SASKATCHEWAN FIRE REGIME ANALYSIS

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ABSTRACT

Saskatchewan has 400 000 km² of boreal forest, where fire is a major natural disturbance with important social, economic, and ecological effects. Sustainable forest management and enhancements to existing fire management policies and practices require a thorough understanding of the current fire regimes in the province. This study analyzed the number of fires, the area burned, the fire cycle, the fire season, causes of fires, potential fire intensity, and the fire climate for two types of ecological units: ecozones and ecoregions (subunits of ecozones). Analyses were performed for all forested ecozones: the Boreal Plain (south), the Boreal Shield (central), and the Taiga Shield (north). Only the ecoregions of the Boreal Plain ecozone were considered. The analysis was based on 20 years (1981–2000) of fire occurrence (ignition) data, a database of large fires (≥200 ha) for the period 1945 to 2000, and 12 years (1990–2001) of daily fire weather observations. The results revealed contrasts in the fire regime of ecozones and ecoregions. For example, fire cycle values were 263, 99, and 114 years for the Boreal Plain, Boreal Shield, and Taiga Shield ecozones, respectively. Divergent seasonal trends in fire occurrence and cause were apparent especially in the Boreal Plain, where most reported fires (65%) were human-caused spring fires. However, such fires were usually responsible for a small proportion (16%) of the area burned in this ecozone. The results of this study illustrate important variations in the fire regime in both time and space and can assist fire and forest managers alike in strategic planning of future activities.

RÉSUMÉ

En Saskatchewan, la forêt boréale couvre 400 000 km² et les feux de forêt y constituent une perturbation naturelle importante puisque ceux-ci peuvent être accompagnés d'impacts sociaux, économiques et écologiques marqués. La gestion durable des forêts et l'amélioration des politiques et des pratiques existantes en matière de gestion des feux nécessitent que les régimes de feu présentement à l'œuvre dans la province soient bien connus et compris. Cette étude consistait à analyser le nombre et la superficie des feux, leurs cycles, leurs saisons, leurs causes, leur intensité potentielle et les climats qui leur sont propices pour deux types d'unités écologiques : les écozones et les écorégions (sous-unité d'une écozone). Des analyses ont été effectuées pour toutes les écozones boisées : les Plaines boréales (sud), le Bouclier boréal (centre) et le Bouclier de la taïga (nord). Nous n'avons étudié que les écorégions de l'écozone des Plaines boréales. L'analyse était basée sur 20 années (1981–2000) de données décrivant les allumages et leurs causes, une base de données pour les grands feux (≥ 200 ha) couvrant la période de 1945 à 2000 et 12 années (1990–2001) d'observations des conditions météorologiques favorables aux feux. L'étude a permis de mettre en évidence des contrastes entre les régimes de feu des différentes écozones et écorégions. Par exemple, le calcul du cycle de feu était de 263 ans, 99 ans et 114 ans, respectivement, pour les Plaines boréales, le Bouclier boréal et le Bouclier de la taïga. Des tendances saisonnières divergentes pour la fréquence et les causes des feux sont apparues, en particulier pour les Plaines boréales, dans lesquelles la plupart des feux répertoriés (65 %) étaient causés par l'homme au printemps. Cependant, ces feux n'étaient habituellement responsables que d'une petite partie (16 %) de la superficie brûlée dans cette écozone. Les résultats de cette étude mettent en valeur d'importantes variations spatiales et temporelles dans le régime de feu et peuvent aider les gestionnaires des feux et des forêts dans la planification stratégique des activités futures.

EXECUTIVE SUMMARY

Saskatchewan has 400 000 km^2 of boreal forest, where fire is a major natural disturbance with important social, economic, and ecological effects. Sustainable forest management and enhancements to existing fire management policies and practices require a thorough understanding of the current fire regimes in the province. This study analyzed the number of fires, the area burned, the fire cycle, the fire season, causes of fires, potential fire intensity, and the fire climate for two types of ecological units: ecozones and ecoregions (subunits of ecozones). Analyses were performed for all forested ecozones: the Boreal Plain (south), the Boreal Shield (central), and the Taiga Shield (north). Only the ecoregions of the Boreal Plain ecozone were considered, because this ecozone is where most of the province's forest management activity is conducted. The analysis was based on 20 years (1981–2000) of fire occurrence (ignition) data, a database of large fires (≥ 200 ha) for the period 1945 to 2000, and 12 years (1990–2001) of daily fire weather observations. The results revealed contrasts in the fire regime of ecozones and ecoregions (Table I).

The following sections summarize the major features of the fire regime in each ecological unit.

