 2000s including total burned area, burned area from human-ignited fires, and burned area during late-season fires (those occurring after 31 July). Also presented is the number of large fire years in each decade (see supplementary online materials for a discussion of the sources for these data).



Fire regime characteristics in the modern era (1950–2009)

Ignition sources: lightning versus human activities

A large proportion of the total annual lightning strikes in Alaska occurs over a few days of regional thunderstorm activity called synoptic thunderstorms. Most wildfires in Alaska, however, are ignited by localized air mass thunderstorms driven by mesoscale properties that influence convection, such as topography, albedo, surface roughness, and sensible heat flux. In the Alaskan boreal forest, the density of lightning strikes varies regionally (with an east-to-west climatic gradient) and locally (with elevation and vegetation type) (Dissing and Verbyla 2003).

A strong seasonal variation in lightning strikes existed for the boreal region of Alaska, where most (87%) occurred in June and July. These percentages were slightly higher in

large fire years compared with small fire years (89% versus 86%) (Fig. 4). There was a significant correlation between total lightning strikes and the number of lightning-ignited fires for the 2000s ($r = 0.79$, $p = 0.01$) but no significant correlation for the 1990s ($r = 0.32$, $p = 0.38$). The lack of correlation in the 1990s may be due to the lower accuracy of the lightning detection sensors at this time.

DeWilde and Chapin (2006) found that the vast majority of human-ignited fires occur in the spring (April–May) when lightning strikes are low (Fig. 4). Calef et al. (2008) found that in the sparsely populated interior Alaska, there were 20 times more human ignitions than lightning ignitions within 5 km of settlements and six times more within 5–10 km of settlements. Similarly, there were 11 times more human than lightning ignitions within 5 km of roads and three times more within 5–10 km of roads. Overall, there were twice as many human ignitions than lightning ignitions for distances up to 20 km of settlements and roads. The areas with enhanced human ignitions amounted to a total footprint of 146 840 km², or 31% of the boreal forest ecoregions of interior Alaska.

Overall, data on ignition sources show that the average number of human-ignited fires increased from the 1960s through the 1990s and then during the 2000s (Fig. 5). The number of lightning-ignited fires was highest during the 1970s and has decreased every decade since (Fig. 5). The increased number of lightning-ignited fires between the 1960s and 1970s may be due to improvements in surveillance methods and reporting criteria. Prior to the 1970s, it was widely believed that most fires in Alaska were human ignited (Lutz 1959), which may have resulted in misclassification of lightning-ignited fires when sources were not known. For both human and lightning fires, there were significantly more fires during large fire years compared with small fire years (two-sample t test, $p < 0.07$: lightning-ignited fires: large fire years, 228 ± 36 (mean \pm SE), versus small fire years, 168 ± 18 ; human-ignited fires: large fire years, 343 ± 28 , versus small fire years, 283 ± 19).

These results suggest that the number of human-ignited fires is likely to continue to increase in the future if Alaska's population continues to grow. The higher number of fires occurring during the drier conditions that are found in large fire years compared with small fire years indicates that if future climate change results in an increase in the frequency of large fire years, then the number of both human- and lightning-ignited fires is likely to increase.

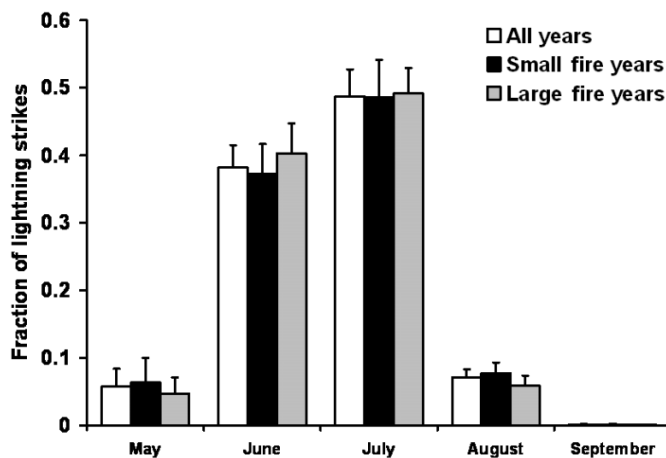
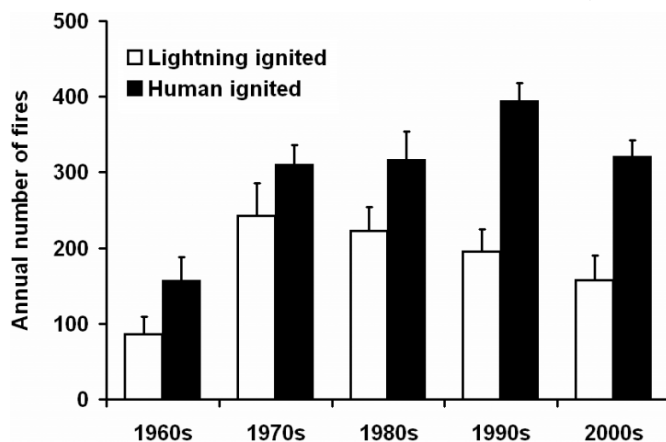
Even though more lightning-ignited fires occurred in large fire years than in small fire years, there was still a decreasing trend in these fires from the 1970s through the 2000s. There are several possible explanations for this decrease. First, during periods of active fire activity, highest priorities for the use of aerial reconnaissance assets are given to monitoring individual fires, with a lower priority placed on searching for new fires. Second, during large fire years, the presence of smoke and haze significantly reduces the probability of detection of new fires. Both of these factors may contribute to a lower number of lightning-ignited fires during large fire years.

