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Analysis of the patterns of large fires in the boreal forest region of Alaska

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Abstract. Analyses of the patterns of fire in Alaska were carried out using three different data sets, including a large-fire database dating back to 1950. Analyses of annual area burned statistics illustrate the episodic nature of fire in Alaska, with most of the area burning during a limited number of high fire years. Over the past 50 years, high fire years occurred once every 4 years. Seasonal fire statistics indicated that high fire years consist of larger fire events that occur later in the growing season. On a decadal basis, average annual area burned has varied little between the 1960s and 1990s. Using a geographic information system (GIS), the spatial distribution of fires (aggregated by ecoregions) was compared with topographic, vegetation cover, and climate features of Alaska. The use of topographic data allows for a more realistic determination of fire cycle by eliminating areas where fires do not occur due to lack of vegetation above the treeline. Geographic analyses show that growing season temperature, precipitation, lightning strike frequency, elevation, aspect, and the level of forest cover interact in a complex fashion to control fire frequency.

Additional keywords: Fire map, fire history, spatial analysis

Introduction

Both resource managers and scientists have long recognized the importance of fire in the boreal forest, with fire management personnel compiling a variety of statistics describing fire. In terms of understanding the occurrence and distribution of fires, statistics that are most widely used include total number of fires, ignition sources, and area burned within specific jurisdictions during a given fire season (Barney 1971; Barney and Stocks 1983; Van Wagner 1988). Within the North American boreal forest region, such seasonal data are available for Alaska back to the 1940s and for most Canadian provinces and Territories back to the 1920s (Murphy *et al.* 2000).

Research has been conducted on the contemporary Alaskan fire regime based on compilation of stand ages or analyses of data from fire records. Yarie (1981) estimated the fire cycle for the east-central portion of Alaska for specific tree species using stand age distributions. On a statewide basis, Barney (1971) analysed seasonal fire statistics for the years 1950 to 1969 in different vegetation cover types and determined that, while lightning resulted in only 24% of all fire ignitions, fires started by this source accounted for nearly 80% of total area burned. This study was extended to include data from 1970 to 1978 by Barney and Stocks (1981), who reached the same conclusion. In the first attempt to study the spatial distribution of fires, Gabriel and Tande (1983) analysed fire data for a 23-year period (1957 to 1979) by compiling information for 56 distinct physiographic provinces. Assuming that each fire burned within the province where it started, fire cycles were calculated. Gabriel and Tande (1983) showed that most of the reported fire in Alaska occurred in the interior region of the state, between the Alaska and Brooks Ranges.

Beginning in the late 1980 s, technologies were developed that permitted detailed quantification of the boundaries on maps contained within fire records (digital scanners) and facilitated analysis of spatial/temporal data (computer-based geographic information systems). In Alaska, an effort was initiated in 1990 to digitize the boundaries of all large fires where records exited. Through this effort, all available fire records have been digitized from 1950 to 1999.

Fig. 1 presents a fire map for the State of Alaska created from digitized maps of fire perimeters, as well as the start locations and relative sizes of fires with missing records. This map shows that the primary region affected by fire is

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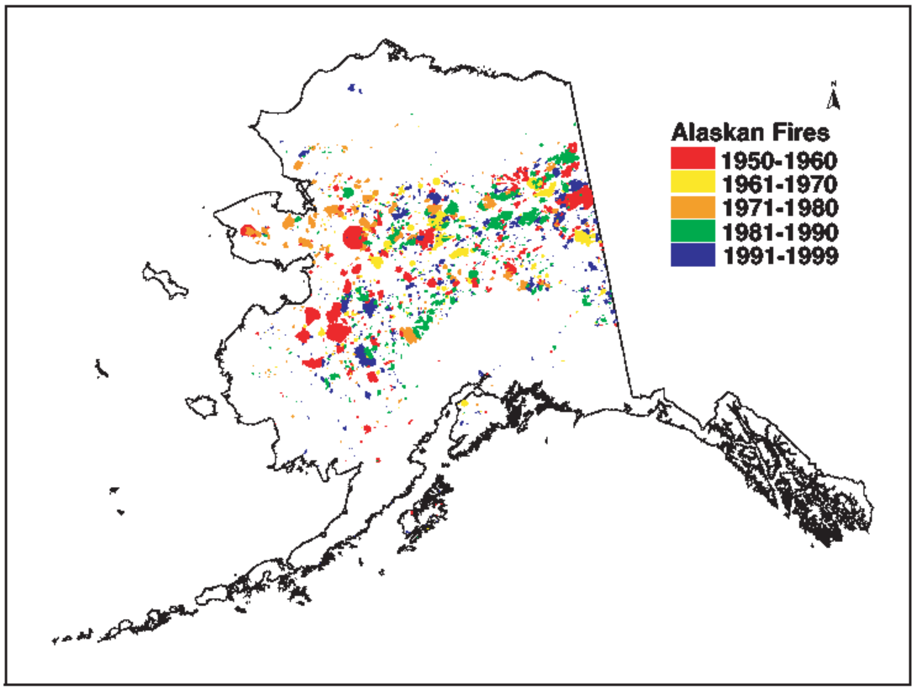

Fig. 1. Map of the fire boundaries for Alaskan from 1950 to 1999 based on information contained within the large-fire database. For fires that did not have perimeter maps, we used a circle whose size is equal to the reported size of the fires.

located between the two east-to-west mountain ranges that dominate the landscape in the state and form the boundaries for the boreal forest region (the Brooks Range to the north and the Alaska Range to the south). Outside of this broad pattern, it is difficult to discern any other generalized patterns to fire distribution. Those familiar with the boreal forest fire regime know, however, that there are distinct spatial and temporal patterns to fire occurrence in this region.

In this paper, we summarize the characteristics of the large-fire database (LFDB) that has been created for the State of Alaska. Using the LFDB and other statistics, we carried out a study of Alaskan fire occurrence, including analysing the inter-annual and seasonal fire patterns, and correlations of the fire location information with spatial information on climate, topography, and the vegetation cover of Alaska.

This paper includes five sections, including this introduction. Section 2 discusses the sources of fire information available for the State of Alaska, and includes an assessment of the quality of these data. Section 3 presents the methods used to analyse these data, and Section 4 summarizes our results. Finally, Section 5 presents a discussion and conclusions from this study.

Sources of Alaskan fire information

The material presented in this section is based on a more detailed review of the wildland fire management history in Alaska and generation of fire information presented by Murphy *et al.* (2000). The jurisdictional responsibility for managing fires in Alaska (including maintenance of records) has co-existed within a number of government agencies since fire monitoring and suppression efforts were instituted in 1939. Fire management activities were initially administered by the General Land Office, but this responsibility was transferred to the Bureau of Land Management (BLM) upon its formation in 1946. In 1957, BLM created two fire management districts (Anchorage and Fairbanks) within the Alaskan Territory.

The granting of statehood to Alaska in 1959 resulted in a further division of fire management responsibilities. At this time, the state was given jurisdiction over 42.1 million ha of land, and fire management responsibilities were split between BLM and the Alaskan Department of Natural Resources. The state created its own wildland fire-fighting organization in 1977—until then, BLM provided services under contract.