Table I. Fire statistics for large fires (≥200 ha) by ecological unit[a]

	Ecozone			Ecoregion (within Boreal Plain)			
Variable	Boreal Plain	Boreal Shield	Taiga Shield	Boreal Transition	Boreal Transition modified	Mid-boreal Lowland	Mid-boreal Upland
Cause of fire (%)							
Human	52.5	6.1	3.6	87.9	84.8	52.0	38.7
Lightning	40.8	75.6	78.3	12.1	15.2	40.0	52.2
Unknown	6.7	17.3	18.2	0	0	8.0	9.1
Annual no. of fires/10^6 ha	1.5	3.34	4.88	0.73	5.17	1.70	2.17
Annual area burned ± CL (%)	0.38 ± 0.21	1.01 ± 0.50	0.88 ± 0.48	0.07 ± 0.05	0.34 ± 0.25	0.19 ± 0.18	0.59 ± 0.37
Estimated fire cycle (years)							
Heinselman method	263	99	114	1488	292	517	169
MLE survival analysis method	288	104	112	2723	423	669	169

[a]The proportions by cause were calculated from the Canadian Forest Service Large Fire Database for fires from 1950 to 1998, whereas the other statistics were calculated from Saskatchewan fire polygon data from 1945 to 2000.
Note: CL = 95% upper and lower confidence limits at $p \leq 0.05$, MLE = maximum likelihood estimator.

Boreal Plain Ecozone

The fire regime of the Boreal Plain (BPl) ecozone, the southernmost of the forested ecozones, is spatially highly variable, ranging from regions where very large, intense fires prevail to regions where a very large number of small fires burn a proportionally small area. These variations are due partly to latitudinal gradients in climate and vegetation but also to significant human activity in some parts of the ecozone. In those areas, humans have had an impact on the fire regime through landscape fragmentation, fire suppression, and ignition of fires. In fact, human-caused ignitions account for the majority of fires in this ecozone, but these occur primarily in the spring near infrastructure and hence are readily actioned.

Boreal Transition Ecoregion

The Boreal Transition (BTr) ecoregion, which represents the southern fringe of the BPl ecozone, is the ecological unit that has undergone the most transformation from human activity, notably because of agricultural practices and urban sprawl. It is also the region with the highest proportion of deciduous and grassland fuel types, which are significantly more flammable in spring than in summer. Fires are ubiquitous throughout the BPl ecozone, but the vast majority are small, human-caused fires occurring chiefly in spring. As most of this ecoregion is no longer forested, a component representing the actual forest boundary, the BTr-modified area, was delimited.

Mid-boreal Lowland Ecoregion

The Mid-boreal Lowland (MbL) ecoregion is one of moderate human land use, where large intense fires occur rarely. The forest landscape is composed mostly of coniferous stands, a large proportion of which lie in low-lying, waterlogged areas, which greatly reduces fuel continuity. Fires occur infrequently in this ecoregion, but severe droughts could potentially allow large, intense fires, given the abundance of the coniferous component.

Mid-boreal Upland Ecoregion

The Mid-boreal Upland (MbU) ecoregion accounts for most of the area burned in the BPl ecozone. Although it experiences generally less severe fire weather conditions, a large proportion of flammable fuel types, as well as greater fuel continuity (notably through reduced fragmentation), make this ecoregion significantly more prone to fire than the BTr and MbL ecoregions. Although human-caused fires are prevalent in the spring, notably because of industrial activity, lightning-caused fires dominate in the summer and burn, on average, a disproportionally greater area.

Boreal Shield Ecozone

Most of the Boreal Shield (BSh) ecozone is dominated by conifers, especially in the north. This ecozone experiences the most area burned per unit area and the highest proportion of very large fires (>50 000 ha) in Saskatchewan. Human activity, as well as fire suppression, is limited in this area; active suppression of fires usually is undertaken only near communities. The ecozone thus has a largely natural fire regime. Because most fires are caused by lightning and because the climate gets colder at more northerly latitudes, the fire season is shorter than in the BPl ecozone. However, this factor is largely counteracted by the high proportion of coniferous forest cover. The difference in physiography from the BPl ecozone may have significant effects on fire behavior, but this remains to be assessed.

Taiga Shield Ecozone

The fire regime of the Taiga Shield (TSh) ecozone is similar to that of the BSh ecozone. Because of minimal land-use activity in this ecozone, human-caused fires are minimal. Conifers are highly dominant throughout the landscape, but exposed or nutrient-poor or harsh sites support only sparse vegetation cover, which reduces fuel continuity. Climate conditions strongly reduce fire season length, but longer daylight, and hence longer drying period, and a high proportion of flammable fuels have a counteractive effect, resulting in a very fire-prone environment.

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INTRODUCTION

Large and intense stand-renewing forest fires represent the main disturbance of western Canada's boreal forest. This holds true for the province of Saskatchewan, where, on average, 785 fires have occurred and an area of 465 000 ha has burned annually in the past decade (Saskatchewan Environment 2002). Of this area, a total of 165 000 ha has burned annually in commercial forestlands (out of about 13 Mha), which is five times more than the area harvested each year (Saskatchewan Environment 2002). In 1980 and 1981, two particularly severe fire seasons, fires consumed 10% of Saskatchewan's forested landmass. Many fires are ignited in a single fire season, but aggressive initial attack extinguishes most of them while they are still very small (2–3 ha) (Hirsch et al. 1998). A fraction of these small fires exceed suppression capabilities and escape to become large fires (McAlpine and Hirsch 1999), which may spread over hundreds of thousands of hectares. In fact, only 2% to 3% of all fires account for 97% of the area burned in Canada (Johnson and Wowchuk 1993; Weber and Stocks 1998). These large fires have the greatest impact on ecosystem processes and pose the greatest threat to human values, such as merchantable timber and infrastructure.

