Recent Changes in Annual Area Burned in Interior Alaska: The Impact of Fire Management

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ABSTRACT: The Alaskan boreal forest is characterized by frequent extensive wildfires whose spatial extent has been mapped for the past 70 years. Simple predictions based on this record indicate that area burned will increase

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as a response to climate warming in Alaska. However, two additional factors have affected the area burned in this time record: the Pacific decadal oscillation (PDO) switched from cool and moist to warm and dry in the late 1970s and the Alaska Fire Service instituted a fire suppression policy in the late 1980s. In this paper a geographic information system (GIS) is used in combination with statistical analyses to reevaluate the changes in area burned through time in Alaska considering both the influence of the PDO and fire management. The authors found that the area burned has increased since the PDO switch and that fire management drastically decreased the area burned in highly suppressed zones. However, the temporal analysis of this study shows that the area burned is increasing more rapidly in suppressed zones than in the unsuppressed zone since the late 1980s. These results indicate that fire policies as well as regional climate patterns are important as large-scale controls on fires over time and across the Alaskan boreal forest.

**KEYWORDS:** North America; Forest fires; Geographic information systems (GIS)

### 1. Introduction

Mean annual temperature in Fairbanks has increased by 1.4°C over the past century (Wendler and Shulski 2009). Simultaneously, the boreal forest ecosystem is changing in response to changes in climate, increases in wildfires, and human encroachment (Calef 2010; Kasischke et al. 2010; Soja et al. 2007).

Human presence in the boreal forest correlates with a steep increase in fire ignitions while simultaneously leading to a reduction in the area burned through suppression close to settlements (Calef et al. 2008; DeWilde and Chapin 2006; Kasischke and Turetsky 2006; Kasischke et al. 2010; Kovacs et al. 2004). While suppression seems to be quite successful with small fires during initial attack, it is not clear what impact large-scale fire suppression has on the boreal forest in terms of overall area burned, stand age distribution, fire return interval, or fuel load buildup (Chapin et al. 2003; Drury and Grissom 2008; Johnson et al. 2001; Kasischke and Turetsky 2006; Miyanishi and Johnson 2001; Ward et al. 2001). Through advances in fire ecology, the initial U.S. policy of aggressive fire suppression has morphed through time into fire management systems that recognize wildfires as an integral part of ecosystem dynamics (Todd and Jewkes 2006). Additionally, it has never been realistic to suppress all fires in the vast boreal forest of Alaska, which is why the state was classified into four fire management options or fire management zones (FMZs) around 1986 to prioritize fire suppression efforts.

At the landscape scale, fires have become more frequent, correlated with increases in forest cover and the presence of late successional, flammable black spruce (Dissing and Verbyla 2003), lightning strike density (Kasischke et al. 2002), or growing season temperature and precipitation (Balshi et al. 2009; Calef et al. 2008; Kovacs et al. 2004). DeWilde and Chapin (2006) found a correlation among fire size, management zone, and vegetation (fuel) type; large fires took place in highly flammable vegetation (forests) and outside of high suppression zones. Humans extend the length of the fire season by roughly 2 months by starting fires in spring (April and May) and fall (September) (Calef et al. 2008; DeWilde and Chapin 2006; Kasischke and Turetsky 2006). According to DeWilde and Chapin (2006), human fires usually stay small because they occur 1) outside the natural fire
season when burning conditions are not ideal, 2) in less flammable vegetation types, and 3) often in areas of active fire suppression. Fire suppression seems to be most effective on small fires (<0.4 ha). In addition, it has reduced the proportion and absolute number of big fires (>200 ha) in northeastern Alberta, Canada (Cumming 2005).

Annual area burned in Alaska has also been correlated with large-scale climate patterns such as Pacific decadal oscillation (PDO) (Duffy et al. 2005), the east Pacific teleconnection indices (Hess et al. 2001), and El Niño–Southern Oscillation (ENSO) (Krawchuk et al. 2006; Rupp et al. 2002). Duffy et al. (2005) showed that annual area burned in Interior Alaska was reasonably estimated using seven climate variables that ranged from the average June temperature and average June precipitation to the average PDO index for January and February, thus clearly linking regional fire extent to large-scale climate events, which in turn influence local weather. The PDO shifted in about 1976 from approximately 30 years of predominantly negative values to predominantly positive values. This was associated with a switch in local climate from cooler and moister to warmer and drier conditions (Hartmann and Wendler 2005; Mantua et al. 1997).