Passage of the Alaska Native Claims Settlement Act by the U.S. Congress in 1971 provided for the selection and management of 21.1 million ha of land by Alaska Native Regional and Village Corporations. While the Native Corporations set policy for management on these lands, fire management services were (and still are) provided by BLM. In 1980, passage of the Alaska National Interest Lands Conservation Act by Congress allocated 42.1 million ha to U.S. National Parks and U.S. Fish and Wildlife Refuges, who assumed responsibility for fire policy and management in areas under their jurisdiction.

To coordinate fire management within the state, the Alaska Land Managers' Cooperative Task Force formed a fire subcommittee in 1978, providing the foundation for the creation of the Fire Planning Working Group in 1980. In 1982, the Alaska Fire Service was formed to provide fire protection support for all agencies of the U.S. Department of the Interior with land management responsibilities in the state (BLM, the National Park Service, the U.S. Fish and Wildlife Service, and the Bureau of Indian Affairs). Protection of lands selected by the native corporations through the Alaska Native Claims Settlement Act and lands under military management were also included. Throughout the 1980s and 1990 s, the State of Alaska and the Alaska Fire Service entered into cooperative agreements to reduce costs associated with providing fire protection services. These cooperative arrangements also led to the centralization of fire records within the Alaska Fire Service. Today, fire data are compiled and published by the Alaska Interagency Coordination Center (AICC) using information provided by the three agencies responsible for active management of wildland fires in Alaska: (1) the Alaska Fire Service (AFS); (2) the State of Alaska, Department of Natural Resources, Division of Forestry; and (3) the U.S. Forest Service.

Origin of fire information

The generation of a permanent record of fire information in Alaska begins with an active fire file created for each fire event as it occurs. Every event is assigned a unique identifying number and a descriptor based on a named geographic feature near the location of the fire's ignition point (e.g. mountain, lake, river, stream, road, etc.). The active file documents the progress of management activities associated with the fire event and its growth over time. It frequently contains hand-written notes as well as preliminary maps of the fire boundary at different points of time.

At year's end, a permanent fire record is created for each fire event, consisting of a page of statistical information (e.g. fire ownership, location, size, and cause, weather parameters, suppression activities, etc.), a map of the fire perimeter, and a narrative of actions taken. During this compilation phase, parts of the fire record are sometimes lost or misplaced, including the fire boundary maps. Thus, many permanent records include only the start location and size of a specific fire event. In some cases, entire permanent records have been lost.

Fire data are available in other formats. Statistics for every fire event are compiled at the end of each year, and summarized in an annual report (e.g. Alaska Fire Service 1998). In addition, over the past few years, fire statistics (including number of fires and area burned) have been compiled and reported on a daily basis through Web Pages maintained by the Alaska Fire Service (http://fire.ak.blm.gov/) and the National Interagency Coordination Center (NICC) (http://www.cidi.org/wildfire/index.html). Most of the daily and seasonal fire statistics for Alaska back to 1994 can be obtained through the NICC web page.

Beginning in the summer of 1990, the permanent fire records maintained by the Alaska Fire Service were reviewed for the purpose of creating a digital large-fire database for the State of Alaska. This effort was directed towards documenting the location of fires for comparison to information derived from satellite imagery (Kasischke *et al.* 1993; French *et al.* 1995; Kasischke and French 1995; Bourgeau-Chavez *et al.* 1997). The data have since been used for estimating trace gas emissions from Alaskan fires (Kasischke *et al.* 1995; French *et al.* in press). Initially, copies were made of all maps from fires >400 ha in size for the period of 1950 through 1992 by non-government scientists working for a number of universities and research organizations. The fire boundaries from these maps were then digitized and entered into a GIS database. Subsequently, personnel from BLM's Alaska Fire Service digitized fire perimeter maps for the years since 1992, and reviewed the records back to 1988 to include boundaries of fires >25 ha in size. They also located many fire records missing from earlier efforts, and checked older records for positional accuracies.

Fire perimeter and location maps within the permanent fire records were assigned one of three quality ratings: poor, fair and good (Fig. 2). Maps in the fair and poor categories received additional scrutiny prior to digitizing the fire boundary. In the fair category, it was often necessary to correct the location of the map relative to the named geographic features identified in the written portion of the permanent record. The fire perimeter was then redrawn on the actual USGS map of the area (so that it was consistent with named geographic features). When possible, the same procedure was used for poor-quality maps but, in many cases, a best guess had to be made with respect to actual fire boundary locations.

The Alaskan LFDB presented in Fig. 1 is available at http://agdc.usgs.gov/data/projects/fhm/#N.

Quality of Alaska fire data

The quality of the fire information present within the Alaska fire database is primarily dependent on the method used to create the fundamental information unit within the permanent fire record—the fire perimeter map. Three techniques are used to map the location and perimeter of fires in Alaska: (*a*) ground surveys; (*b*) airborne surveys; and (*c*) interpretation of aerial photography or satellite imagery.

One might initially assume that ground surveys produce the least accurate maps of fire location and perimeter. However, because much of the area in Alaska where fire occurs is in hilly or mountainous terrain, this is not the case. Topographic

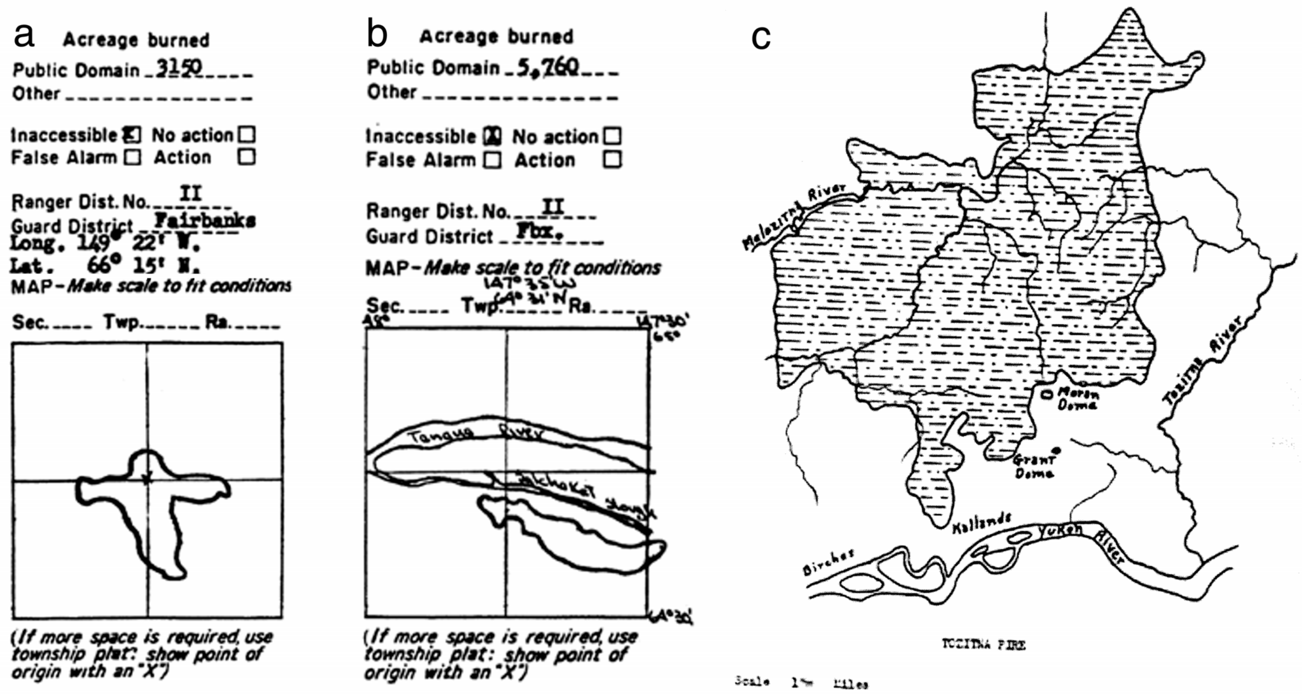

Fig. 2. Examples of fire perimeter maps found within the permanent records of the Alaska Fire Service that illustrate different levels of information quality: (*a*) poor quality map; (*b*) fair quality map; (*c*) good quality map.