In the wake of new ecosystem-based forest management policies (e.g., Saskatchewan Environment 2002), forest managers, prompted by the general public, have committed to ensuring the sustainable (i.e., long-term) use of forests while preserving their ecological integrity (Canadian Standards Association 1996). In the boreal forest, such management objectives should consider fire, as this process plays a crucial role in determining forest structure and composition (Heinselman 1973). General management philosophies based on the emulation of disturbance (Hunter 1993; Galindo-Leal and Bunnell 1995; Johnson et al. 1996; Bergeron et al. 1999; Cissel et al. 1999; Bergeron et al. 2002; Harvey et al. 2002), as well as techniques to explicitly incorporate loss to fire in timber supply models (Reed and Errico 1986; Boychuk and Martell 1996), and strategies to mitigate the area burned by large fires (Helms 1979; Weatherspoon and Skinner 1996; Hirsch et al. 2001) have been proposed. However, except for some small areas, the basic fire regime information necessary to apply these techniques or strategies is often lacking. Here, fire regime is defined by six factors: intensity, occurrence (number of fires), timing (season), size, severity (e.g., duff consumption), and type (surface or crown) (Weber and Flannigan 1997, elaborated from Heinselman 1978).

The biological community of the boreal forest has evolved within a mosaic of fire-originating stands of different ages. Therefore, to achieve the goal of sustainability, modern forestry must identify and explicitly incorporate landscape metrics related to the fire regime. Fire management agencies throughout Canada have collected impressive amounts of fire-related data, but, with a few exceptions (Wein and Moore 1977, 1979 in New Brunswick and Nova Scotia; Stocks et al. 2002 for all of Canada), these data sets have not been used to assess the various aspects of a fire regime on a provincial basis.

The central goal of this study was to compare the fire regimes of different regions of Saskatchewan. As these regions are ecological units delimited on the basis of vegetation, topography, and climate, all of which affect wildfires, it is fair to presume that they will have different fire regimes. The specific objectives consisted of

(1) analyzing fire occurrence (i.e., the number of fires) patterns by cause and season,

(2) evaluating the area burned by cause and season,

(3) calculating the fire cycle,

(4) examining fire climatology on a seasonal basis, and

(5) assessing the fire behavior potential (i.e., fire intensity) by season.

In this report, considerable emphasis is placed on the methods used, to facilitate accurate replication of the analyses, either in different study areas (e.g., another Canadian province) or in the same study area in the future, when more extensive data sets exist. Because of the extent of the study area, the analysis focuses on the fire regime components that are best described at a large scale (i.e., ≥10^6 ha), such as fire occurrence, timing, size, and potential intensity. Fire climatology is given significant attention because the fire regime in the boreal forest is largely driven by weather and climate at a large spatial scale (Bessie and Johnson 1995; Skinner et al. 1999; Hély et al. 2001), and also because climatology can be related to all six components of the fire regime. More site-specific components, such as fire type and fire severity, are therefore excluded from this study.

STUDY AREA

The study area consisted of the entire forested part of Saskatchewan, except for the Cypress Hills (a total of 411 413 km^2), as delimited by the ecozones described by the Ecological Stratification Working Group (ESWG 1995). The study area was subdivided into two types of ecological units: ecozones and their subunits, ecoregions (ESWG 1995) (Table 1, Fig. 1). The ecozones and ecoregions have ecological boundaries, but administrative boundaries also exist in relation to the Saskatchewan Environment (SE) fire protection zones: the full response zone (FRZ) and the modified response zone (MRZ). These zones are areas of different suppression effort: full suppression effort in the FRZ and modified or limited suppression in the MRZ. The commercial forest of Saskatchewan corresponds closely to the FRZ. To limit the present analysis, only ecozones and ecoregions were considered. Furthermore, only the ecoregions of the Boreal Plain ecozone were considered, because the data for these ecoregions are more reliable than for ecoregions in other ecozones. All information pertaining to ecological units was obtained from ESWG (1995).

The study area is generally flat, with gentle increases in elevation in some regions, usually from approximately 200 m to a maximum of 800 m. The area sits upon two major physiographic landforms: the Precambrian Shield, typified by rocky outcrops, and the Plains, where deep

Table 1. Ecological units[a] of the study area

Ecological unit	Area[b] (ha)	Area of lakes ≥2000 ha (ha)
Ecozones		
Boreal Plain (BPl)	17 747 150	772 891
Boreal Shield (BSh)	18 715 612	2 221 294
Taiga Shield (TSh)	4 678 565	229 406
Ecoregions		
Boreal Transition (BTr)	5 403 733	71 870
Boreal Transition modified (BTr-mod)	870 134	14 784
Mid-boreal Lowland (MbL)	2 147 856	91 848
Mid-boreal Upland (MbU)	10 190 054	609 132

[a]Ecological units based on ESWG (1995).
[b]Total area includes lakes.