The Alaska Fire Service has been mapping wildfire extent since the 1940s (which is not very long considering the enormous interannual variability in the area burned), and projections based on this historical record suggest a future increase in the frequency, severity, and extent of wildfires (Balshi et al. 2009; Wotton et al. 2010). When Kasischke and Turetsky (2006) analyzed changes in the fire regime across the entire North American boreal region using fire scars from 1959 to 1999, they found a doubling of annual burned area between the 1960s/70s and 1980s/90s and more than doubling of the frequency of larger fire years because of more large fire events (>1000 km²). However, the relative importance of changes in fire management policies in Alaska instituted in 1986 or the PDO switch in 1976 in causing these changes in the fire regime is unknown. Increases in human population (3% between 2010 and 2012; http://quickfacts.census.gov) and associated expansion of roads and the wildland urban interface are additional potential causes of changes in the fire regime in Alaska.

Therefore, we decided to reanalyze changes in the Alaska fire extent across the entire record, which now spans 70 years, to better understand recent trends: Is there a sudden increase in fire extent around the switch of the PDO in 1976 or do we see a consistent increase in area burned that would be more reflective of continuous warming? And how have nearly 30 years of human fire management influenced the area burned across the region?

2. Methods

2.1. Study area

Interior Alaska extends from the Brooks Range in the north to the Alaska Range in the south and from the Canadian border in the east to the coastal zone in the west (Figure 1). For the purpose of this study, we define Interior Alaska as the area of overlap between the boreal zone of the Omernik–Bailey ecosystem classification of Alaska (Gallant et al. 1995) and the area of frequent wildfires with simplified borders on its east and west sides. This yields a total study area size of 292 172 km². This ecosystem consists of four major community types: black spruce, white
Figure 1. Interior Alaska is located within the intermontane boreal ecosystem and experiences more fires than other locations. These maps show our delineation of Interior Alaska with a thick gray outline as well as the five subregional study sites McGrath, Tanana, Beaver, Fairbanks, and Circle and their respective 100-km radius circles. FMZs are shown within the subregional study areas using the color coding of the Alaska Fire Service; firescars include 1943 to 2012.
spruce, deciduous forest (mostly aspen and birch), and tundra at higher elevations [for more detail, see Calef et al. (2005)].

We subdivided this area into five subregional study sites to be able to analyze fire changes at two scales and to have multiple samples for statistical analysis. Each subregional study site was defined as the area of a circle with a 100-km radius. We chose 100 km because it allowed a good representation of the area without overlap among study sites or extension beyond the regional boundary. Each subregional study site included a human settlement so that we could compare fire regimes among fire suppression categories (some of which, e.g., Critical, are located only near settlements). The five subregional study sites differed in settlement size from about 35,000 people (Fairbanks) to about 200 people in Beaver as well as the presence or absence of a road system. The study areas were centered on Beaver, Circle, Fairbanks, McGrath, and Tanana (Figure 1).

Since it is unrealistic to suppress fires in the entire state, the land was divided into four categories in 1986 to prioritize fire suppression efforts by the Alaska Fire Service, the U.S. Forest Service, and the state of Alaska; however, the ultimate decisions on how to attack any fire depend on the Fire Management Officer in charge of the particular location and circumstances. These FMZs are based primarily on risk to human life and property rather than natural resources and are (in decreasing order of suppression)

1) Critical (lands containing human lives and property receive top priority fire protection, and all fires are immediately and aggressively suppressed);
2) Full (generally uninhabited lands that have high cultural, historical, or other resource value, usually also fully suppressed);
3) Modified (a buffer zone where fires are suppressed during times of high fire danger but only monitored otherwise); and
4) Limited (essentially a natural fire regime).

2.2. Data

The area burned was calculated from the Alaska Large Firescar database, which is maintained by the Alaska Fire Service (available online at http://agdc.usgs.gov) and includes outlines of all firescars greater than 405 ha (1000 acres) since 1942. Although the early decades of the firescar record are somewhat incomplete (Kasischke et al. 2002), this is the longest and best record available for this area. Since 1988, the record includes fires between 40.5 ha (100 acres) and 405 ha as well. While these small fires contribute a very small percentage of total area burned, they are often human caused and occur in high protection zones (i.e., Critical); thus, they are of particular interest to us in any analysis regarding the Critical suppression zone or human impacts on fires. Therefore, whenever we analyzed the effect of suppression, we used only the record from 1988 to 2012.