relief aids mapping in two ways. First, it provides the elevation needed to visually scan large areas and view the edges of fire perimeters. And second, it provides easily identifiable map features (such as streams, rivers and drainage basins) to locate and document the position of the fire perimeter. Quite frequently, these landscape features serve as natural fire breaks, and hence represent the border of a fire. Using topographic maps, the boundary of a fire relative to specific watersheds and other distinct geographic features (ponds, lakes, and mountains) can often be determined via visual, ground-based surveys.

Surveys from aerial platforms (airplanes and helicopters) provide a more synoptic overview that is helpful in mapping fires in areas of low relief or with large perimeters. This mapping still depends on the presence of identifiable terrain features, or the use of global positioning system (GPS) technology to accurately locate perimeter locations.

Prior to 1970, standard baseline maps were not used, and most fire perimeters and locations were drawn by hand on plain or gridded paper. Beginning in 1970, this practice was discontinued, with the boundaries and locations of fires being drawn directly onto U.S. Geological Survey (USGS) maps at a scale of 1:250 000 or 1:63 360. In the 1940s, aircraft were not readily available for use in mapping fires. Most fires at this time were probably mapped on foot, and large, remote interior fires were probably not mapped at all. Beginning in the early 1950s, fire management agencies acquired aircraft for detection, monitoring, and mapping of fires.

As mentioned, the fire boundary maps for Alaska can be given an overall quality rating of poor, fair, and good (Fig. 2), as described below:

POOR: Fire perimeters are drawn using generic shapes (e.g. a circle or an ellipse) and no map scales are provided. Inaccurate coordinates are often recorded, and no named geographic references are provided or generic geographic reference terms (e.g. river, lake, mountain) are used (Fig. 2*a*).

FAIR: The fire map has a scale and at least one named geographic reference. Sometimes map coordinates are in error. The perimeter boundary conforms to the general outline of the fire (Fig. 2*b*).

GOOD: The fire map has a scale and a distinctly drawn fire perimeter. It contains a number of geographic reference points, and the reference latitude/longitude coordinates for the fire location are consistent with these features (Fig. 2*c*).

One shortcoming of the Alaska LFDB is the absence of fire maps within a number of permanent fire records. It is estimated that missing maps account for 15% of the total fire area reported for this region since 1950 (based on seasonally aggregated forest statistics). Individual fire maps can be documented as missing because of databases that list the identifying number for most fires, their start location, and area burned, as well as summary tables of the total area burned for a given year.

Table 1. Summary of annual area burned in Alaska from 1950 to 2001 from seasonal fire summaries of the Alaska Fire Service and the large-fire database

	Area burned (ha)	
	Alaska Fire Service data	Large-Fire Database
1950	833 124	1221 016
1951	88 945	117 872
1952	29 879	1 088
1953	188 967	45 302
1954	562 721	501 103
1955	15 074	2 243
1956	192 953	358 502
1957	2 044 397	1 491 079
1958	128 427	106 828
1959	241 528	226 798
1960	35 296	21 248
1961	2 065	553 318
1962	15 779	5 390
1963	6 595	852
1964	1 389	0
1965	2 872	518
1966	272 374	0
1967	44 132	2 982
1968	410 243	73 865
1969	1 713 287	850 993
1970	45 946	11 816
1971	432 837	329 762
1972	391 193	312 449
1973	24 217	22 384
1974	268 405	106 718
1975	51 759	23 406
1976	27 983	27 209
1977	929 477	960 342
1978	3 140	2 284
1979	157 864	246 885
1980	52 588	60 791
1981	217 092	221 145
1982	28 663	17 464
1983	39 743	30 896
1984	46 911	40 833
1985	150 700	135 582
1986	159 987	186 663
1987	67 529	61 734
1988	864 182	885 841
1989	27 892	22 363
1990	1 291 125	1 256 452
1991	708 766	661 228
1992	60 169	49 785
1993	288 711	282 367
1994	107 580	100 679
1995	19 028	14 658
1996	242 618	235 687
1997	774 696	764 298
1998	72 874	47 283
1999	425 884	392 343
2000	304 345	Not available
2001	88 730	Not available

Most of the missing data records occurred in five years (1954, 1966, 1968, 1969 and 1971). On a decadal basis, missing records account for account for 14% of the total area burned during the 1950s, 57% for the 1960s, 12% for the 1970s, 8% for the 1980s and 0.2% for the 1990s.

The overall quality of the data within the Alaska LFDB was assessed as follows:

1950s: The overall quality of the fire maps is fair, ranging from poor to good in individual years. While most large (>50 000 ha) fires were documented, it is questionable whether all fires were actually detected and mapped during this time period.

1960s: Although the quality of the maps improved, as noted below, many permanent data records are missing for this decade. During the 1960 s, aerial monitoring activities increased and the likelihood of missed fires decreased. The overall quality of the data is rated as fair.

1970s: Although record maintenance procedures improved during this decade, some maps for larger fires are poor or missing. The overall quality of the data is rated between fair and good.

1980s and 1990s: The quality of data maps for this time period is rated good, with consistent mapping of fire boundaries and low number of missing data records.

Methods

Three different fire databases were used in this study:

(1) Total seasonal area burned estimates for 1960–2001 based on combining data reported by the Alaska Fire Service and information from the large-fire database where significant discrepancies were found. Because of uncertain data quality, data from 1950 to 1959 were excluded;

(2) Inter-seasonal area burned estimates reported by the National Interagency Coordination Center for the years 1994–2001; and

(3) The Alaskan large-fire database for the years 1950–1999, which contains not only fire perimeter maps, but also the start location and size of fires where maps were missing from the permanent record. Data from 2000 and 2001 have yet to be made available by the Alaska Fire Service.

Comparisons between total area burned within the AFS data and the LFDB (Table 1) showed that the latter had significantly higher area burned estimates during four years: 1950 (by 388 000 ha), 1956 (by 165 000 ha), 1961 (by 551 000 ha), and 1979 (by 89 000 ha). During these four years, errors in scaling in the original fire maps most likely account for the higher estimates in the LFDB. We substituted the LFDB for the AFS data for these four years.

Fig. 3 (based on the data summarized in Table 1) illustrates the high degree of variability in annual area burned in Alaska, with very large or high fire years being interspersed with low fire years. We analysed three issues regarding these inter-annual patterns of fire: (1) the sources of the variation in the decadal average area burned; (2) the differences in the size distribution of fires between large and small fire years; and (3) the differences in the timing of fires during the growing season between large and small fire years.