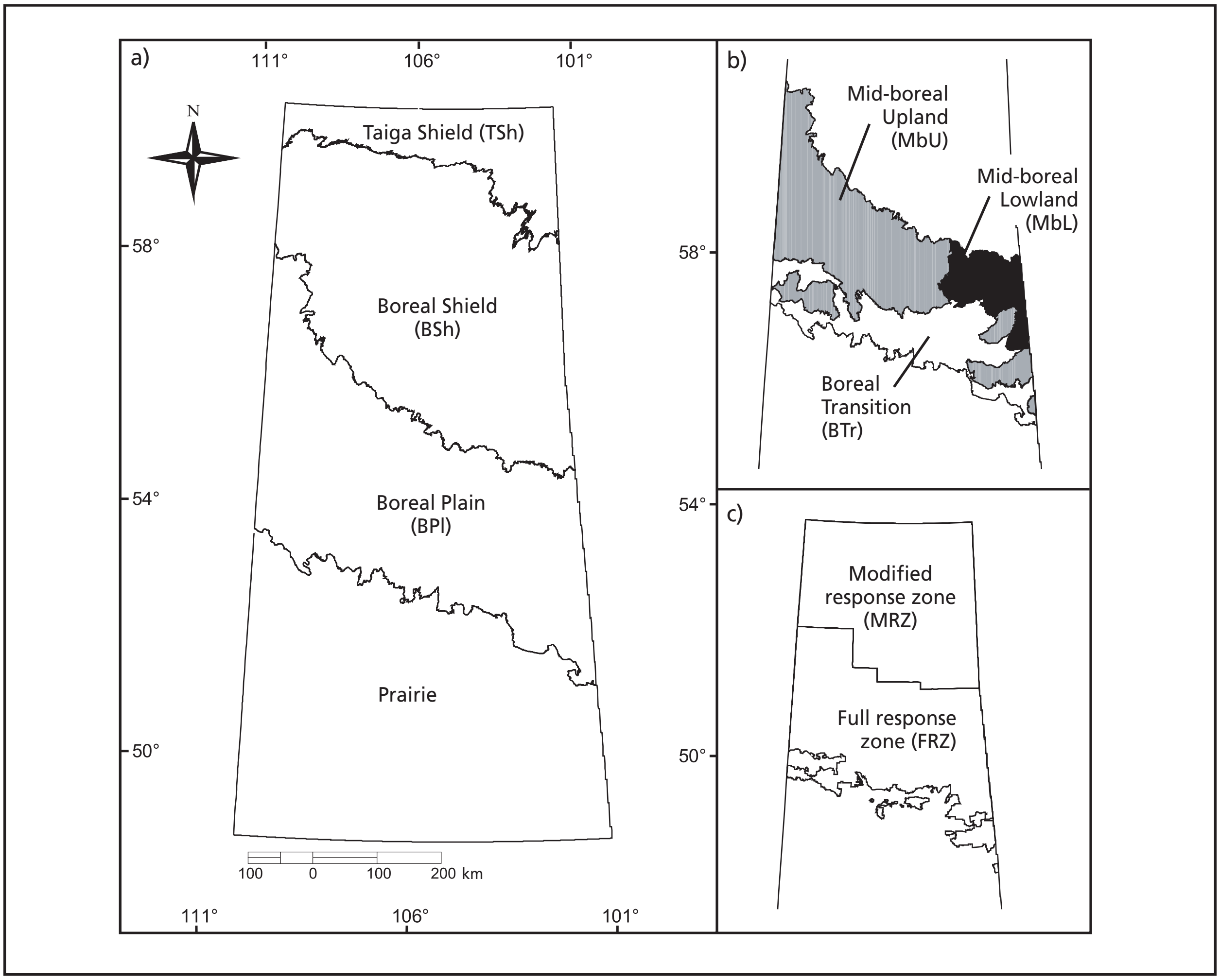


Figure 1. (a) Ecozones, (b) the ecoregions of the Boreal Plain ecozone, and (c) the protection zones of the study area in Saskatchewan.

surface deposits largely conceal the underlying topography. The Boreal Shield (BSh) and Taiga Shield (TSh) ecozones are in the first physiographic landform, and the Boreal Plain (BPl) ecozone is in the second. Many north-south gradients exist within the study area; for example, species diversity (i.e., the total number of species) and forest productivity decrease from south to north. Gradients are also observed in meteorologic variables, and it is generally colder and drier in the northern part of the boreal forest (Environment Canada 1986).