FMZs dictate the level of suppression and are adjusted slightly each year by the Alaska Fire Service, but we chose zones for 2013 for the entire analysis for consistency (available online at http://agdc.usgs.gov).

While the majority of lightning strikes in Interior Alaska stem from intense synoptic storms that are accompanied by lots of rain, fires are usually started by (dry) airmass thunderstorms with low lightning strike frequency (Duffy et al. 2005; Hess et al. 2001). One straightforward way to distinguish between the two types of
storms is to use 1000 strikes per day as a threshold (Dissing and Verbyla 2003). Therefore, after creating a 100-km buffer around our study area to avoid boundary issues, we extracted lightning events from 1988 to 2012 for days when less than 1000 strikes were recorded by the Alaska observation network.

Vegetation was extracted from the 2010 North American Land Change Monitoring System (NALCMS) land cover, which maintains 19 land-cover classes at a 250-m pixel size (available online at www.cec.org). We reduced these 19 classes into six manageable categories: needleleaf forest, broadleaf forest, mixed forest, shrubland, grassland, and other.

2.3. Statistical analysis

First, we analyzed changes in the annual area burned through time at the regional scale as well as in the five subregional study sites and considered the influence of the FMZ as a proxy for the fire-fighting effort. When we analyzed general trends, we used the entire record from 1943 to 2012 (Figure 2); whenever we analyzed human influences such as FMZs, we used only the more detailed record from 1988

![Figure 2. Annual area burned (ha) from 1943 to 2012 in Interior Alaska.](image-url)
to 2012 after fire management zones had been established. This was followed up by an analysis of lightning strike density and vegetation composition to determine whether these parameters could explain any of the observed differences.

2.3.1. Annual area burned through time

Since the annual area burned in hectares for Interior Alaska from 1943 to 2012 was not normally distributed, we log transformed it before creating a simple linear regression model. The residuals (Figure 3) indicated that the linear model is appropriate but that the parametric tests for significance may be problematic because there are two outliers years (1962 and 1989) and the last two decades show smaller variability. Thus, we used the nonparametric bootstrap method with 6000 bootstrap samples to estimate confidence intervals for the correlation coefficient and the slope. To further gauge the effect of the two outliers, we redid the analysis with data that excluded the years 1962 and 1989.

To determine whether fire suppression influences the annual area burned, we considered four simple linear regressions using data for each of the FMZs from 1988 to 2012 (each with 25 observations). Statistical significance analysis was done using the bootstrap method with 6000 bootstrap samples. To gauge the effect of the outlier year 1989, we redid the statistical significance analysis excluding data from that year.

We followed up with linear regression analysis on each of the five subregions to consider subregional variability in the relationship between the annual area burned and the time from 1988 to 2012 with and without the outlier (each with 25 observations). Statistical significance and 95% confidence intervals for slope and correlation were determined using bootstrap methods with 6000 bootstrap samples.

2.3.2. A history of fire suppression

We compared the mean percent of FMZ burned annually from 1988 to 2012 in Interior Alaska as well as in the five subregions. To reduce the skewness of the data,
we applied a shift logarithmic transformation to each annual percentage of FMZ burned before performing one-way analysis of variance (ANOVA) followed by a Scheffé test.

### 2.3.3. Influence of lightning and vegetation

Following the methods of Fletcher et al. (2005), we analyzed whether the fact that an area burned and the percent area burned can be predicted using FMZ designation, dry lightning strike density, or vegetation type. To run this analysis, we calculated the following variables for each year from 1988 to 2012 by subregion and by FMZ:

- **Percent_burned**: Annual percentage of the area burned. For each region, we determined what percentage of it was burned that year.
- **Burn**: A Boolean indicator of whether or not the area burned at all that year: 1 = yes, 0 = no.
- **Year**.
- **C, F, M, and L**: Dummy coding for the Critical, Full, Modified, and Limited FMZ, respectively. For a given region, \( C = 1 \) if the region is within the Critical FMZ, otherwise \( C = 0 \), which is similar for Full, Modified, and Limited.
- **Lightning**: Lightning strike density; we used the number of recorded (dry) lightning strikes per 100 km\(^2\). Because of the skewness of the data, we used the logarithmic transformation \( \ln(x + 1) \).
- **Broadleaf, grassland, mixed_forest, needleleaf, shrubland**: Percent of each type of vegetation cover.