For these analyses, we divided our data sets into two categories: (*a*) high fires years, where the area burned was greater than 1.5 times the long-term, average annual area burned in Alaska; and (*b*) low fire years, which includes all other years. For issue (1), we examined average area burned in high and low fire years for four decades: the 1960s, 70s, 80s,

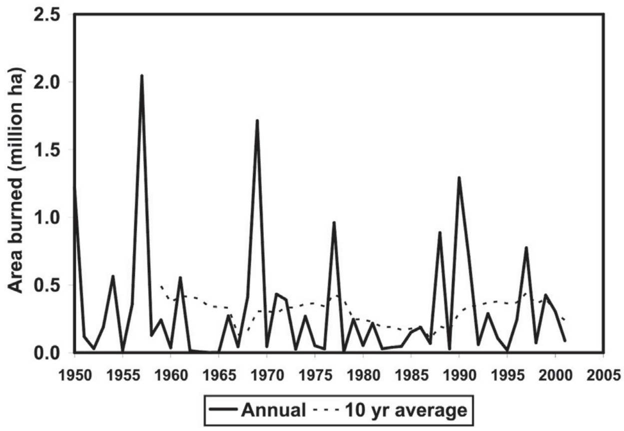

Fig. 3. Plot of annual area burned in Alaska and a 10-year running average area burned based on seasonal statistics reported by the Alaska Fire Service. Area burned information from the LFDB was used for four years: 1950, 1956, 1961 and 1979).

and 90s. For issue (2), we compared the sizes of the fires in the high and low fire years. For issue (3), we divided the 7 fire years between 1994 and 2001 into high and low fires years, and plotted percentage of seasonal area burned for three time periods: (*a*) early season (pre-July), mid-season (July) and late-season (post-July).

While the spatial distribution of fires in Fig. 1 is consistent with the observation of Gabriel and Tandes (1983) that most of the fire activity occurs in the interior region of the state, it still does not answer the question of whether or not there are underlying landscape and climate features associated with fire activity. To address this question, we used the following spatial data sets depicting vegetation cover, topography, and climate:

(1) Two data sets were used to describe the vegetation cover of the state of Alaska. We defined broad vegetation cover patterns using the Ecoregions of Alaska and Neighboring Territories map available from the Alaska Geophysical Data Center (AGDC) at ftp://agdcftp1.wr.usgs.gov/pub/projects/fhm/akecoregions.jpg) and described by Gallant *et al.* (1995). More detailed vegetation cover was based on a land cover map created by classification of AVHRR data (available from the AGDC at ftp://agdcftp1.wr.usgs.gov/pub/projects/fhm/vegcls.gif).
(2) The 3-arc second, 1° by 1° (1:250 000 scale) digital elevation model (DEM) created by the U.S. Geological Survey (USGS) was used to define elevation and aspect for the fires within the LFDB. The data in this DEM have been sampled to a horizontal spacing of 300×300 m, and a vertical resolution of ~50 m. They were obtained from the AGDC at http://agdc.usgs.gov/data/usgs/erosafo/300 m/300 m.html.
(3) Statewide climate data summaries were obtained from the Western Regional Climate Center at http://www.ftw.nrcs.usda.gov/prism/prismdata.html. These data sets were created using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) of Daly *et al.* (1994, 1997). Information used in this study included maps of annual and monthly precipitation (for an example Alaskan precipitation map, see http://www.ocs.orst.edu/pub/maps/Precipitation/Total/States/AK/ak_ppt.gif) and average annual and monthly temperatures and average minimum and maximum temperatures (for an example Alaskan temperature map, see http://www.ocs.orst.edu/pub/maps/Other/States/AK/ak_tmax.GIF).
(4) A map of average annual lightning strikes for the years 1986–1999 compiled by the Alaska Fire Service. These data were aggregated at a 10×10 km grid spacing by Dissing and Verbyla (in review) and are available at http://www.lter.uaf.edu/Data_catalog_detail.cfm? dataset_id = 57.

We selected fire cycle to characterize the fire regime of Alaska, which has been used by previous researchers (Gabriel and Tande 1983; Yarie 1981). Fire cycle is defined by Johnson (1992) as the time required to burn an area equal in size to the study area. We used the individual ecoregions defined for Alaska by Gallant *et al.* (1995) as a basis for aggregating the spatial information and estimating the fire cycle. For each ecoregion, we calculated a fire cycle using the area burned information within the LFDB, including the areas within the perimeter of the digitized fire boundaries and the areas within the missing fire records. In the latter case, we assumed that the entire fire burned within the ecoregion where it started.

Fire cycle was then statistically correlated with the following data for each region: (*a*) growing season temperature defined as the average temperature between May and August; (*b*) average annual precipitation; (*c*) growing season precipitation between May and August; (*d*) average annual lightning strikes; (*e*) total tree cover; and (*f*) total conifer cover.

In addition, for each ecoregion we calculated a fire cycle for six different elevation categories using only the areas representing mapped fire perimeters within the LFDB (the areas of missing fire records were not used). The elevation categories included: (*a*) all elevations; (*b*) elevations below 800 m above sea level. (*c*) elevations between 0 and 199 m; (*d*) elevations between 200 and 399 m; (*e*) elevations between 400 and 599 m; (*f*) elevations between 600 and 799 m; and (*g*) elevations between 800 and 1000 m. Because of the horizontal resolution of the digital elevation data (50 m), we felt that having increments at 100 m would be inappropriate; therefore, a 200 m increment was selected.

Our initial expectations were that areas above the treeline (600–700 m as defined by Viereck 1979) would have longer fire cycles. At higher elevations, insufficient forest fuels exist to sustain large fires. In addition, we expected longer fire cycles at lower elevations (0–200 m) relative to mid-level elevations (200–600 m). Many low elevation regions of Alaska are a mixture of poorly-drained sites (e.g. muskeg and peatlands) interspersed with drier sites that contain sufficient fuels to support fires; however, this mosaic of fuel types makes it less likely that fires will spread over large areas.

Finally, we calculated the aspect of each topographic unit where a fire occurred within the LFDB and had a slope greater than 5º, and divided these into eight categories (each 45° wide): North, South, East, West, North-east, North-west, South-east, South-west. This analysis was performed for fires throughout the state, and again did not include missing fire record areas. The basis for this analysis is the observation that distribution of forest ecosystems in Alaska is associated with aspect, with white spruce ecosystems dominating on south-facing slopes and black spruce ecosystems on north-facing slopes (Viereck *et al.* 1986). The early successional stages of white spruce ecosystems are dominated by aspen and birch for the first 60–100 years after disturbance, while black spruce ecosystems reach maturity within 50–70 years after a fire. Given that black spruce foliage has a higher flammability than either birch or aspen foliage (Forestry Canada Fire Danger Group 1992), we expected more frequent fires in this forest ecosystem type; hence, the percentage of total area burned on north-facing slopes should be higher than on south facing slopes.

Limitations of fire databases in analysis of the Alaskan fire regime

The fire data sets used in this study have a several limitations that should be noted. Not all fires were detected and mapped during the 1950s and early 1960s, which means that the area burned estimates for these time periods are probably low. Beginning in the 1960s, it is unlikely that large fire events went undetected; therefore, missed fires are likely to have little influence on the patterns of high and low fire years between the 1960s and the present.

