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Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska

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[1] We used historic records from 1959–99 to explore fire regime characteristics at ecozone scales across the entire North American boreal region (NABR). Shifts in the NABR fire regime between the 1960s/70s and the 1980s/90s were characterized by a doubling of annual burned area and more than a doubling of the frequency of larger fire years because of more large fire events (>1,000 km^2). The proportion of total burned area from human-ignited fires decreased over this same time period, while the proportion of burning during the early and late- growing-seasons increased. Trends in increased burned area were consistent across the NABR ecozones, though the western ecozones experienced greater increases in larger fire years compared to the eastern ecozones. Seasonal patterns of burning differed among ecozones. Along with the climate warming, changes in the fire regime characteristics may be an important driver of future ecosystem processes in the NABR.

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1. Introduction

[2] Fire is an important process in the boreal region, affecting upland and lowland forests [*Wein and MacLean*, 1983] as well as peatlands [*Turetsky et al.*, 2002]. In addition to initiating secondary succession, boreal fires control a number of important ecosystem processes. Variation in depth of burning of the surface organic layer in black spruce [*Picea mariana*] forests affects tree recruitment and vegetation recovery [*Landhaeusser and Wein*, 1993], long-term accumulation of carbon [*Kurz and Apps*, 1999; *Harden et al.*, 2000; *Turetsky et al.*, 2002], and post-fire soil temperature and moisture [*Kasischke and Johnstone*, 2005], which in turn, regulate soil respiration [*Bergner et al.*, 2004] and surface/atmosphere energy exchange [*Liu et al.*, 2005]. At continental and global scales, variations in boreal burned area, fire severity, and depth of burning control direct fire emissions, affecting the atmospheric concentration of a number of atmospheric trace gases [*Kasischke et al.*, 2005].

[3] *Gillett et al.* [2004] showed that increases in burned area across Canada from the 1920s to 1990s were correlated with regional warming trends. Here, we explore the hypothesis that sub-regional variations in climate-wildfire relationships [*Skinner et al.*, 1999; *Hess et al.*, 2001; *Flannigan and Wotton*, 2001; *Duffy et al.*, 2005] could contribute to variability in the fire regime across the North American boreal region (NABR). We use historical fire records to support continental and sub-regional analyses of characteristics of the fire regime, including the frequency of fire years categorized by annual burned area, the size of individual fire events, and the seasonality of burning.

2. Methods

[4] Information for fires >2 km^2 in size were obtained from large-fire databases for Alaska [*Kasischke et al.*, 2002] and Canada [*Stocks et al.*, 2002], which contained data for the years 1959–1999 on start location, area burned, ignition source (human, lightning, unknown), ecozone of fire origination, and fire start date. Exclusion of fires <2 km^2 did not significantly bias our analysis because they represent a small portion of total burned area (<3.5% in Canada [*Stocks et al.*, 2002] and <1% in Alaska). The ecozone map given by *Bourgeau-Chavez et al.* [2000] was used to define the sub-regions used in this study.

[5] Fire years in the NABR tend to be episodic in nature, where periodic droughts result in larger fire seasons [*Skinner et al.*, 1999; *Flannigan and Wotton*, 2001]. We separated the individual years in each sub-region into one of four categories: small (<1% of the land surface in an ecozone burned); large (1–2% of the land surface burned); very large (2–3% of the land surface burned); and ultra large (>3% of the land surface burned).

[6] *Stocks et al.* [2002] analyzed the seasonal patterns of fire in the Canadian boreal forest using the start times for individual fire events. Where this approach provides information on seasonal distribution of fire ignitions, it does not depict the seasonal patterns of burned area because many fires (especially larger ones) burn over extended periods. To estimate the length of time over which a fire burned as a function of fire size, we used daily fire reports from the Alaska Fire Service (AFS) for 2004 and 2005, and estimates derived from burn maps generated by the U.S. Forest Service from MODIS satellite data (http://activefiremaps.fs.fed.us/). The data showed that the length of time over which a fire burned was proportional to fire size, with the AFS reported burned area lagging behind the MODIS observed area by 4 to 5 days. These results were used to estimate the fraction of total burned area as a function of fire

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Table 1. Summary of Decadal Average Number and Sizes of Fire Events >2 km^2 Resulting From Human and Lightning Ignitions

	Fires yr^{-1}	Average Fire Size, km^2	Average Annual Burned Area, km^2 yr^{-1}	Percent of Burned Area
			Human-Ignited Fires	
1960s	91	40.0	3,642	35.8
1970s	67	18.6	1,246	8.3
1980s	77	48.7	3,754	13.2
1990s	43	47.5	2,041	6.4
			Lightning-Ignited Fires	
1960s	162	40.3	6,533	64.2
1970s	200	69.1	13,819	91.7
1980s	288	85.4	24,604	86.8
1990s	306	96.9	29,665	93.6

size in 10-day increments (see auxiliary materials[1]). We distributed burned area from each fire event across the fire season based on these fractions and the reported fire start date.