Since 1989 was abnormally wet, represented a severe outlier with an area burned more than 1.5 interquartile ranges (IQRs) away from the first quartile (Figure 3), and had been shown to skew other analyses (Tables 2, 3, and 4 below), we decided to exclude it from this regression analysis. This left us with 480 observations; however, 56.5% did not have any recorded area burned. Since we were identifying characteristics of areas that burned, we dropped these as well, thus reducing the data to 219 highly skewed observations that were converted to base 10 logarithms (Figure 4). To predict whether an area burned at all, we developed a generalized linear regression model using the logit link function in R [for details on the logit function, see Fox (2008)].

To determine if the observed differences in medians among FMZs is statistically significant, we used the Kruskal–Wallis rank sum test followed by a two-sided Wilcoxon rank sum test for each pair of FMZs. Because only the Full FMZ showed statistical significance, it was the only FMZ we included in the follow-up multiple regression analysis.

### 3. Results

#### 3.1. Annual area burned through time

There is a statistically significant positive linear relationship between the annual area burned and the time from 1943 to 2012 with an average increase of 2.4% yr\(^{-1}\) (Table 1). Since there is some concern that the record of wildfires is less complete
for early decades, we reran the model, dropping more and more of the earlier
decades and noted that the increase in the total area burned remained statistically
significant if we consider solely the later decades. Furthermore, we observed a
decrease in the average annual area burned up to 1985 that was not statistically
significant. As we dropped older data, a small rise in the annual area burned was
noticeable (average annual increases of 4.8%, 5.6%, and 6.8% for the years since
1960, 1970, and 1980, respectively, all statistically significant). However, the in-
crease in area burned since the new fire management system started in 1986 is only
4.8% and is not statistically significant. Increases in annual area burned were
clearly much larger during the positive phase of the PDO (8.9%) than during any
other time period analyzed. In summary, the overall increase in the area burned
since 1943 is most strongly influenced by extensive areas burned since the PDO
shifted to its positive (warmer, drier) phase around 1976.

Table 1. Changes in annual area burned (natural log of area in ha) from 1943 to 2012
in Interior Alaska. Regression results based on the entire record are highlighted in
bold.

<table>
<thead>
<tr>
<th>Years analyzed</th>
<th>Correlation</th>
<th>Coefficient</th>
<th>Annual increase</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1943–2012</td>
<td>0.243*</td>
<td>0.024*</td>
<td>2.4%*</td>
<td>Entire data record</td>
</tr>
<tr>
<td>1960–2012</td>
<td>0.346*</td>
<td>0.048*</td>
<td>4.8%*</td>
<td></td>
</tr>
<tr>
<td>1970–2012</td>
<td>0.382**</td>
<td>0.056**</td>
<td>5.6%**</td>
<td></td>
</tr>
<tr>
<td>1980–2012</td>
<td>0.357*</td>
<td>0.068*</td>
<td>6.8%*</td>
<td></td>
</tr>
<tr>
<td>1943–85</td>
<td>0.064</td>
<td>−0.009</td>
<td>−0.9%</td>
<td>Before institution of FMZ system</td>
</tr>
<tr>
<td>1986–2012</td>
<td>0.214</td>
<td>0.048</td>
<td>4.8%</td>
<td>After institution of FMZ system</td>
</tr>
<tr>
<td>1951–75</td>
<td>0.034</td>
<td>0.009</td>
<td>0.9%</td>
<td>Negative PDO phase</td>
</tr>
<tr>
<td>1976–2006</td>
<td>0.404*</td>
<td>0.089*</td>
<td>8.9%*</td>
<td>Positive PDO phase</td>
</tr>
</tbody>
</table>

* Statistical significance alpha level 0.05.
** Statistical significance alpha level 0.01.
When we excluded the two outlier years 1962 and 1989, results were very similar, but trends were less pronounced except for the decreasing trend from 1943 to 1985 that was now 1.3% (Table 2). The average annual increase in the area burned since 1943 went down by only a fifth of a percent to 2.2%. The decrease during the positive PDO phase dropped to only 1% yr\(^{-1}\). We urge caution in overinterpreting the changes in the annual increase for the different subsets of the data, since an outlier year could have a strong influence in a small dataset.