The overall accuracy of fire maps generated during the 1950s and 1960s (in terms of depicting the boundary of a fire event) is lower than during latter years. Whether these inaccuracies lead to over- or under-estimation of fire area, however, is difficult to determine. A reasonable assumption is that in some cases burned areas were over-estimated, while in others they were under-estimated.

The method of using the fire boundary to estimate burned area leads to an over-estimation of fire area because these perimeters do not depict unburned islands that are present in many large fire events. On the other hand, the LFDB neglects fires smaller than 400 ha during most years, and these omissions lead to lower estimates of annual area burned.

While the LFDB does not contain all fires, we believe that the information present within it represents a reasonable *sample* of fire activity within the state of Alaska, if the assumption is made that the missing fire records, fires that were not mapped, and fires<400 ha in size are uniformly distributed throughout regions where fire is most common. While this database cannot be used to determine fire cycle in an absolute sense, if the assumption of uniform distribution is true, it can support analysis of fire cycle in a relative sense.

Results

Comparison of annual area burned estimates

Comparison of the seasonal area burned within the Alaska Fire Service statistics and the LFDB shows reasonably good agreement for 80% of the years (Table 1). The sources for the differences between the databases originates from three sources: (*a*) the LFDB does not include fires under 400 in size for many years; (*b*) lost fire records in some years will lead to lower fire area estimates within the LFDB; and (*c*) higher or lower burned areas in the LFDB as a result of scaling errors in the hand-drawn fire maps. With few exceptions, it is difficult to assign errors (*b*) and (*c*) above to any given year. Lost fire records most likely resulted in significant under-estimation within the LFDB in 1953 (by 143 000 ha), 1957 (by 553 000 ha), 1967 (by 272 000 ha), 1969 (by 862 000 ha), 1971 (by 103 000 ha), and 1974 (by 162 000 ha). As noted previously, scaling errors most likely account for the higher estimates in the LFDB in four years:1950 (by 388 000 ha), 1956 (by 165 000 ha), 1961 (by 551 000 ha), and 1979 (by 89 000 ha).

Annual and seasonal fire patterns

Fig. 4 presents two plots of the long-term average of annual area burned for the 1960s through the 1990s in 10, 20, and 40 year time increments. A large fraction (73%) of the area burned during the 40 year time period occurred during the 10 high fire seasons. Since one of the high fire years occurred in 1990, calculation of the decadal average for the 1980s and 1990s depends on the definition of the start of the decade (i.e. in year 0 or 1). The two plots in Fig. 4 present the average area burned using each of these starting points.

Three conclusions can be drawn from the data presented in Fig. 4. First, over the 40 year data record, there has been little change in annual area burned. Second, there are no long-term trends in average area burned in high and low fire seasons. And third, at a decadal scale, the primary factor determining average area burned is the number of high fire years.

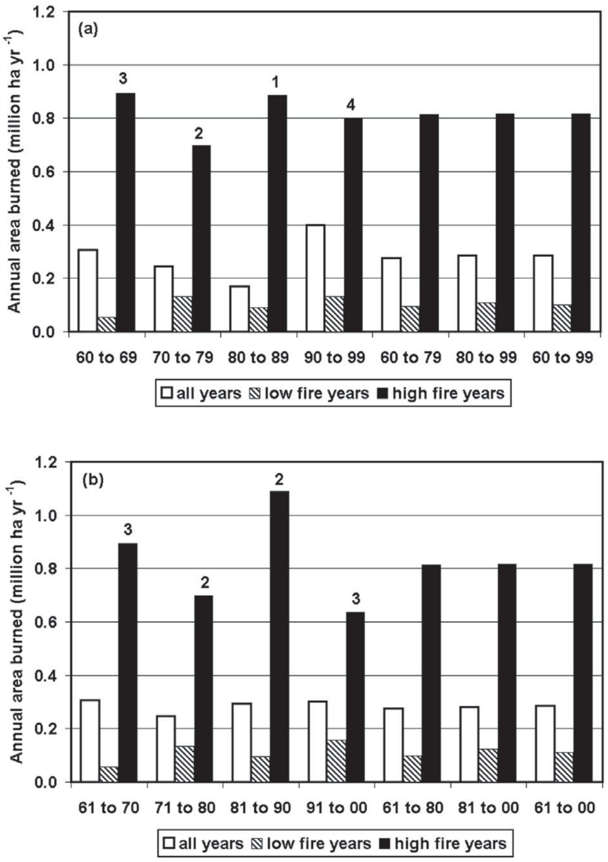

Fig. 4. Average area burned for Alaska over 10, 20, and 40 year time periods between 1960 and 2000 for two different levels of fire activity (high and low fire years). The numbers above the bars refer to the number of high fire years in each decade. Two plots are presented: (*a*) assuming that the decade begins in the year 0; (*b*) assuming that the decade begins in the year 1.

Fig. 5 presents the distribution of percentage area burned as a function of fire size for high and low fire years for the period 1950–1999. During high fire years, there was an average of 66 fires>400 ha with an average size of 20 300 ha. In contrast, during smaller fire years, there was an average of 17 fires per year >400 ha with an average size of 7800 ha. Furthermore, during smaller fire years, 73% of the total area burned occurred in fires <50 000 ha in size. In high fire years, 65% of the total area burned in fires ≥50 000 ha in size. In smaller fire years, 9% of the total area burned in fires ≥100 000 ha in size, with no fires exceeding 200 000 ha. During high fire years, 33% of the total area burned in fires ≥100 000 ha in size, and fires >200 000 ha in size were more frequent.

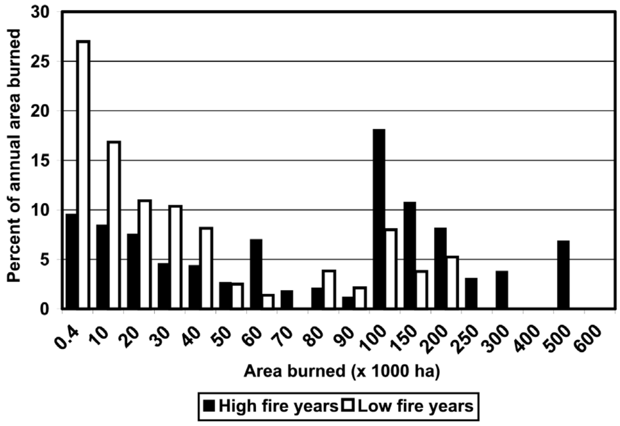

Fig. 5. Comparison of percentage of total seasonal area burned as a function of fire size category (defined arbitrarily) for high and low fire years.

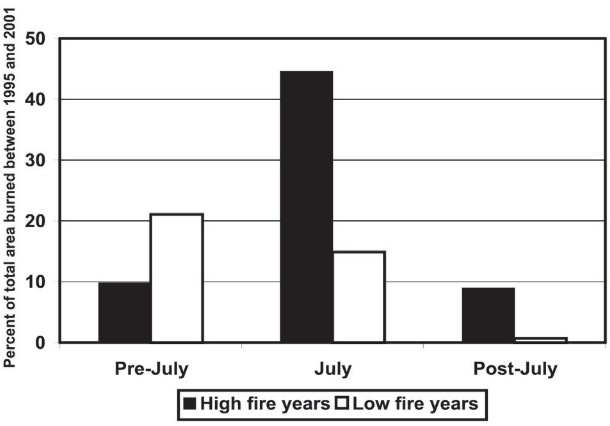

Fig. 6. Percentage of total area burned between 1994 and 2001 as a function of time during the growing season for two levels of fire activity (high and low fire years).