Boreal Plain Ecozone

The BPl ecozone is a flat to gently rolling plain. Glacial moraines as well as lacustrine deposits cover the landform of Cretaceous shales. Luvisols are the dominant soil types, with some Black Chernozems toward the south and Brunisols and Organics in the north. Much of this ecozone (25% to 50%) is covered by wetlands. Cold winters and moderately warm summers characterize the climate of the BPl ecozone, which, as for the rest of Saskatchewan, is strongly influenced by continental climatic conditions. Mean annual temperatures are –2ºC to 2ºC, and mean annual precipitation is approximately 400 mm.

The BPl ecozone has the highest tree species diversity in Saskatchewan. The coniferous component is represented by white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.), jack pine (*Pinus banksiana* Lamb.), and tamarack (*Larix laricina* (Du Roi) K. Koch.).

Conifers are more dominant in the northern parts of this ecozone. The deciduous species, which mostly occur at the transition with the prairie grassland, are mainly represented by trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and, to a lesser extent, white birch (*Betula papyrifera* Marsh.).

Agriculture is the main human land use in the southern part of the ecozone, where much of the land base has been converted to this use. Forestry, mining, oil and gas exploration and production, hunting and trapping, and tourism are also common in the BPl ecozone, and many roads and infrastructure have been built to support these activities.

Three ecoregions are found within the BPl ecozone: the Boreal Transition (BTr), the Mid-boreal Lowland (MbL), and the Mid-boreal Upland (MbU).

Boreal Transition Ecoregion

The BTr ecoregion corresponds to the southern limit of the closed boreal forest. In Saskatchewan, most of this ecoregion (84%) is farmland. The forests are typified by tall trembling aspen, often with a balsam poplar component, and a thick understory of herbs and tall shrubs. White spruce and balsam fir (*Abies balsamea* (L.) Mill.) are sometimes present in older forests, whereas poorly drained sites are occupied by sedges (*Carex* spp.), willow (*Salix* spp.), and, more rarely, black spruce and tamarack.

A subregion, the modified Boreal Transition (BTr-mod), was defined for the purpose of this study. This subregion represents the forested part of the Boreal Transition ecoregion and is therefore much smaller than the BTr ecoregion (Table 1). The main purpose in creating this unit was to exclude land converted to agricultural use from the estimates of forest fire statistics.

Mid-boreal Lowland Ecoregion

Approximately half of the MbL ecoregion is covered with large wetlands. The southeastern portion of this ecoregion is part of the Cumberland Delta, a zone of cold wet soils. Black spruce and tamarack are abundant in the poorly drained fens and bogs. Permafrost also occurs in some peatlands. The well-drained sites are covered with closed mixedwood stands of trembling aspen, white and black spruce, and balsam fir in late-successional forests. The main activities of the region are related to forestry and recreation, but some agriculture is practiced in the more suitable sites.

Mid-boreal Upland Ecoregion

In Saskatchewan, the MbU ecoregion represents five geographically separated areas that are generally at higher elevation than their surroundings (Fig. 1). As for the MbL ecoregion, in well-drained sites the dominant forest type is mixedwood, closed stands of trembling aspen, balsam poplar, white and black spruce, and balsam fir in older forests. While the deciduous stands have an understory of herbs and shrubs, the forest floor of the coniferous stands is usually covered with pleurocarpous mosses. Pulpwood and sawlog forestry constitutes this ecoregion's main forest activities; however, recreational activities, as well as agriculture in the south, are also common.

Boreal Shield Ecozone

The BSh ecozone, the middle forested ecozone of Saskatchewan, lies on the southern part of the Precambrian Shield. It is characterized by a landscape of alternating rolling hills and wetlands with innumerable lakes. The landform consists mostly of Precambrian granitic bedrock often overlaid with deposits of glacial moraine, fluvioglacial deposits, and colluvium. Dominant soil types are Humo-Ferric Podzols in the south and Brunisols toward the north, with some Luvisols in fine-textured soils. The climate is characterized by long, cold winters and short, warm summers, with a mean annual temperature of –4ºC, and a mean annual precipitation of 400 mm.

Most forests of the BSh ecozone are closed coniferous stands dominated by white and black spruce, with some jack pine and tamarack. White and black spruce and jack pine are dominant on upland sites, whereas black spruce and tamarack dominate the lowlands. The deciduous component increases in diversity and abundance in the southern part of the ecozone, with species such as white birch, trembling aspen, and balsam poplar. Sporadic exposed bedrock and the wide variety of surface materials promote many types of understory communities.

Mining, forestry, hydropower, recreation, and tourism are the main economic activities in the BSh ecozone. Unlike the situation in neighboring provinces, forestry activities in this ecozone are not widespread; instead, they are restricted to a few areas in its southernmost part.