Our comparison of the relationships between the annual area burned across time within the four FMZs in Interior Alaska show that fire suppression matters (Table 3; Figure 5). While there is no statistically significant annual increase in the area burned for Limited and Modified FMZs, the annual area burned in Full increases on average by 10.4% yr\(^{-1}\) (\(p < 0.05\)), and the annual area burned in Critical increases on average by 23.8% yr\(^{-1}\) (\(p < 0.01\)). We considered whether the relationships are unduly affected by the outlier year 1989. Removing the year did not substantially affect the correlation for the Critical FMZ (average annual increase by 23.6%; \(p < 0.01\)) but did noticeably decrease the correlation for Full, which is only marginally statistically significant (average annual increase by 7.8%, \(p < 0.1\)). The relationships for Modified and Limited remain not statistically significant.

Changes in annual area burned were quite variable at the subregional scale (Table 4; Figure 6), though the only statistically significant relationship is around Fairbanks, where the annual increase in area burned is on average 19% yr\(^{-1}\) (\(p < 0.01\)). Removing the outlier year 1989 reduces the average annual increase in area burned to 12.4% (\(p < 0.05\)), still an impressive increase. The scatterplots of the

### Table 2. Changes in the annual area burned (natural log of area in ha) from 1943 to 2012 disregarding data from the two outlier years (1962 and 1989).

<table>
<thead>
<tr>
<th>Years analyzed</th>
<th>Correlation</th>
<th>Coefficient</th>
<th>Annual increase</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1943–2012</td>
<td>0.264*</td>
<td>0.022*</td>
<td>2.2%*</td>
<td>Entire data record</td>
</tr>
<tr>
<td>1960–2012</td>
<td>0.308*</td>
<td>0.036*</td>
<td>3.6%*</td>
<td></td>
</tr>
<tr>
<td>1970–2012</td>
<td>0.424**</td>
<td>0.055**</td>
<td>5.5%**</td>
<td></td>
</tr>
<tr>
<td>1980–2012</td>
<td>0.349*</td>
<td>0.054*</td>
<td>5.4%*</td>
<td></td>
</tr>
<tr>
<td>1943–85</td>
<td>0.093</td>
<td>−0.013</td>
<td>−1.3%</td>
<td>Before institution of FMZ system</td>
</tr>
<tr>
<td>1986–2012</td>
<td>0.054</td>
<td>0.009</td>
<td>0.9%</td>
<td>After institution of FMZ system</td>
</tr>
<tr>
<td>1951–75</td>
<td>0.020</td>
<td>0.004</td>
<td>0.4%</td>
<td>Negative PDO phase</td>
</tr>
<tr>
<td>1976–2006</td>
<td>0.488**</td>
<td>0.095**</td>
<td>9.5%**</td>
<td>Positive PDO phase</td>
</tr>
</tbody>
</table>

* Statistical significance alpha level 0.05.
** Statistical significance alpha level 0.01.

### Table 3. Changes in the annual area burned (natural log of area in ha) from 1988 to 2012 accounting for FMZ with (and without) the 1989 outlier year.

<table>
<thead>
<tr>
<th>FMZ</th>
<th>Correlation</th>
<th>Coefficient</th>
<th>Annual increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>0.557** (0.534**)</td>
<td>0.238** (0.236**)</td>
<td>23.8%** (23.6%**</td>
</tr>
<tr>
<td>Full</td>
<td>0.416* (0.327*)</td>
<td>0.104* (0.078*)</td>
<td>10.4%* (7.8%*)</td>
</tr>
<tr>
<td>Modified</td>
<td>0.210 (−0.013)</td>
<td>0.078 (−0.004)</td>
<td>7.8% (−0.4%)</td>
</tr>
<tr>
<td>Limited</td>
<td>0.240 (−0.044)</td>
<td>0.090 (−0.009)</td>
<td>9.0% (−0.9%)</td>
</tr>
</tbody>
</table>

* Statistical significance alpha level 0.05.
** Statistical significance alpha level 0.01.
annual area burned by subregional study site (Figure 6) indicate a steady increase in area burned near Fairbanks.