Between 1995 and 2001, there were two high fire years (1997 and 1999) and five low fire years. The seasonal fire data reported by NICC demonstrate that most fires (76%) in Alaska occur during the 6-week period between the beginning of June and mid-July but, during some years, the fire season extends into August and September. Fig. 6 plots percentage of seasonal area burned as a function of time during the fire season for low and high fire years. From 1995 to 2001, 31% of the fires occurred prior to July, 59% occurred in July, and 10% occurred after July. Almost all of the area burned after July occurs during the high fire years. During low fire years, most of the area burned occurs in June and July, while during high fire years, most of the activity occurs during July.

In summary, the analyses show that fire characteristics have a significant year-to-year fluctuation. During high fire years, there are not only a considerable number of large fires, but these fires occur in bigger events that burn later in the growing season. These patterns are directly related to climate. Most of the area burned in Alaska is due to fires started by lightning strikes. In turn, 90% of the lightning strikes occur during the months of June and July (Reap 1991). Hess *et al.* (2001) showed that, during El Niño events, there were warmer and drier conditions in Alaska which, in turn, were correlated with high fire years. The warmer, drier conditions during high fire years influence fire behavior in several ways. They foster more fire ignitions, and permit fires to burn longer into the growing season, resulting in the larger fires during the high fire seasons.

Spatial aspects of Alaskan fires

Combining the fire location information within the LFDB with the topographic information showed that 99.8% of the fires in Alaska occur at elevations<1000 m above sea level, 98.7% of the fires occur at altitudes <800 m, and 94.0% occur at elevations lower than 600 m. This observation supports the hypothesis that the lower fuel levels found in tundra and bare surface conditions above the treeline (at 600–700 m elevation) inhibit propagation of fires over large areas.

Table 2 presents the distribution of fire activity as a function of aspect. North facing slopes (i.e. north-west, north, and north-east slopes in Table 2) had 44.0% of the fire activity, while south facing slopes (i.e. the south-west, south and south-east slopes) had 33.5% of the fire activity. This observation supports the hypothesis that fire cycle should be dependent on aspect because of its control on fuel types.

Analysis of the spatial distribution of fires showed that 96% of the fires occurred within the 11 ecoregions that cover Alaska's interior region (Fig. 7). Because of this pattern, we focused our additional analyses to data from these 11 ecoregions.

Table 3 summarizes the variations in fire cycle as a function of elevation categories for the non-coastal ecoregions of the Alaskan interior. The two coastal ecoregions (Nulato Hills and Seward Peninsula) were not included in this table because elevations in these regions fall within a single elevation category (0–199 m). The data in Table 3 demonstrate that fire cycle varies as a function of

Table 2. Percentage area burned as a function of aspect based on analysis of the Alaskan large-fire database

Aspect	% of area burned
North	18.7
North-east	10.4
East	10.4
South-east	14.8
South	8.0
South-west	10.7
West	12.2
North-west	14.9

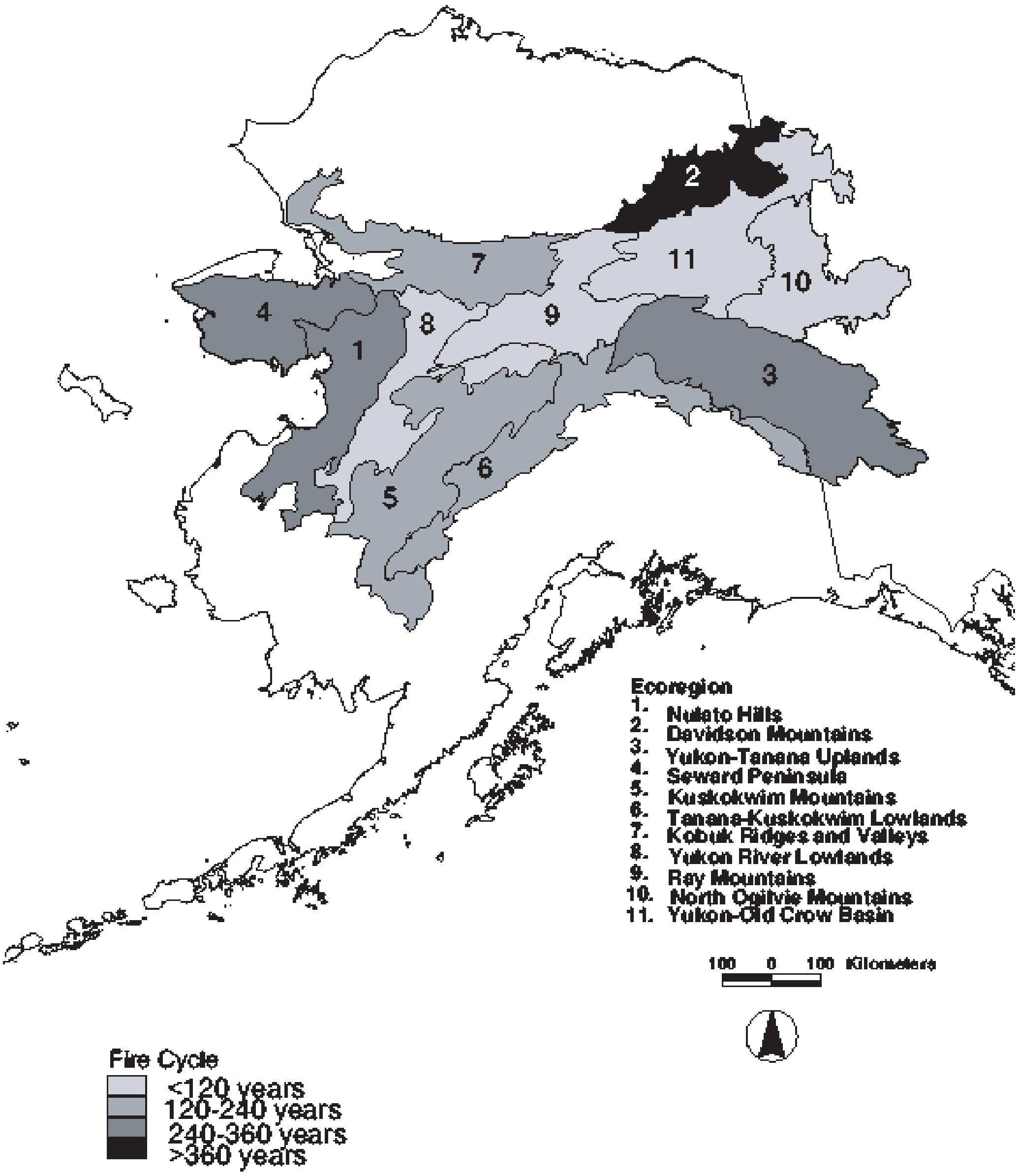

Fig. 7. Patterns of fire cycles in the 11 Alaskan ecoregions where 96% of all fire activity occurs.

elevation. The fire cycle was shortest between elevations of 200 and 400 m, and increases with elevation, most likely because forest production is proportional to temperature (Van Cleve and Yarie 1986; Bonan and Van Cleve 1992), which decreases as elevation increases. Finally, as expected, the fire cycles at the lowest elevations (0–199 m) are longer than those at mid-elevations.