Burned area: human- versus lightning-ignited fires

Over the past six decades, the human influence on burned

Table 1. Characteristics of the Alaskan fire regime over the past six decades.

Decade	Largest fire (ha)			Fires >50 000 ha		
	Human	Lightning	Total area (ha)	Human (number)	Lightning (number)	% area human fires
1940s	na	na	na	na	na	na
1950s	553 332	461 233	3 323 255	4	15	28
1960s	212 460	325 133	1 324 383	3	6	37
1970s	12 161	207 199	897 350	0	6	0
1980s	50 586	219 028	692 796	1	7	7
1990s	52 115	245 622	1 627 143	1	14	3
2000s	76 804	217 217	4 298 264	2	43	3

Fig. 4. Fraction of lightning strikes per month for 1990–2008 for all years, small fire years, and large fire years (error bars represent standard errors) (see supplementary online materials for a discussion of the sources for these data).**Fig. 5.** Comparison of the average annual number of human- versus lightning-ignited fires for each decade between the 1960s and 2000s (error bars represent standard errors) (see supplementary online materials for a discussion of the sources for these data).

area has diminished. During the 1950s and 1960s, human-ignited fires accounted for over 25% of total burned area, which was reduced to 5% during the 1990s and 2000s (Fig. 3). The lowering of burned area from human-ignited fires resulted from the reduction in the number of extreme fire events (>50 000 ha) caused by humans. During the 1950s and 1960s, the largest human-caused fires were

greater than 500 000 ha, but since that time, the largest human-caused fire was 76 800 ha (Table 1).

The decrease in the total number of lightning-ignited fires (Fig. 5) is consistent with the continuing rise in the area burned in large fire events ignited by lightning (Table 1). Large fire events typically do not occur as the result of a single ignition but from multiple events growing together to form a single large event. The longer fire seasons (indicated by the increase in late season burning in Fig. 3) allow fires in remote areas that are not being suppressed to continue to grow and merge into events that are counted as a single event, resulting in a reduction in the total number of fires.

Seasonal variations in burned area

While the 1950s were similar to the 1990s and 2000s in terms of the number and size of large fire years, during the 1950s, fires occurred much earlier in the growing season. Over the past five decades, the total area burned during late season fires remained fairly constant before experiencing a large increase in the 2000s when burned area during late-season fires was nearly four times greater than during any previous decade (Fig. 3).

Fire return interval in boreal forest ecoregions

During the 2000s, 13.5% of the land surface below tree-line (<800 m asl) in the nine ecoregions that comprise the boreal forest of interior Alaska was impacted by fire, affecting 26.6% of the area in the North Ogilvie Mountains and 25.3% of the area in the Yukon–Tanana Uplands (Table 2). The increases in burned area during the 2000s lowered the fire return interval in all ecoregions compared with previous estimates (Kasischke et al. 2002) (Table 2). The decrease was particularly dramatic in the Yukon–Tanana Uplands (where more than 1×10^6 ha of fire occurred during the 2000s) and the North Ogilvie Mountains. Overall, the estimated fire return interval based on assuming that all area within a fire perimeter burned decreased from 196 to 144 years (Table 2).