### 3.2. A history of fire suppression

Suppression significantly reduced the percentage of FMZ burned in Interior Alaska (Table 5). ANOVA shows that all differences in the means are statistically significant except for the difference between Full and Modified FMZs and the difference between Modified and Limited FMZs ($R^2 = 22\%$, $F = 9.1$, $p < 0.001$).

Table 4. Changes in the annual area burned (natural log of area in ha) from 1988 to 2012 by subregion with (and without) the 1989 outlier year. Results for Fairbanks are highlighted in bold.

<table>
<thead>
<tr>
<th>Region</th>
<th>Correlation</th>
<th>Coefficient</th>
<th>Annual increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>0.004 (−0.069)</td>
<td>0.002 (−0.029)</td>
<td>0.2% (−2.9%)</td>
</tr>
<tr>
<td><strong>Fairbanks</strong></td>
<td><em><em>0.547</em> (0.489</em>*)</td>
<td><em><em>0.190</em> (0.124</em>*)</td>
<td>*<em>19.0%</em> (12.4%**)</td>
</tr>
<tr>
<td>Tanana</td>
<td>0.198 (0.064)</td>
<td>0.101 (0.031)</td>
<td>10.1% (3.1%)</td>
</tr>
<tr>
<td>Beaver</td>
<td>−0.047 (0.064)</td>
<td>−0.026 (−0.101)</td>
<td>−2.6% (−10.1%)</td>
</tr>
<tr>
<td>McGrath</td>
<td>0.048 (0.064)</td>
<td>0.028 (−0.101)</td>
<td>2.8% (−3.4%)</td>
</tr>
</tbody>
</table>

* Statistical significance alpha level 0.001.

** Statistical significance alpha level 0.01.
and Scheffé test using $\alpha = 0.05$). Combining the annual percentages of FMZ burned for the five subregions confirmed that the differences in means are statistically significant, with exception of the difference between Full and Modified FMZ ($R^2 = 18\%, F = 35.1, p < 0.001$, and Scheffé test using $\alpha = 0.01$).

### 3.3. Influence of lightning and vegetation

The arrival and spread of a wildfire large enough to be recorded by the Alaska Large Firescar database vary widely among FMZs; Critical experienced fire in only 9% of the years, compared to 48% of years in Full, 43% in Modified, and 83% in the Limited FMZ. Fires were less likely in Critical and more likely in Limited and Full regardless of dry lightning strike density and vegetation type (Table 6).

The median area burned was only statistically significant in Full ($\chi^2 = 9.85$, degrees of freedom = 3, $p = 0.02$ in Kruskal Wallis, and $p < 0.05$ in Wilcoxon) compared to the other FMZs (Figure 4). The multiple regression analysis indicated

| Table 5. Mean annual area burned (percent) by FMZ from 1988 to 2012 in Interior Alaska. |
|----------------|----------------|----------------|----------------|
|                | Critical       | Full           | Modified       | Limited       |
| Mean           | 0.24           | 0.69           | 1.43           | 1.64          |
| Std dev        | 1.14           | 1.75           | 4.28           | 2.88          |
| Median         | 0              | 0.03           | 0.03           | 0.41          |
that the percent of the area burned was significantly influenced by being in the Full FMZ \((p = 0.03)\), while lighting and vegetation type had no influence (see Table 7).

### Table 6. Generalized regression analysis predicting that an area burns using the logit link function.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Std error</th>
<th>(z) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>2.276</td>
<td>0.655</td>
</tr>
<tr>
<td>Critical FMZ</td>
<td>-1.820</td>
<td>-3.854*</td>
</tr>
<tr>
<td>Full FMZ</td>
<td>0.617</td>
<td>1.834</td>
</tr>
<tr>
<td>Limited FMZ</td>
<td>1.313</td>
<td>2.939**</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.003</td>
<td>0.055</td>
</tr>
<tr>
<td>Needleleaf</td>
<td>-0.035</td>
<td>-0.767</td>
</tr>
<tr>
<td>Mixed_forest</td>
<td>-0.044</td>
<td>-1.188</td>
</tr>
<tr>
<td>Broadleaf</td>
<td>-0.024</td>
<td>-0.540</td>
</tr>
<tr>
<td>Shrubland</td>
<td>-0.009</td>
<td>-0.277</td>
</tr>
<tr>
<td>Lightning</td>
<td>-0.222</td>
<td>-0.938</td>
</tr>
</tbody>
</table>

* Statistical significance alpha level 0.001.
** Statistical significance alpha level 0.01.