In terms of fire cycle, the 11 ecoregions where most of the fire activity occurred fell into four general groups (Fig. 7). The shortest fire cycles (<120 years) are located in the interior most ecoregions (the Ray Mountains, North Ogilvie Mountains, and Yukon/Old Crow Basin) that are distant from major mountain ranges. West, north and south of this group, are ecoregions with moderate-length fire cycles (120–240 years). The two ecoregions on the west coast (Nulato Hills and Seward Peninsula), along with the large ecoregion with uplands in the interior of the state (Yukon–Tanana Uplands) had long fire cycles (240–360 years). Finally, the Davidson Mountain ecoregion had the longest fire cycle (>360 years).

Table 4 summarizes average climate and vegetation cover data for the 11 ecoregions where fire was most common. Because we determined that most fire activity occurs at lower elevations (Table 3), we estimated a *modified* fire cycle for these ecoregions by considering only the land area under

Table 3. Fire cycle as a function of elevation class in the non-coastal ecoregions of central Alaska

	Fire cycle (years)				
	<800 m	0–199 m	200–399 m	400–599 m	600–799 m
Davidson Mountains	484	n/a	224	314	949
North Ogilvie Mountains	150	318	118	131	210
Yukon-Old Crow Basin	107	149	87	93	76
Ray Mountains	179	205	132	175	322
Kobuk Ridges and Valleys	229	207	206	763	2172
Tanana–Kuskokwim Lowlands	244	285	170	311	294
Yukon–Tanana Uplands	588	1322	443	329	454
Kuskokwim Mountains	281	195	331	571	1536
Yukon River Lowlands	174	171	230	n/a	n/a
All non-coastal ecoregions	200	193	166	237	427

Table 4. Average climate and forest cover and calculated fire cycles for the 11 ecoregions where the majority of Alaskan fires occur

	Average elevation (m asl)	Average growing season temperature (ºC)	Average annual precipitation (cm)	Average growing season precipitation (cm)	Average lightning strikes (per 10×10 km per year)	Tree cover (%)	Total conifer cover (%)	Modified fire cycle (years)	Fire cycle (years)
Davidson Mountains	630	9.7	20.3	14.8	1.6	92	70	403	464
North Ogilvie Mountains	532	12.2	25.8	17.6	3.7	92	40	112	138
Yukon-Old Crow Basin	240	8.8	19.1	18.8	4.9	90	27	81	97
Ray Mountains	440	14.7	34.0	17.4	4.7	73	45	109	136
Kobuk Ridges and Valleys	194	13.0	32.4	16.6	3.0	47	43	175	215
Tanana-Kuskokwim Lowlands	300	14.9	31.0	18.5	3.7	83	64	178	214
Yukon-Tanana Uplands	759	16.3	33.0	17.1	5.4	71	54	330	540
Kuskokwim Mountains	262	15.8	36.5	17.1	3.4	70	43	218	253
Nulato Hills	238	16.5	41.9	11.3	1.2	19	17	306	356
Seward Peninsula	160	11.1	29.6	17.6	0.3	1	1	273	340
Yukon River Lowlands	79	12.2	29.6	13.8	0.3	78	55	120	146

800 m in elevation and adjusting for the fraction of each ecoregion covered by lakes and rivers. For comparison purposes, Table 4 also presents the fire cycle using the entire area of the ecoregion. These data show that shorter fire cycles are calculated considering only those areas likely to burn.

Fig. 8 presents fire cycle plotted against the various climate and vegetation patterns presented in Table 4. Plots are not presented for fire cycle as a function of total precipitation (because it is almost identical to the plot of fire cycle versus seasonal precipitation), and fire cycle as a function of total conifer cover (because of the low correlation coefficient [<0.10] for this relationship). The patterns of fire cycle as a function of the various factors in Fig. 8 are consistent with expected trends. The fire cycle gets shorter as tree cover, lightning frequency, and growing season temperature increase, while it gets longer as elevation and growing season precipitation increase.

In the plots of fire cycle as a function of tree cover and growing season precipitation, we noted that the fire cycle for the Davidson Mountain ecoregion fell well outside of the trends represented by the other points (see the empty diamond in Figs 8*b* and 8*e*). While this ecoregion has the low precipitation and high tree cover that would be expected to support a shorter fire cycle, it in fact had the longest fire cycle of any ecoregion. We attribute the lack of fire activity in this ecoregion to the relatively low amount of lightning activity, which results in a lower number of fire ignitions. Calculation of the linear regression equations presented in Figs 9*b* and 9*e* excluded the data from the Davidson Mountain ecoregion.

The longer fire cycle for the Davidson Mountain ecoregion underscores an important point regarding the complexity of interactions that determine the fire cycle for a specific region. An additional example is the Yukon–Tanana Uplands ecoregion, which has the highest frequency of lightning strikes and a fairly warm growing season temperature to support a high level of fire activity. Yet these factors are outweighed by factors that suppress fire activity: higher precipitation, higher elevations, and lower vegetation density. In contrast, the Yukon River Lowlands ecoregion has a very low number of lightning strikes, yet a short fire cycle. Factors favoring fire in this region include low precipitation and a moderate amount of tree cover.