Taiga Shield Ecozone

The physiography of the TSh ecozone is very similar to that of the BSh ecozone. The lowlands, however, are usually covered with waterlogged peatlands (Organic Cryosols) that often have widespread permafrost, which greatly limits tree growth. In Saskatchewan, the soil types of the upland sites of this ecozone are generally Brunisols and Humo-Ferric Podzols. Typically, the climate is one of relatively short summers with prolonged daylight periods and long, very cold winters. The mean annual temperature is −8ºC, and the mean annual precipitation is about 300 mm.

The forest vegetation of the TSh ecozone usually consists of open lichen woodlands on upland sites. Black spruce and jack pine are the most common upland species, whereas fens and bogs support mostly shrubby vegetation with some black spruce and tamarack. Open mixedwood stands of white spruce, trembling aspen, balsam poplar, and white birch are sometimes found along rivers and streams. The TSh ecozone of Saskatchewan is very sparsely populated. No forestry activities occur; mining, recreation, and tourism are the main activities.

DATA SOURCES

Saskatchewan Environment Fire Occurrence Database

The Saskatchewan Environment fire occurrence (SE-FO) database consists of the point source locations of all reported fires (about 15 000 fires) in Saskatchewan from 1981 to 2000 and includes a large number of attributes related to the period of burning, fire weather conditions, fire cause, suppression effort, and final fire size.

For the purposes of this study, this database was used primarily to describe the spatial and seasonal patterns of fire occurrence. Unfortunately, for many large fires, the fire size as recorded in this database differs considerably from the corresponding data in large-fire databases (see the following sections) and were therefore deemed unreliable for calculating area burned. The main shortcoming of this database is the different detection levels throughout the province. Detection is much more efficient in the FRZ of the study area (i.e., most of the BPl ecozone) than in the MRZ, where intensive detection is confined to the areas immediately surrounding communities.

Forest Fire Chronology of Saskatchewan

Data for the Forest Fire Chronology of Saskatchewan (FFCS) were initially developed by the Fish and Wildlife Branch of Saskatchewan Environment (SE) to assess management parameters for woodland caribou in Saskatchewan. The database consists of digitized polygons of fires ≥1000 ha that occurred from 1945 to 2000 (Fig. 2), with yearly updates. Fire data from a variety of sources, notably maps at various scales and most recently global positioning system receivers in aircraft, have been digitized for this database. A detailed description of the database is included in the document that accompanies the FFCS (Naelapea, O. 1997. Forest Fire Chronology of Saskatchewan digital data documentation. Sask. Environ. Resour. Manage., Fish Wildl. Br., Prince Albert, SK. Unpubl. Rep.).

As noted by the SE Fish and Wildlife Branch (Naelapea, O. 1997. Forest Fire Chronology of Saskatchewan digital data documentation. Sask. Environ. Resour. Manage., Fish Wildl. Br., Prince Albert, SK. Unpubl. Rep.), this database contains many inaccuracies and should by no means be considered complete. It is, however, the best and most thorough database of fire polygons available for the province and was therefore deemed adequate for analyses pertaining to area burned. The most important shortcoming of the FFCS is missing data, especially for fires in the sparsely populated northern part of the province. This inevitable problem, experienced by all Canadian provincial fire management agencies, is mostly