4. Discussion

While Alaska has been warming at twice the rate of the rest of the United States over the past 50 years (Markon et al. 2012), extreme interannual and subregional variability in the area burned make it difficult to identify clear trends. However, our detailed analysis using the 70-yr large fire record provides a valuable contribution to the understanding of changes in fire extent in Alaska and the human influence on fires via suppression and climate change.

One problem with analyzing the temporal trend is that the annual area burned underwent a shift in the late 1980s from larger variability to reduced variability, accompanied by a steep increase in the area burned; this might or might not have been the result of the Pacific decadal oscillation (PDO) shift from a predominantly cool and moist (negative) phase to a warm and dry (positive) phase (Hartmann and Wendler 2005). This trend was robust to the removal of two outlier years: 1962 and 1989. Removal of these outliers does not significantly affect the overall trend; we

### Table 7. Summary of multiple regression analysis predicting annual area burned (including only cases where it burned) using the Full FMZ, dry lightning strike density, and vegetation.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Std error</th>
<th>(t) stat</th>
<th>(P) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.20</td>
<td>0.60</td>
<td>0.55</td>
</tr>
<tr>
<td>Full FMZ</td>
<td>-0.47</td>
<td>-2.16</td>
<td>0.03*</td>
</tr>
<tr>
<td>Broadleaf</td>
<td>-0.01</td>
<td>-0.39</td>
<td>0.70</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.00</td>
<td>-0.08</td>
<td>0.94</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>-0.02</td>
<td>-0.68</td>
<td>0.49</td>
</tr>
<tr>
<td>Needleleaf</td>
<td>-0.01</td>
<td>-0.54</td>
<td>0.59</td>
</tr>
<tr>
<td>Shrubland</td>
<td>-0.02</td>
<td>-0.98</td>
<td>0.33</td>
</tr>
<tr>
<td>Lightning</td>
<td>-0.04</td>
<td>-0.25</td>
<td>0.80</td>
</tr>
</tbody>
</table>

* Statistical significance alpha level 0.01.
found an increase in the annual area burned in Interior Alaska by 2.2% yr\(^{-1}\) since 1943. Added together over the 70 years analyzed, this amounts to a 4.6-fold increase or a doubling in 32 years that is reasonably consistent with the doubling Kasischke and Turetsky (2006) observed between the 1960s/70s and the 1980s/90s across the entire North American boreal zone of which Interior Alaska is only a small part. The area burned increased significantly during the positive PDO phase, echoing the relationship already established by Duffy et al. (2005) between the area burned in Alaska and the large-scale regional climate patterns. The PDO shift around 1976 accelerated the rise in the area burned from the three decades prior to the following three decades. Since we are at the transition to another negative PDO phase, predicting the future area burned should consider PDO shifts. In contrast to the response to PDO, the area burned did not change significantly before and after the institution of the fire management zone system in Alaska. This makes sense, since fire management is concentrated in a few areas deemed important. In general, we conclude that the area burned has been increasing steadily, which can possibly be attributed to climate change but might have been accelerated by the PDO shift in the middle of the existing fire record.

Alarmingly, we found that annual area burned is increasing steeply in highly suppressed zones, where there is greater risk to life and property, even when discounting the outlier year 1989; the area burned has increased in the Critical FMZ by 23.6% since 1988 and in Full by 7.8%. There has been discussion among fire managers and scientists on whether suppression ultimately leads to increased fire risk due to fuel load and succession of mixed forests to pure and highly flammable black spruce stands (Johnson et al. 2001; Miyanishi and Johnson 2001; Ward et al. 2001). While the land cover of Alaska has been classified a few times over the past 30 years, the vegetation classifications differ so widely from each other that it is basically impossible to track vegetation change at the local level. Therefore, we were not able to provide explanations as to what is causing this observed increase in the area burned.