Fire severity

Black spruce (*Picea mariana* (Mill.) BSP) is the dominant tree species found in the boreal forest region of Alaska, occurring primarily in monospecific stands containing deep (10 to >40 cm) surface organic layers. Tree mortality is not used as a measure of severity in these forests because black spruce has low resistance to high temperatures and exposure to even moderately intense surface fires results in death. Rather, the reduction in depth of the surface organic layer

Table 2. Estimated fire return intervals for different ecoregions in the boreal forest region of Alaska based on data from two periods (1950–1999 and 1950–2009).

Ecoregion	Area (ha)		Fire return intervals				Elevation <800 m		% area 2000 fires	
	All elevations		All elevations		Elevation <800 m		Elevation <800 m		All	
	1950–1999	1950–2009	1950–1999	1950–2009	1950–1999	1950–2009	1950–1999	1950–2009	1950–1999	1950–2009
Davidson Mountains	2 903 082	2 390 634	484	326	421	282	7.9	9.3	7.9	9.3
North Ogilvie Mountains	1 273 852	1 166 809	150	74	141	69	22.9	23.9	22.9	23.9
Yukon – Old Crow Basin	5 663 211	5 420 618	107	92	102	88	16.7	17.5	16.7	17.5
Ray Mountains	5 124 269	4 671 383	179	129	164	118	18.6	20.2	18.6	20.2
Kobuk Ridges and Valleys	6 178 407	5 779 597	229	169	215	159	4.6	4.9	4.6	4.9
Tanana-Kuskokwim Lowlands	6 401 527	6 084 689	244	195	234	187	10.1	10.6	10.1	10.6
Yukon–Tanana Uplands	6 374 713	3 581 351	588	191	413	138	20.3	26.6	20.3	26.6
Kuskokwim Mountains	8 535 914	8 483 030	281	213	279	211	10.4	10.5	10.4	10.5
Yukon River Lowlands	5 172 976	4 906 352	174	150	165	143	11.2	11.8	11.2	11.8
Total	47 627 951	42 484 462	216	156	196	144	12.8	13.5	12.8	13.5

is felt to be the most relevant measure of severity in this forest type (Vioreck 1973; Kasischke et al. 2008).

Recent studies using data collected in Canadian black spruce forests have shown that weather-driven variations in the moisture of the surface organic layer (as indicated by the drought code of the Canadian Forest Fire Danger Rating System) are a good predictor of the level of surface fuel consumption in all forest types (de Groot et al. 2009). In contrast, studies have shown that the drought code is not a good predictor of surface fuel consumption in Alaskan black spruce forests (Kasischke and Johnstone 2005), most likely because the moisture content of deeper organic layers in interior Alaska is strongly influenced by seasonal thawing of soils in areas underlain by permafrost (a characteristic that is not reflected in the drought code). Studies showed that within a single fire event, black spruce sites without permafrost have shallower residual surface organic layers following the fires than sites with permafrost (Kasischke and Johnstone 2005; Harden et al. 2006). The depth of the pre-fire organic layer in black spruce forests is related to site drainage, which in turn controls depth of burning and residual depth (Kane et al. 2007). Sites located on poorly drained north aspect backslopes and foot and toe slopes were more resistant to deep burning. Sites with permafrost that burned late in the growing season experienced deeper burning than sites that burned in the middle of the growing season as a result of seasonal increases in the thaw depth (Kasischke and Johnstone 2005).

Finally, the hydrologic conditions of the forest floors of Alaskan black spruce forests control moss species composition, which has a strong influence on the consumption of ground layer fuels. Wetter sites with higher proportions of *Sphagnum* mosses tended to have high spatial variability in fuel consumption due to the efficient moisture retention traits of many *Sphagnum* species that inhibit combustion (Shetler et al. 2008). As a result, *Sphagnum* hummocks often were the only fuels left remaining following severe fire activity.

Recent advances in satellite information products

Several programs initiated by US federal land management agencies have processed satellite remote sensing data (Landsat TM/ETM+) to generate information products that can be used to analyze fire regime characteristics. These include burned area and severity products from the Monitoring Trends in Burn Severity program and land cover products from the National Land Cover Dataset generated by the Multi-Resolution Land Cover consortium.

Analysis of Monitoring Trends in Burn Severity data from the 2004 and 2006 fire seasons in Alaska shows that a significant fraction of the area within mapped fire perimeters did not burn. For the large fire year of 2004, some 20% of the area within fire perimeters did not burn, with this fraction remaining constant as a function of fire size (slope = 0.78, $R^2 = 0.97$, $p < 0.0001$). In contrast, for the small fire year of 2006, only one third of the area within the perimeter was classified as being burned (slope = 0.32, $R^2 = 0.97$, $p < 0.0001$). These results are consistent with those of Fraser et al. (2004) who found that crown fires mapped using Landsat

TM in Canadian forests represented only 52% of the area within the perimeters.