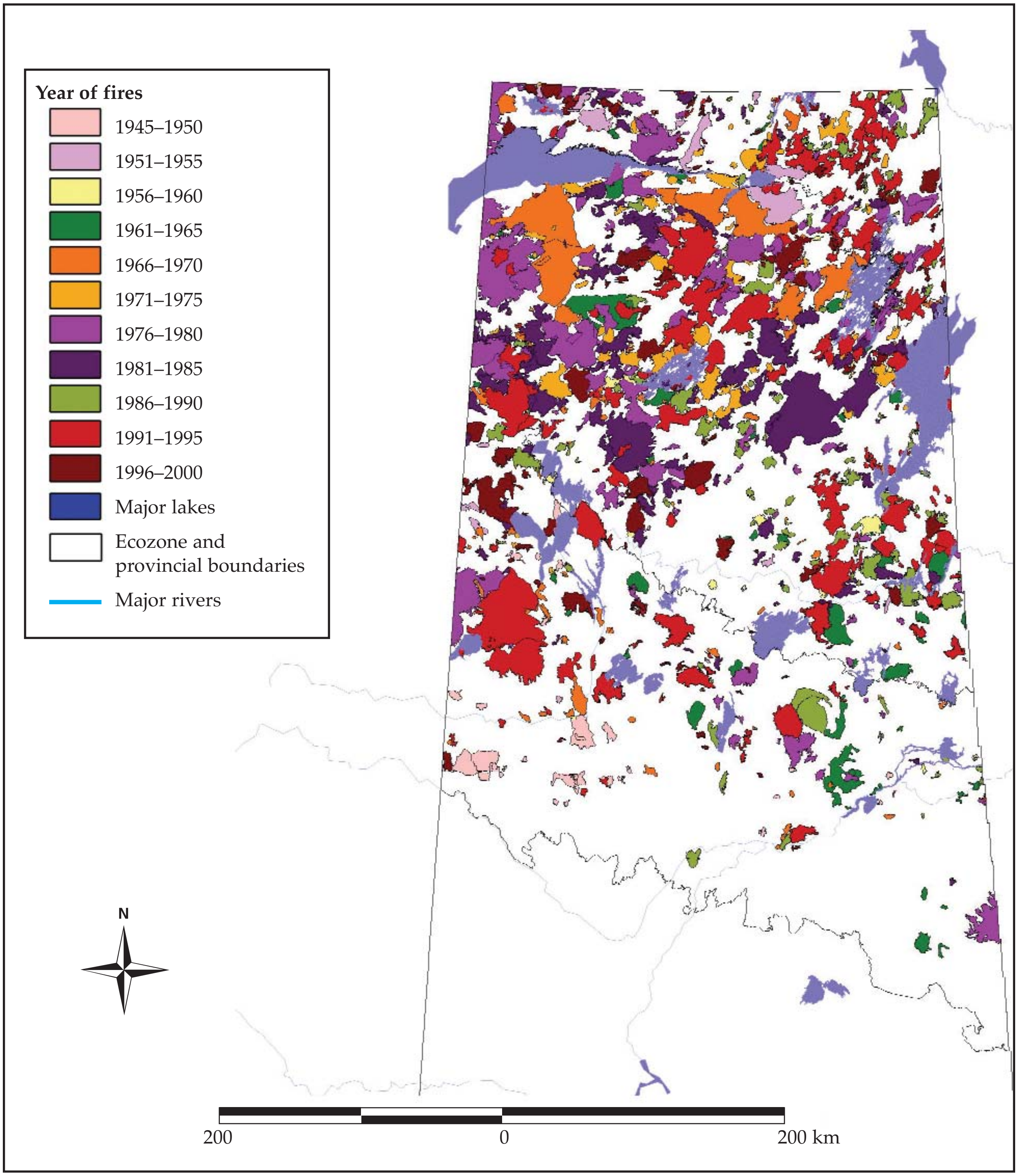


Figure 2. Large fires (≥1000 ha) in Saskatchewan from 1945 to 2000.

due to the fact that in the past (notably the 1940s and 1950s) the agencies did not have the means to detect and record all large fires. Also, fires that burned solely on federal lands (e.g., Prince Albert National Park) are not included in the data set. Furthermore, there has been considerable interannual variability in recording the spatial extent of fires, mainly because of limited resources, particularly for the earlier decades. It must be noted that the delineation of fires in the FFCS does not indicate complete burning, as unburned islands occur in virtually all large fires (Eberhart and Woodard 1987; Bergeron et al. 2002; Andison 2003). Potential errors could also arise if fire boundaries have not captured surface fires in intact forest cover. Area burned is likely underestimated because of the missing fires and unmapped surface fires, but this problem is partly compensated by unburned islands that are not accounted for.

Canadian Forest Service Large Fire Database

The Canadian Forest Service Large Fire Database (LFDB) is a database of the presumed point of ignition of fires ≥200 ha from 1950 to 1998. It was provided to the authors by the Canadian Forest Service (CFS) and is described in Stocks et al. (2002). The bulk of the Saskatchewan component of the LFDB was derived from the FFCS, in addition to other provincial fire reports and various maps on which fires have been recorded. Unlike the FFCS, the LFDB contains attributes such as date and cause of each fire. Although most fires ≥200 ha are included, some smaller fires (200 to 1000 ha) that occurred in the 1970s in Saskatchewan are missing.

All of the limitations of the FFCS data also apply to the LFDB, and are compounded by attribute-related errors. However, as for the FFCS, these data have undergone considerable quality control and are considered reliable for various analyses of fire regimes. The FFCS was used for all analyses of large fires, except when specific attributes were required, in which case the LFDB was used.

Fire Weather Data

The fire weather data used in these analyses consisted of daily 12:00 local standard time (LST) weather observations (temperature, relative humidity, wind speed, wind direction, and 24-h precipitation) and their associated Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) codes and indices for the period 1990 to 2001. The FWI System, a subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS), has six components: three fuel moisture codes and three fire behavior indices (Van Wagner 1987). The moisture codes are the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC), which respectively correspond to the moisture content of surface, intermediate, and deep organic soil layers. The fire behavior indices are the Initial Spread Index (ISI), the Buildup Index (BUI), and the Fire Weather Index (FWI), which are, respectively, relative measures of rate of spread, fuel available for burning, and fire intensity. The Daily Severity Rating (DSR) is an exponential function of the FWI that allots proportionally more weight to the most extreme fire danger days than the FWI (Van Wagner 1987).

For this study, 39 stations within or adjacent to the forest ecozones (Fig. 3) were used. The weather data were taken from two types of weather stations, maintained by Environment Canada (EC) and SE. Most EC stations are located at airports or other federally managed installations, whereas most SE stations are set up within the forest.