When we studied subregional variability, the annual area burned increased most rapidly (at a rate of 12.4% yr\(^{-1}\)) in the area surrounding Fairbanks—the most populated subregion in Interior Alaska—even when the outlier year 1989 was discounted. This trend was observed in the Full, Modified, and Limited suppression zones of the Fairbanks study site, though only the trends for Full and Limited FMZs are statistically significant. Possible explanations for this observed increase in area burned are increased human fire ignitions, vegetation change (the gold mining legacy), increased fuel load due to past suppression, climate change, or chance. Human fire ignitions play an important role near access points such as settlements and roads (Calef et al. 2008; DeWilde and Chapin 2006). Thus, Fairbanks, with its fairly large population and high road density (especially in contrast to some of our subregions without road access), experiences more human ignitions. Within 5 km of the Interior Alaska settlements, human fire ignitions exceeded lightning ignitions by a rate of 20 to 1 (Calef et al. 2008; Kovacs et al. 2004), but human ignitions were responsible for only 5% of the total area burned regionally during the 1990s and 2000s (Kasischke et al. 2010), so it is unlikely that human fire ignitions explain the increased area burned. The forest surrounding Fairbanks was completely logged during the Gold Rush at the beginning of the twentieth century, has been recovering for the past 100 yr, and is probably now approaching its peak
flammability, but we have no detailed stand age data to prove it. Wendler and Shulski (2009) found that mean annual temperature has increased in Fairbanks by 1.4°C over the past century; this warming led to an extension of the length of the growing season by 45% and was accompanied by a decrease in precipitation. Each of these factors is conducive to fire spread, and while each subregional study area experiences slight variations in climate (Shulski and Wendler 2007), we cannot tell if this is sufficient to explain the observed differences in the area burned. To summarize, our analysis does not identify a specific reason for the observed increase in the area burned near Fairbanks; increasing stand age, a changing climate, increased fuel load, or chance might all be contributing.

Our study clearly indicates that fire suppression is effective in controlling the overall area burned. Much like DeWilde and Chapin (2006), who documented a 50% reduction in the area burned for the combined Critical and Full zones, our analysis demonstrates that the level of suppression priority has profoundly reduced area burned in the past. The Critical zone was the most different and had the lowest area burned, which can possibly be explained by the combined impacts of suppression and the lower flammability of an urban and suburban landscape compared to an undisturbed black spruce forest. However, Modified and Full zones also experienced a reduction in the relative area burned compared to the Limited (but did not differ significantly from one another), indicating that even the intermittent suppression enacted on Modified has significantly changed the fire history in this zone.

The influence of suppression was more important than the vegetation type or dry lightning strike density; fire occurrence (we are referring here to fires that cover at least 40.5 ha) was less likely in Critical and more likely in Limited and Full, and the area burned was linked to the Full fire management zone. In contrast, DeWilde and Chapin (2006) found that vegetation type (and thus flammability) had a strong effect on the percent area burned when the data were aggregated regionally, and only very large fires (>40 000 ha) burned equally on all vegetation types. At the scale of individual fires or years, there are many exceptions to the general effectiveness of suppression. In general, the initial attack is most effective when fires are very small: 97% of fires that were attacked at <0.4 ha remained <0.4 ha (Cumming 2005; DeWilde and Chapin 2006), and hence all fires in Critical are immediately attacked (and often successfully so as our analysis shows). In Alberta, Canada, the total number of large fires (>200 ha) and the proportion of fires that became large every year were reduced after the introduction of a fire management policy (Cumming 2005); prior to the policy, the probability of large fires was higher by a factor of 2.41. But this can also mean that a fire starting in another zone might become too large to be stopped easily when it unexpectedly spreads into Full and Critical suppression zones. The ultimate size of individual fires is often the result of transient conditions at a particular locality, such as high afternoon winds that might quickly expand a fire or an intense rain shower that might stop it before it can become large. The significant differences in the area burned among fire management zones indicate that suppression had an important impact and that the zones should not be combined indiscriminately in analyses of fire patterns.

This study provides new insights into regional and spatial differences of large fires and suppression effects. Our analysis shows that suppression has generally been effective in reducing the area burned over the past several decades. However,
our temporal analysis shows that the area burned is increasing more rapidly in suppressed zones than in the unsuppressed Limited zone. This finescale examination of years and study areas demonstrates that fire policies as well as regional climate patterns are important as large-scale controls on fires over time and across the Alaskan boreal forest.

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**References**