An analysis of the burned and unburned fuel types within 40 fire perimeters from 2004 showed that the occurrence of mature spruce forests was higher within the perimeters (47% of the area) than was found across all boreal forest ecoregions in interior Alaska (39%). The occurrence of deciduous and nonforested vegetation was lower within the perimeters (40%) compared with the entire region (53%) (Fig. 6). Within the fire perimeters, there were only small differences in the fraction of the fuel types that burned and those that did not (Fig. 6). These results indicate that fuel type plays an important role in controlling where fires occur, but during large fire years, fire burns evenly across fuel types within the landscapes where it occurs.

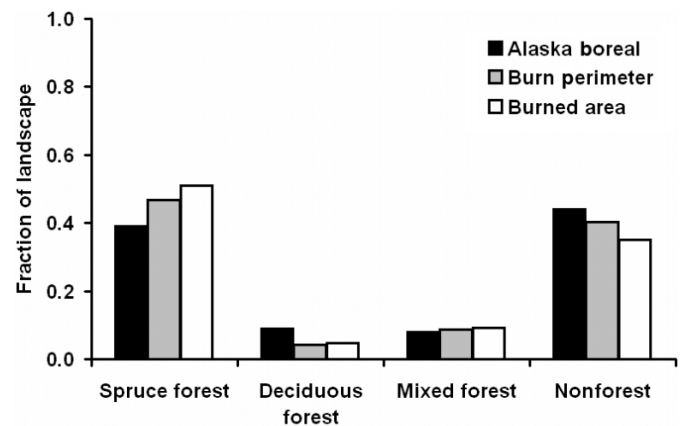
Over the past decade, there has been substantial research on developing approaches to map fire severity using Landsat TM/ETM+ data based primarily on the normalized burn ratio (NBR) and the differenced NBR ratio (dNBR) of Key and Benson (2006) but also using other indices derived from remotely sensed data (see French et al. 2008). There were mixed results in estimating fire severity using NBR-based indices in the Alaskan boreal forest. Allen and Sorbel (2008) found a strong linear relationship ($R^2 > 0.75$) between a visual field index termed the composite burn index (CBI) and dNBR for seven burns within Denali and Yukon Charley National Preserves in the boreal region of Alaska. In an evaluation of 13 remotely sensed severity indices within one lowland and three upland burns in boreal Alaska, Epting et al. (2005) concluded that the NBR and dNBR indices provided the strongest correlations with the CBI. Two recent studies (Hoy et al. 2008; Murphy et al. 2008), however, found weak correlations between NBR or dNBR and CBI from nine different 2004 wildfires in Alaska, and Hoy et al. (2008) did not find significant correlations between a number of different indices and various other (non-CBI) ground measures of fire severity, including the CBI.

There are a number of factors that may lead to low correlations between satellite indices and ground measures of burn severity in Alaska, including saturation of spectral response at high fire severity levels, presence of standing water in lowland areas, high densities of the colonizing plants, the presence of fallen trees with unburned canopies, differences in vegetation type and topography, and changes in solar zenith angle and vegetation phenology (Epting et al. 2005; Allen and Sorbel 2008; Murphy et al. 2008; Verbyla and Lord 2008; Verbyla et al. 2008). In summary, the results indicate that if adequate field data are available for calibration, Landsat TM/ETM+ data can be used to map severity in fires experiencing low to moderate levels of damage but that mapping longer-term trends in fire severity in Alaska may be problematic.

Drivers of longer-term trends in burned area

When examining patterns of burned area over the time for which fire management data are available (1940–2009), an argument can be made that there were three distinct periods of fire activity: two periods with a high frequency of large fire years and high average annual area burned (the 1940s through the early 1960s and the mid-1980s through the

2000s) and one period with a low frequency of large fire years and low average annual area burned (the early 1960s through the mid-1980s). Variations in annual area burned between these three periods can be explained by both climate and anthropogenic activities.