3. Results

3.1. Total Burned Area

[7] Between 1959–1999, 87.4 × 10^4 km^2 were affected by fire in the NABR, with 87% of this area being due to lightning ignitions. The burned area from lightning-ignited fires increased during each decade as a result of increases in the number of fires and the average fire size (Table 1). While there was a decrease in number of human-ignited fires between the 1960s and 1990s, their average size remained constant (Table 1). Across the entire NABR, the proportion of total burned area from human-ignited fires decreased from 35.8% during the 1960s to 6.4% during the 1990s. As previously reported by *Stocks et al.* [2002], human-ignited fires were more prevalent in the southern and eastern ecozones because of the higher population densities found in these sub-regions (see auxiliary materials). With the exception of the Mountain Cordillera and W. Boreal Shield, all ecozones experienced a decrease in the burning from human-ignited fires from the 1960s and 1990s.

[8] Historic fire records indicated several changes in the fire regime across the entire NABR for the time period analyzed here, including a large increase in total burned area in small fire years between the 1960s and 1970s, and increased total burned area in the larger fire year categories (large, very large, and ultra large fire years) between the 1970s and 1980s (Figure 1). Across the NABR, there was a doubling in burned area between the 1960s/70s and the 1980s/90s.

[9] Over the entire period analyzed, during small fire years, 71% of the total burned area occurred in small- (<100 km^2) and medium- (100 to 500 km^2) sized fire events (Figure 2a). As the size of the fire year increased, the proportion of burned area in larger-sized-fire events (>1,000 km^2) continuously increased, reaching 55% of total burned area in ultra large fire years (Figure 2a). As a result of the increase in frequency of larger fire years, larger fire events accounted for a greater proportion of total burned area compared to smaller fire events between the 1960s/70s and the 1980s/90s (Figure 2b). Trends in the size of lightning-ignited fires mimicked the trends in total burn area over time described above. However, the proportion of total burned area attributable to human-ignited fires in the smallest and largest fire size categories declined between the 60s/70s and 80s/90s, while human-ignited burning in the medium fire size categories (100 to 500 km^2) increased over time (Figure 2b).

[10] Changes in characteristics of the fire regime also were evident at the ecozone scale. With the exception of the Taiga Cordillera, every ecozone experienced increases in total burned area between the 1960s/70s and the 1980s/90s, although the magnitude of change varied from region to region (see auxiliary materials). In particular, the Taiga Plains and W. Boreal Shield ecozones experienced the largest increases in total burned area (Figure 1).

3.2. Frequency of Large Fire Years

[11] In addition to changes in total burned area over the past several decades, historic fire records show changes in the frequency of larger (where >1% of the region burned) fire years in individual ecozones of the NABR. While larger fire years occurred on average 5 times per decade during the 1960s/70s, they averaged 13 per decade during the 1980s/90s (Table 2). These larger fire years accounted for 31% of the total decadal burned area during the 1960s/70s, but

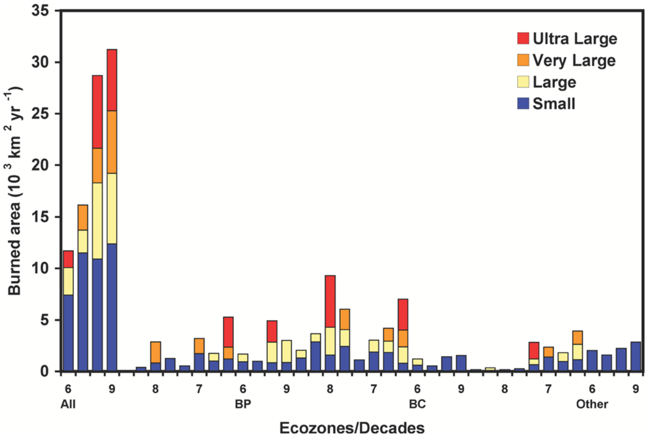

Figure 1. Decadal patterns in burned area across the NABR and in individual ecozones (on the x-axis, 6 = 1960s, 7 = 1970s, etc.; see Table 2 for the key to the ecozones).