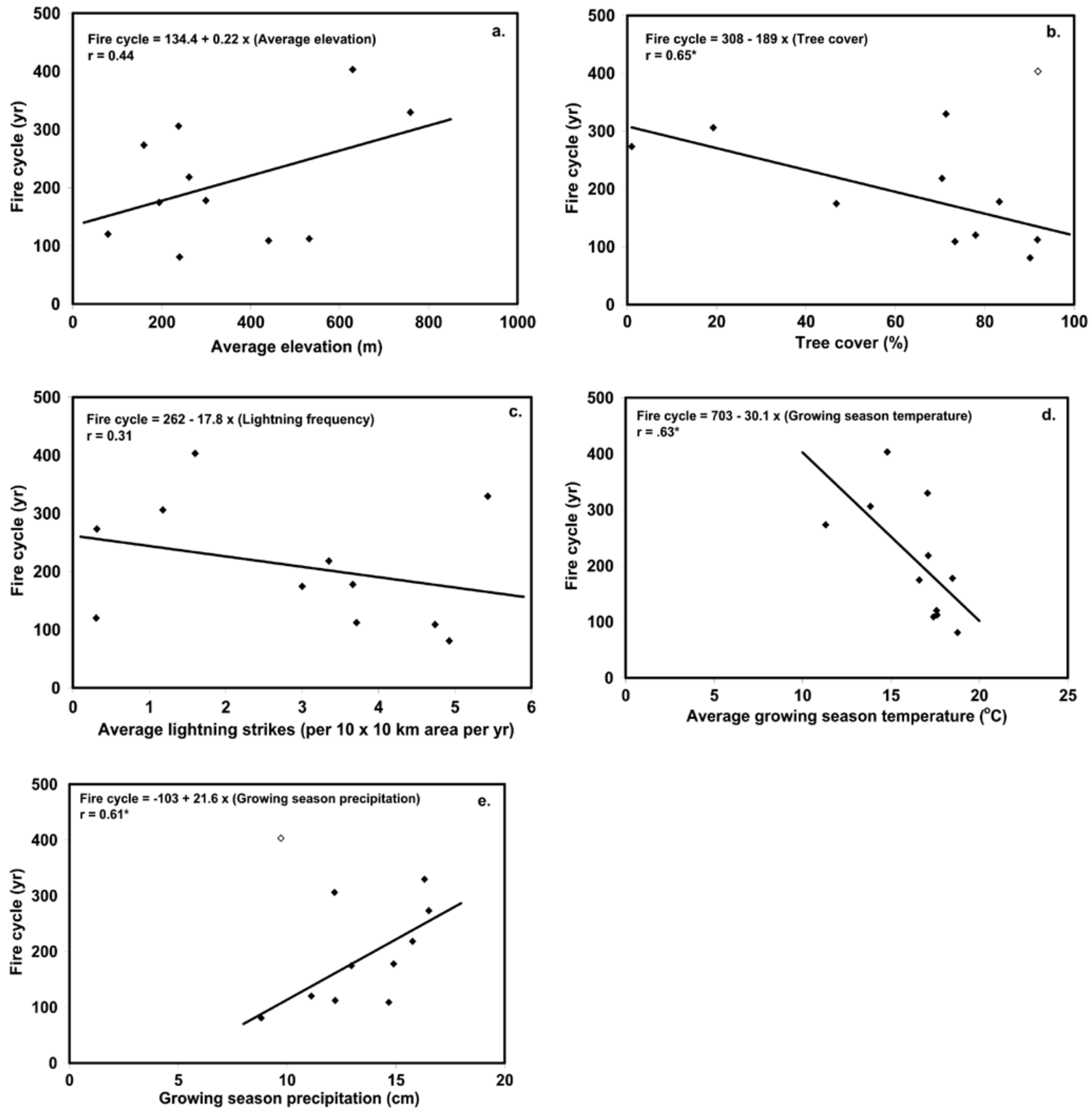

Fig. 8. Fire cycle plotted as a function of: (*a*) average elevation; (*b*) percentage tree cover; (*c*) average lightning strikes; (*d*) average growing season precipitation; and (*e*) average growing season temperature. Correlation coefficients (r) marked with an asterisk (*) are significant at $P<0.06$.

We assessed how combinations of factors account for the variation in fire cycle using two- and three-factor multiple linear regressions (Table 5). Using two factors, average elevation and the average number of lightning strikes account for 77% of the variation in fire cycle. Using three factors, average elevation, average number of lightning strikes, and percentage tree cover account for 84% of the variation.

Discussion

The results of this study should not come as a surprise to those managers and scientists familiar with the fire regime in the North American boreal forest region. The purpose for creating the Alaskan LFDB was not only to provide an information resource for those interested in studying patterns of fire in this region, but also to allow for a more

Table 5. Summary of multiple linear correlation coefficients of fire cycle as a function of different climate, topography, and vegetation factors

Factors	Correlation coefficient (r)	Significance (P)
Elevation, Growing Season Temperature	0.66	<0.10
Elevation, Percentage Tree Cover	0.71	<0.06
Elevation, Lightning Strikes	0.77	<0.03
Elevation, Lightning Strikes, Percentage Conifer Cover	0.78	<0.08
Elevation, Lightning Strikes, Growing Season Temperature	0.78	<0.08
Elevation, Growing Season Temperature, Percentage Tree Cover	0.79	<0.06
Elevation, Lightning Strikes, Growing Season Precipitation	0.80	<0.06
Elevation, Total Tree Cover, Total Conifer Cover	0.80	<0.05
Elevation, Lightning Strikes, Percentage Tree Cover	0.84	<0.03

quantitative analysis and assessment of previously developed concepts concerning fire.

Previous studies of fire in Alaska focused on seasonal data collected through the 1970s (Barney 1971; Barney and Stocks 1983; Gabriel and Tande 1983); the addition of two decades of information in this study allowed for a more definitive analysis of seasonal fire patterns. In addition, the compilation of seasonal statistics on area burned made it possible to examine the distribution of fire activity during the growing season. While Gabriel and Tande (1983) were able to examine the spatial distribution of fire based on the ignition location, the development of the Alaskan LFDB along with the availability of databases describing important factors known to influence fire (such as climate, lightning strikes, topography, and forest cover) made it possible to examine the spatial aspects of fire occurrence in much greater detail.

The pattern of episodic fire years observed in Alaska (Fig. 1) is consistent with those observed for the North American boreal forest region, where high fire years account for nearly 60% of the total area burned (Murphy *et al.* 2000). During high fire years in Canada, large fires occur on a regional basis (Stocks *et al.* in press) dependent on continental-scale atmospheric circulation patterns, which in turn, control precipitation patterns (Skinner *et al.* 1999).

The observation that fire activity is concentrated in the interior of the state, in a region bounded on the north by the Brooks Range and, on the south, by the Alaska Range (Figs 1 and 7) is consistent with the results from Gabriel and Tande (1983). Large fires do take place in other parts of Alaska (in particular, the Kenai Peninsula as documented by DeVolder 1999), but their occurrence in these regions is less common as in the interior region of the state.

The observed seasonal patterns of fires in Alaska are consistent with seasonal precipitation patterns (Hess *et al.* 2001) and lightning strikes (Reap 1991). The variations in seasonal fire activity pattern between high and low fire years may be quite important from the perspective of levels surface fuel consumption and long-term ecological impacts. One of the factors that control burning of organic mat material in black spruce forests of Alaska is the overall moisture of the organic soil layer which, in turn, is controlled by a combination of seasonal precipitation patterns and the seasonal thawing of permafrost. Because the depth of the active layer becomes greater later in the growing season, the potential for burning of the deeper layers of organic soil in black spruce forests increases during high fire years (Kasischke *et al.* 2000*a*). The amount of organic soil left after a fire, in turn, strongly controls site factors such as soil temperature and moisture, which in turn, control patterns of post-fire succession (Viereck 1983; Kasischke *et al.* 2000*b*).

The results from this study support previous observations that the occurrence of fires in the boreal forests is strongly controlled by climatic factors. At larger scales, it is known that the occurrence of fires in this region is closely related to larger-scale atmospheric circulation patterns (Skinner *et al.* 1999; Hess *et al.* 2001) as well as longer-term climatic patterns (Flannigan and Harrington 1988; Wotton and Flannigan 1993; Flannigan *et al.* 2000; Stocks *et al.* 2000). In this study, the west-to-east gradient in fire activity observed in Alaska (Fig. 7) is partially due to temperature and precipitation gradients. Overall, lightning strike frequency, precipitation and temperature are correlated with fire cycle (Fig. 8).

This study represents the first attempt to spatially correlate fire activity with features known to control ignitions, fuel availability, and larger-scale climate patterns. The results provide the framework for understanding how future changes in landscape features may influence the occurrence of fire. In particular, the impacts of global climate change on the boreal fire regime have largely focused on very broad-scale studies of the effects of climate on fire weather indices (Stocks *et al.* 1998, 2000). Resource managers need more specific information on how variations in climate and vegetation at local to regional scales will affect the fire regime (Grissom *et al.* 2000). In order to provide such information, studies that relate fire activity to specific landscape scale features are needed. However, even though the results of this study point towards possible cause and effect relationships between fire, vegetation, and climate, these simple statistical correlations cannot be used as predictors of actual fire activity. Developing such a predictive capacity will require further refinement and validation of models that quantitatively relate fire ignition, fuel moisture, forest cover and fire behavior (Martell *et al.* 1989; Anderson *et al.* 2000).

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