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Climate control on burned area

At regional and continental scales, atmospheric teleconnections play a central role in generating the short-term weather anomalies that influence burned area. As correlated anomalies of geopotential height accompany recurring and persistent shifts in atmospheric pressure and circulation, large-scale teleconnections impact regional weather across the Northern Hemisphere (Hurrell et al. 2003). As a result, linkages between teleconnection-mediated weather and fire activity have been found in Canada (Bonsal and Lawford 1999; Skinner et al. 2002; Girardin et al. 2004; Macias Fauria and Johnson 2006; Balshi et al. 2009a), the Pacific northwestern United States (Hessl et al. 2004), and the southwestern United States (Swetnam and Betancourt 1990). In Alaska, deviations from synoptic weather patterns have been correlated with the Pacific Decadal Oscillation (Papineau 2001; Hartmann and Wendler 2003) as well as the El Niño/Southern Oscillation (Hess et al. 2001). Because of these linkages, at regional spatial scales, atmospheric teleconnection indices (strong to moderate El Niño/Southern Oscillation conditions or variations in the Pacific Decadal Oscillation) influence seasonal fire weather conditions and burned area in Alaska (Hess et al. 2001; Duffy et al. 2005).

Studies at regional to continental scales using climate–fire linkages have produced mixed results. These ranged from relatively weak (Flannigan and Harrington 1988; Hély et al. 2001; Westerling et al. 2002) to somewhat stronger associations (Duffy et al. 2005; Flannigan et al. 2005; Balshi et al. 2009a). While differences existed in the specifics from region to region, in general, interannual variability in climate modulated by changes in large-scale atmospheric circulation drove variability in annual area burned. For example, a modified version of the model by Duffy et al. (2005) showed that climatic variables explained 71% of the varia-

tion in annual burned area in Alaska for the period 1950–2008. In contrast, our analyses show that the number of lightning-ignited fires explains only 11% of the variation in annual burned area, while the number of human-ignited fires explains only 7%.

Role of fire suppression

As noted previously, changes in the fire management policies beginning in the early 1980s have effectively reduced the influence of human-ignited fires in terms of the number of and area burned in extreme fire events (Table 1) and total annual area burned (Fig. 3). Calef et al. (2008) showed that there was a clear spatial dimension to human suppression activities in interior Alaska. This was done through the development of a model that predicted area burned by lightning-ignited fires based on three spatial metrics (distance from settlements, roads, and rivers) and several additional parameters to determine how fire was affected by proximity to humans. This study showed that total burned area (from human- and lightning-ignited fires) was very low close to settlements and increased with distance from villages, peaking at 35–45 km from villages (which is also roughly the average distance between settlements in Alaska, which are located primarily along rivers and roads). For distances up to 30 km, burned area was lower along both highways than in adjacent areas. Burned area was also low in the vicinity of rivers and rose gradually with distance up to approximately 30 km. This finding is consistent with that of Martell and Sun (2008) who showed that the probability of fire expanding decreases as the level of protection increases. In Alaska, as elsewhere, the level of protection success increases nearer to human settlements and roads due to increased rates of detection and reduction in response time that result from being closer to roads, rivers, and fire management resources.

Relative roles of climate and humans in Alaskan fire activity

The research by Duffy et al. (2005), which has been extended through the 2000s for this paper, clearly shows that in Alaska, climate is the primary driver of the frequency of large fire years and annual area burned, which to a large extent explains the decadal patterns of average annual area burned (Fig. 3). Research has also shown, however, that while human ignitions have increased since the 1950s (Fig. 5), the occurrence of extreme human-ignited fire events has decreased (Table 1) and that fire suppression activities have significantly lowered burned area from human-ignited fires over the past four decades (Fig. 3).

An argument can be made that from the 1940s through the early 1960s, the high average annual area burned ($458\,000\text{ ha}\cdot\text{year}^{-1}$) was due to a combination of a warmer, drier climate and limitations in the availability of resources to suppress both human- and lightning-ignited fires. Beginning in the 1960s, there was an increase in the availability of fire suppression resources; thus, while cooler and wetter conditions were a primary driver in the decrease in average annual area burned from the early 1960s through the mid-1980s ($236\,000\text{ ha}\cdot\text{year}^{-1}$), part of the decrease has to be attributed to the increasing effectiveness of fire suppression activities. Note that during this time, equal priority was

given to suppression of all fires; thus, management activities were focused on both human- and lightning-ignited fires. This policy changed in the mid-1980s when higher priority for suppression was effectively given to human-ignited fires. Thus, while warmer and drier conditions have likely been the primary driver in the increases in average annual area burned in the 1990s and 2000s ($581\,000\text{ ha}\cdot\text{year}^{-1}$), one could also argue that part of this increase has been due to the decrease in suppression of lightning-ignited fires relative to the levels that took place during the previous two and a half decades.