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2006gl025677.

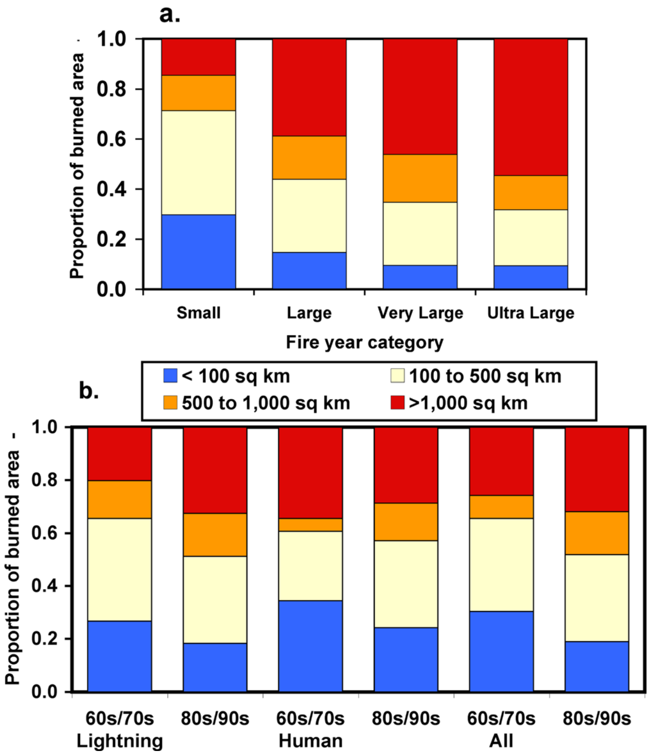

Figure 2. (a) Proportion of burned area as a function of individual fire event sizes for different fire year size categories; (b) Proportion of burned area as a function of individual fire event sizes for different decades.

accounted for 61% of the decadal area burned during the 1980s/90s (Figure 1).

[12] While the frequency of larger fire years (thus the area burned as a result of larger fire events/years) has increased across the NABR over the past four decades, we also explored whether this trend occurred synchronously at ecozone scales. The 36 larger fires documented across the NABR from the 1960's to the 1990's occurred in 8 different ecozones (Table 2) in 16 different years. Both 1989 and 1998 had larger fire years in four ecozones, demonstrating that the factors contributing to high burned area in these two years occurred at least in part at a regional scale. The western NABR ecozones (W. Boreal Shield, Taiga Shield, Boreal Plains, and Alaskan Boreal Interior) experienced larger fire years more frequently than ecozones found in the central and eastern NABR. For example, while these western ecozones had a larger fire year occurring once every 5 to 7 years (Table 2), the E. Taiga Shield experienced only one larger fire year over the past four decades.

3.3. Seasonal Patterns of Burning

[13] For all ignition sources, there was a 2% increase in the proportion of burning that occurred later in the growing season (Aug.–Oct.) during the 1980s/90s compared to the 1960s/70s (Figure 3). The differences in seasonal patterns of burning were more pronounced when burned area was attributed to ignition source. Human-ignited fires occurred earlier during the growing season (Apr.–Jun.) compared to lightning ignited fires (Figure 3; for monthly fire distribution plots and data, see auxiliary materials). These results are consistent with *Stocks et al.* [2002], who studied seasonal patterns of fire ignitions across Canada. Early-growing-season burned area attributable to human-ignited fires increased 8% between the 1960s/70s and the 1980s/90s, while mid-season (Jul.) and late-season (Aug–Oct), human ignited burned area decreased over the same period. In contrast, early-season and late-season (Aug.–Oct.) burning from lightning-ignited fires increased modestly between the 1960s/70s and the 1980s/90s (2% and 4% increases, respectively).

[14] Seasonal patterns of burned area varied between ecozones (Table 3; see also auxiliary materials). Four ecozones (E. and W. Taiga Shields, W. Boreal Shield, Boreal Plains) experienced large increases in lightning-ignited, late-season burning area between the 1960s/70s and 1980s/90s, while all other ecozones experienced decreases (Table 3). The seasonal patterns in burning from to human-ignited fires among ecozones generally followed the trends exhibited for the entire NABR, except 3 ecozones that experienced only a small increase (W. Boreal Shield) or a decrease (W. Boreal Shield, Boreal Cordillera) in early-season burning from human-ignited fires.

4. Discussion

[15] This study relied on historical fire records of burn area and other fire characteristics (type of ignition, start date, etc.) across Canada and Alaska. Concerns that missing fire records for these regions prior to the 1970s [*Kasischke et al.*, 2002; *Stocks et al.*, 2002] influenced our results are valid, though we do not believe this bias was significant. The lower levels of fire activity estimated for the 1960s are consistent with the prevailing cooler conditions in the region [*Stocks et al.*, 2002]. As an informal assessment of the sensitivity of our results to any potential bias presented by early fire records, we note that increasing burned area

Table 2. Decadal Frequency of Larger Fire Years in the NABR Region in Different Ecozones for All Fires[a]

	1960s	1970s	1980s	1990s	Total
East Taiga Shield (ETS)	0,0,0	0,0,0	0,1,0	0,0,0	0,1,0
West Taiga Shield (WTS)	0,0,0	0,1,0	1,0,0	0,1,1	1,2,1
Boreal Plains (BP)	1,0,0	0,0,0	2,0,1	2,0,0	5,0,1
West Boreal Shield (WBS)	1,0,0	1,0,0	2,0,2	2,1,0	6,1,2
Taiga Plains (TP)	0,0,0	1,0,0	1,1,0	2,1,1	4,2,1
Taiga Cordillera (TC)	0,0,0	0,1,0	0,0,0	0,0,0	0,1,0
Boreal Cordillera (BC)	1,0,0	0,0,0	0,0,0	0,0,0	1,0,0
Alaska Boreal Interior (ABI)	1,0,1	0,1,0	1,0,0	2,1,0	4,2,1
Total	4,0,1	2,3,0	7,2,3	8,4,2	22,9,6

[a] Numbers listed are for large, very large, and ultra large fire years.

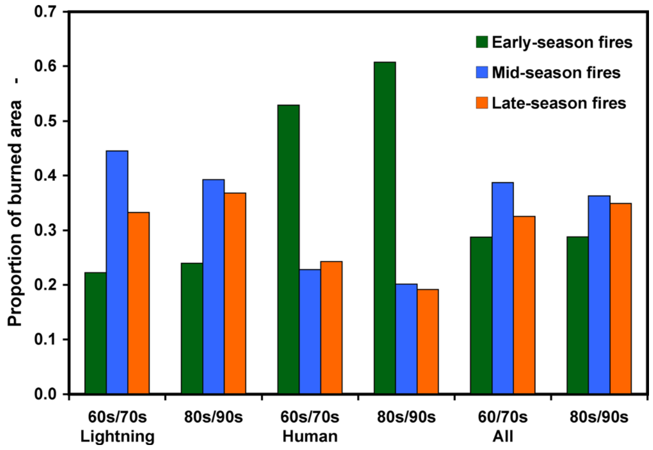

Figure 3. Seasonal variations in proportion of burned area for the NABR as a function of ignition source for the periods of the 1960s/70s and 1980s/90s.

during the 1960s by as much as 25% would not significantly change the trends reported here.

[16] The correlations found by *Gillett et al.* [2004] between burned area and increasing surface temperatures in Canada are likely the result of inter-annual variations in the location of Arctic high-pressure systems during the summer [*Skinner et al.*, 1999]. At sub-regional scales, larger fire years occur when Arctic high-pressure systems are stationary and block the movement of moist maritime air masses into a sub-region [*Flannigan and Wotton*, 2001]. Because of this linkage, the warmer and drier (drought) conditions leading to higher fire activity do not occur simultaneously across the entire NABR, but are focused in specific sub-regions. Thus, the variability we found in the occurrence of large fire years among NABR ecozones (Table 2) is consistent with previous studies and serves as an underlying cause of increases in the decadal trends of total burned area across the region (Figure 1).