Implications of the changing fire regime

Boreal forest vulnerability

Black spruce has been the dominant tree species in Alaska's boreal region for the past 5500 years (Lynch et al. 2003). While black spruce forests are well adapted to fire, they are vulnerable to changes in the fire regime, e.g., they can undergo significant ecological change in response to variations in certain characteristics of the fire regime. Research has also shown, however, that certain landscape characteristics provide resilience to black spruce forests to the effects of changes to the fire regime.

Two fire regime characteristics directly impact postfire responses in black spruce ecosystems: changes in fire return interval or fire-free period and changes in depth of burning in the surface organic layer. Johnstone (2006) found that a shortening of the fire-free period reduced postfire recruitment of spruce seedlings in black spruce forests because trees did not have time to reach sexual maturity. Johnstone (2006) also found that the fire-free period controlled depth of the surface organic layer following fire where sites with the lowest fire-free period had the shallowest immediate postfire organic layers.

Several studies found that depth of the organic layers controlled postfire seedling recruitment (see Johnstone et al. 2010). In particular, deciduous tree species experienced higher levels of recruitment when postfire surface organic layers were less than 3 cm and very low rates of recruitment when they were deeper than 5 cm. In addition, the depth of the postfire surface organic layer has been shown to control postfire soil temperature and moisture in sites containing permafrost (Kasischke and Johnstone 2005) where sites with postfire surface organic layers less than 8–10 cm deep are likely to experience loss of permafrost (Yoshikawa et al. 2002). Thus, deep-burning fires in black spruce forests provide the pathway for significant changes in postfire ecosystem structure and function.

While recent changes in fire return intervals in Alaska's boreal forests increase exposure to the impacts of shorter fire-free periods, some ecoregions are more vulnerable than others (Table 2). In addition, the recent increase in the frequency of large fire years means that a higher fraction of the landscape is actually being impacted by fire. Since seasonal thaw depth controls the depth of burning in black spruce forests, the rise in late-season burning (Fig. 3) has also increased the vulnerability of black spruce forests. Regardless of recent changes in fire regime, however, black spruce forests on poorly drained areas will likely remain resilient to change because their organic layers are resistant to

deep burning because of the greater impacts of permafrost as well as the presence of *Sphagnum* mosses.

Management implications

The impacts of variations in the fire regime in response to climate change have implications for ecosystem services that are primarily related to climate regulation and subsistence. The effects on climate regulation are twofold. First, fire regulates the storage of terrestrial carbon, which if lost from boreal forests and peatlands has the potential to increase the atmospheric concentration of CO₂ (Kasischke et al. 1995). Second, variations in the fire regime will cause changes to vegetation cover, which in turn regulates the exchange of water and energy between the land surface and the atmosphere (Randerson et al. 2006).

Balshi et al. (2007) incorporated a fuel consumption component within a theoretical biogeochemical cycle model to account for the impacts of fire on terrestrial carbon cycling in boreal forests. By linking an understanding of how variations in weather control burned area, Balshi et al. (2009b) showed that there would likely be a 2.4- to 4.4-fold increase in carbon emissions across the North American boreal forest by the end of the 21st century in response to climate warming and increases in burned area. This estimate is considerably higher than those of Amiro et al. (2009) who predicted a much lower increase in burned area across Canada in response to climate warming. In addition, several recent studies (Zhuang et al. 2002; Yi et al. 2009) have developed approaches to account for the impacts of reductions in the surface organic layers on soil temperature and moisture, which in turn provides an improved ability to assess the impacts of fire on heterotrophic respiration.

Variations in ecosystem community structure associated with a changing fire regime have the potential to influence regional climate through alterations to surface albedo and energy and water exchanges with the atmosphere. Using satellite-based products, Lyons et al. (2008) showed that post-fire changes in vegetation cover from a coniferous-dominated forest to deciduous-dominated vegetation resulted in a net increase in surface albedo in interior Alaska. Randerson et al. (2006) showed that there was potential for the net effects of fire to result in cooling of the atmosphere because the cooling effects of increased albedo associated with forest cover change were greater than the warming associated with direct emissions of greenhouse gases through combustion. Finally, Euskirchen et al. (2009) showed that decreases in surface albedo from the lessening of snow cover associated with earlier spring snowmelt had the potential to result in a greater warming than the cooling effect from increases in albedo associated with changes in vegetation cover caused by more frequent fires.