[17] Previous work also has supported the hypothesis that the climate conditions resulting in large fire years in some North American boreal sub-regions are linked to larger-scale ocean circulation patterns such as ENSO [*Hess et al.*, 2001] and the Pacific decadal oscillation [*Duffy et al.*, 2005], as well as variations in sea surface temperature [*Flannigan and Wotton*, 2001]. The increased frequency of large fire years between the 1960s/70s and the 1980s/1990s suggests there has been a shift in the large-scale atmospheric circulation patterns affecting climate/fire weather across the NABR region. While future climate change in the NABR is expected to increase fire frequency and severity across much of the NABR [*Flannigan et al.*, 2005], the teleconnections between large-scale atmospheric circulation patterns and continental and sub-regional climate also are likely to control future NABR fire activity [*Flannigan and Wotton*, 2001].

[18] Increased total burned area across the NABR between the 1960s/70s and the 1980s/90s occurred as the importance of human-ignited fires to total burn area decreased. During the 1970s/80s, government agencies instituted fire management policies giving priority to suppressing fires that threatened human life, property, and other high-value natural and cultural resources, where fires occurring in remote regions were allowed to burn [*Stocks et al.*, 2002]. Since most human ignitions occurred in regions with the highest suppression priority (e.g., near human settlements), these policies resulted in a reduction in human-ignited fires by nearly 50%. However, the average size of human-ignited fires remained constant (Table 1). Nonetheless, as a result of fire management, the proportion of area burned due to human-caused fires dropped across the NABR and in most ecozones.

[19] Our study shows that recent changes in the NABR fire regime are not limited to increases in total burned area. Since the early 1960s, increases in the number of individual fire events and in the size of fires both contributed to more frequent occurrence of large fire years across the NABR, particularly in the western ecozones. This likely has occurred because drier conditions have increasingly allowed fires to grow faster and/or burn over a longer time period. In addition, while burning from human-ignited fires tended to occur earlier in the growing season, burning from lightning-ignited fires tended to occur both earlier and later in the growing season,. These observations are consistent with predictions that climate warming will result in longer fire seasons [*Flannigan and Wotton*, 2001; *Flannigan et al.*, 2005].

[20] Changes in fire regime characteristics present challenges to scientists trying to understand the impact of recent and future climate change in the boreal region. In particular, we showed that changes in the fire regime have been particularly pronounced in the western NABR ecozones (W. Taiga and Boreal Shields, Taiga and Boreal Plains, and Alaska Boreal Interior), where large expanses of forests and

Table 3. Changes in Proportion of Seasonal-Burned Area Between the 1960s/70s and 1980s/90s for NABR Ecozones[a]

	Lightning-Ignited Fires			Human-Ignited Fires		
	Early-season	Mid-Season	Late-Season	Early-Season	Mid-Season	Late-Season
East Taiga Shield	0.013	−0.120	0.107	0.096	0.143	−0.238
West Taiga Shield	−0.037	−0.084	0.121	−0.342	−0.054	0.396
Boreal Plains	−0.054	−0.180	0.234	0.186	−0.030	−0.156
West Boreal Shield	−0.073	−0.094	0.167	0.004	−0.077	0.073
Taiga Plains	0.032	0.007	−0.039	0.198	−0.042	−0.156
Taiga Cordillera	−0.057	0.198	−0.141	0.793	−1.000	0.207
Boreal Cordillera	−0.093	0.121	−0.028	−0.038	0.089	−0.052
Alaska Boreal Interior	0.126	0.063	−0.188	0.213	−0.103	−0.110
Other	0.187	−0.065	−0.122	0.105	−0.055	−0.051

[a] A positive value means there was more burned area in the 1980s/90s compared to the 1960s/70s, while a negative value means there was less.

peatlands with deep organic layers that are vulnerable to burning during fires are common [*Kasischke and Johnstone*, 2005; *Turetsky et al.*, 2002]. While increases in fire frequency will result in shifts in vegetation cover toward younger-aged forests [*Kurz and Apps*, 1999], changes in the sizes and seasonal distribution of fires may have more far-reaching consequences. Increases in the average annual fire size and/or shifts to later season burning may result in increases in the depth of burning of these organic layers because of drier conditions and deeper seasonal thawing of permafrost that are present in many boreal ecosystems. Besides potentially exacerbating atmospheric emissions of carbon during burning, deeper burning of surface organic layers will accelerate changes in a number of important ecosystem processes and functions, including permafrost stability, soil respiration, nutrient pools, species composition, and vegetation recruitment and growth rates [*Landhaeusser and Wein*, 1993; *Bergner et al.*, 2004]. The fact that many important ecosystem processes in the boreal region are linked to both climate and fire means that changes to the NABR fire regime must be carefully studied and monitored.

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