Changes in ecosystem structure associated with the response of the fire regime to a changing climate also have implications for the use of subsistence resources because the species composition as well as the stand age structure of Alaska's boreal forests influence the suitability of these forests as wildlife habitat (Fig. 1). This is particularly true for the two large-mammal species (caribou and moose) that represent major subsistence food sources for many Native Peoples. While older mature black spruce woodlands with arboreal lichens are the preferred winter forage for caribou,

early-postfire-successional forests with willow and aspen re-growth are preferred by moose (Maier et al. 2005; Chapin et al. 2008). Thus, future increases in fire frequency and fire severity are likely to result in a vegetation cover mosaic that favors moose over caribou (Rupp et al. 2006), making Alaska's interior caribou herds vulnerable to forest cover changes that are being driven by changes in the fire regime.

Major shifts in vegetation type and distribution as a result of changes in the fire regime could substantially impact land management policies. At present, fire suppression policies are based on the perception that black spruce forests represent the fuel type that is required for sustaining large fire growth and thus provides for increased fire risk in the wildland-urban interface. Yet, recent modeling of the impacts of fires shows that the landscape will be transformed in such a way that future fire suppression activities will occur during the smaller fire events caused by the increased presence of multiaged stands (Rupp et al. 2006). This represents a paradigm shift from the picture of black spruce forests underlain by feathermoss as being the most prevalent problem-fuel type and will eventually force a reexamination of current forest fuels management and hazard fuel reduction practices.

For wildland fire management programs within land management agencies (primarily the US Fish and Wildlife Service and the US National Park Service), managing the landscape to maintain the values in the natural ecosystems present in the landscape has become increasingly complex. As changes in the interlinked relationships among climate, fire frequency, fire severity, vegetation patterns, and permafrost that result from changes to the fire regime become more clearly understood, new strategies will have to be considered for managing for biodiversity and other important natural resource values. With the recent development of remotely sensed data and modeling tools following the large fire years of 2004 and 2005, land and fire managers are now discussing and developing different options to manage fire to meet various agency mandates. Ideas being considered range from increasing the desired suppression level for older-aged black spruce stands in a rotational pattern to maintain a portion of an area in older classes to using prescribed fire or mechanical treatments to change fuel composition in large contiguous stands to decrease the potential for a single fire to burn over a large area.

For fire management agencies, the length of the fire season also has a large impact on planning and budget. As noted previously, the increase in the frequency of large fire years has resulted in an increase in late-season burning, thus lengthening the fire season. In addition, warming summer temperatures clearly trigger more convective storm activity and increase the number of lightning strikes, requiring additional surveillance (McGuiney et al. 2005). A larger, warmer expanse of Arctic Ocean in September may contribute to more fires in tundra areas in the northern part of Alaska (Jones et al. 2009). All of the factors above seem to point toward more wildland fire across a broader area in Alaska if the climate continues to warm.

At the same time, fire management agencies are experiencing flat or shrinking budgets. This fact, along with a fire management plan calling for limited suppression activity in remote sections of the state, has resulted in agencies dismantling their remote field stations, paring down staff, and cen-

tralizing and sharing more firefighting resources to focus primarily on fire suppression activities in more populated areas. It would seem that a conflict may be developing between the services that the public expects and the infrastructure that is needed to provide the required levels of suppression, a situation that is recognized across Canada and the western United States.

Because boreal forests represent important stores of carbon, it has been proposed that fire management could be used to mitigate carbon release to the atmosphere (and slow climate warming) by suppressing a certain number of starts in particular areas or at times when forest carbon stocks are vulnerable. Banking credits of carbon stocks in forest and tundra has even been proposed as a revenue source (Alaska Department of Environmental Conservation 2009). To determine the feasibility of such practices, managers need to know (*i*) how much carbon is in the bank, (*ii*) how much carbon is released from a fuel type under given burning conditions, and (*iii*) whether burning represents a net source or sink of carbon over the long term.

Future research directions

The availability of burned area and vegetation cover products derived from high-resolution (30 m pixels) Landsat satellite data provides an opportunity to study the spatial variations in burning as a function of fuel type. When combined with remotely sensed hotspot products, studies of the seasonal patterns of fire as a function of fuel type and topography are now possible for the period since 2000 (when MODIS hotspot data were first collected). The seasonal timing of fire information makes it possible to examine how variations in vegetation cover, topography, and climate combine to influence patterns of burning at landscape scales (Zackrisson 1977; Renkin and Despain 1992; Johnson et al. 1998; Cumming 2001).

In addition, these new data sets provide the capability to more carefully examine how the fire-free period affects the patterns of burned and unburned areas within fire perimeters. One would expect that when reburning of recent (<50 years old) burns occurs, the fraction of actual burned area would be less than in areas with older vegetation but that susceptibility to burning increases as the time since the previous fire increases. Since different forest and ecosystem types recover at different rates, the fraction of area burned in these scars will also depend on different trajectories of postfire recovery. The higher-resolution satellite products provide an opportunity to test these hypotheses.

While analysis of satellite remote sensing data is providing new and valuable insights on the characteristics of Alaska's fire regime, a method to reliably map spatial variations in fire severity using satellite remote sensing data is needed to analyze larger-scale and longer-term trends in burn severity. To fully account for factors that influence fire activity, producing maps of fire severity may require other geospatial data, such as prefire vegetation type, topography, and timing of the fire during the growing season.

To date, field studies that have measured variations in fire severity and their effects have largely focused on black spruce forests. Similar studies in other forest and vegetation types (especially tundra) are needed, including investigations

on the combined effects of changes in the fire regime and climate on post-disturbance recovery.

One of the potential applications for backcasting annual area burned in Alaska is a comparison with other records of fire activity (information derived from examination of sediment cores from lakes or stand-age reconstructions through analysis of tree rings). Such studies would provide multiple lines of evidence over longer time periods needed to generate a more informed consensus of historical fire activity. To effectively assimilate the results of backcasts of burned area into an overall conceptual model of the boreal forest, it is important to recognize that the current linkage between climate and fire is conditional on the spatial distribution of differentially flammable vegetation on the landscape. The application of the backcast model (Fig. 2) in this manner assumes that the relationship between fire and climate has changed little as a function of changes in vegetation over the past 150 years. The degree to which this assumption is true should be examined by the integration of data from dendrochronological and sediment core analyses with observations obtained from recent field-based studies.

Finally, further refinement of approaches to model the impacts of changes to the fire regime are needed to incorporate recent advances in our understanding of the characteristics of Alaska's fire regime and the linkages to climatic, topographic, and vegetation characteristics that control fire behavior. These refinements not only need to incorporate recent improvements in the understanding of how variations in the fire regime influence important landscape characteristics such as postfire soil temperature and moisture that regulate permafrost and vegetation recovery but should also include the results that will continue to emerge from the research conducted through or affiliated with the Bonanza Creek LTER program.

Conclusions

It is clear from recent research that lightning ignitions have been the principal source for burned area in the boreal forest region of Alaska since the 1950s; however, during the 1950s and 1960s, human-ignited fires contributed significantly to annual burned area (30% of the total). Because of their proximity to suppression resources, human-caused fires are more easily controlled than lightning-ignited fires. With the increase in the availability of fire suppression resources, as well as the change in fire management policy in the mid-1980s that gave higher priority to suppressing fires in areas near human settlements, the number of large human-caused fires has been drastically reduced, and the portion of annual area burned from humans is now low (<5% of the total). An unintended consequence of fire suppression around settlements, however, is the increase in hazardous fuel types, which may require fuels mitigation in the future if the potential for rapid fire spread continues to be high in a warming climate.

Recent changes in climate have resulted in increases in the frequency of large fire years and have resulted in a dramatic increase in extreme fire events. Four of the 11 largest fire years on record since 1940 have occurred between 2002 and 2009, and the increase in frequency of large fire years has been accompanied by an fourfold increase in late-season

burning that occurs because large and increasing numbers of extreme fire events in remote areas are too large to control. The evidence now points toward the fire regime being vulnerable to climate warming over the near term with the potential for a continuation of large fire years and events and more late-season burning being high. Given the fact that management options are limited by both economic considerations and difficulties in suppressing fires in remote regions (especially during droughts), opportunities for reducing burned area through suppression are limited. Because permafrost is warming, the likelihood of increases in the frequency of deep-burning fires that change forest ecosystems is also high. At some point, however, increases in early-successional vegetation combined with changes to postfire succession in black spruce forests will reduce the vulnerability of the landscape to fire spread.

There is a need for education of stakeholders (public, land managers, and policy makers) of the limited options that are presently available to allow for future accommodations with changes to the fire regime and their impacts. Of particular importance is developing a better understanding of how changes to the fire regime will impact the services provided by Alaska's boreal forests. There will be important feedbacks between these forests and the climate as a result of changes to the fire regime, but it remains to be seen if these feedbacks will be positive or negative. Subsistence use of Alaska's boreal forest will undoubtedly change in the near future in response to the effects of the large area burned during the 1990s and 2000s (>25% of Alaska's boreal forest). Land management agencies are now working on determining how recent and future changes to the fire regime will impact the metrics used to evaluate the values the natural ecosystems represent in Alaska's boreal forest region.

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