At each station, seasonal start-up values are used for the three moisture codes. The start-up values for the FFMC and the DMC are fixed at 85 and 6, respectively, and the start-up value for the DC is adjusted on the basis of winter precipitation. In the western boreal forest of Canada, where winter conditions are comparatively dryer than the eastern boreal forest, calculation of the DC for spring start-up is critical (Alexander 1982). Because FWI System codes and indices were often missing for the first few days of a given fire season, it was important to determine (by trial and error) the start-up DC for those days. When weather observations were missing for days within the fire season, the average weather observations of the two closest stations were used to calculate the FWI System values; this was necessary because the FWI System components are cumulative and require a continuous dataset of days. Three weather stations that were missing more than 2 years of data were omitted from the analyses: Maclennan

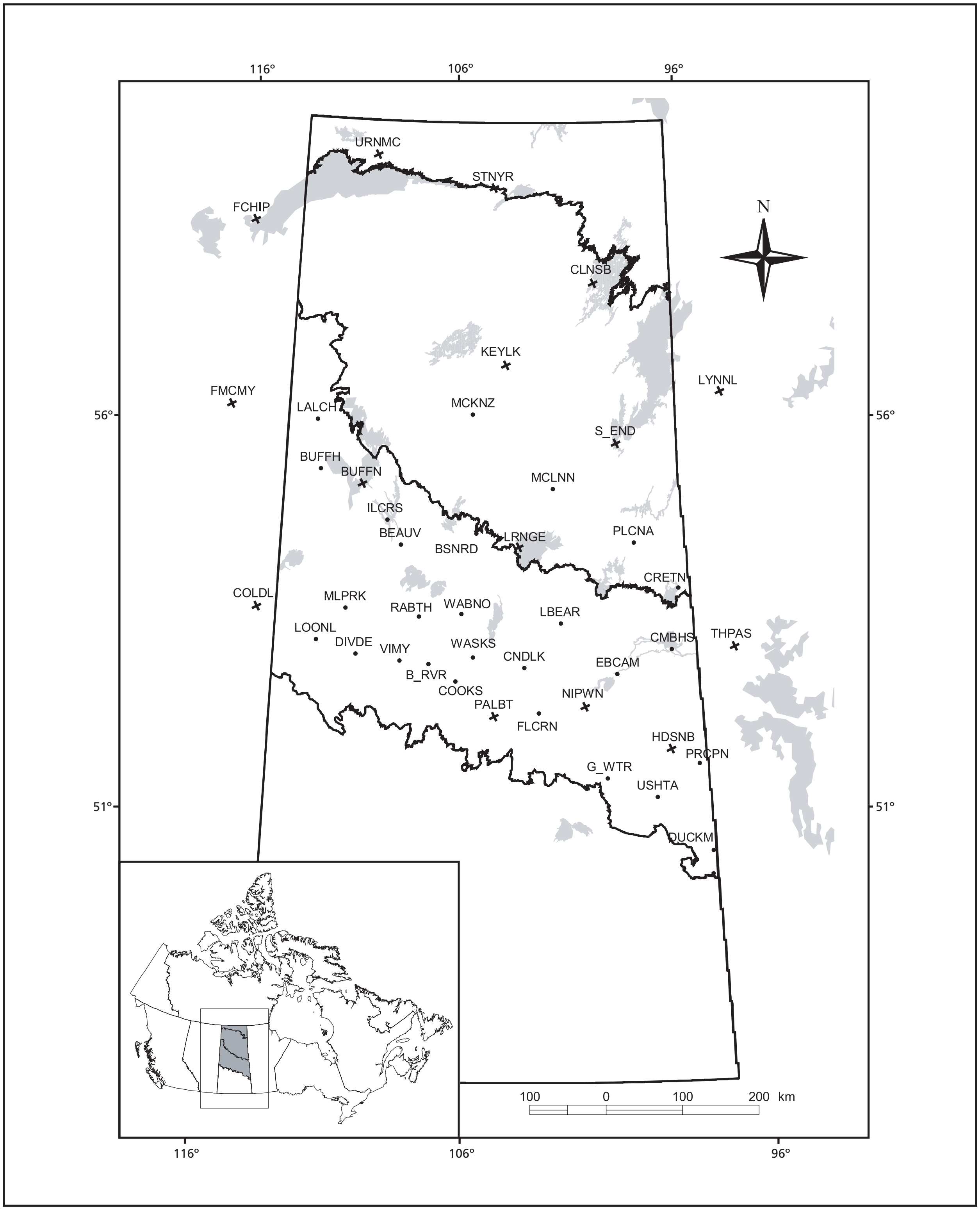


Figure 3. Location of weather stations in and around the study area of Saskatchewan (inset). Saskatchewan Environment stations are represented by points and Environment Canada stations by crosses. Gray areas represent large lakes. The full names and coordinates of the stations are listed in Appendix 1.

Lake, Mackenzie Falls, and Key Lake (Fig. 3). The remaining 39 stations had almost complete weather records.

The low density (number per unit area) of weather stations in some areas also posed a problem, because weather and FWI System codes and indices had to be interpolated for grid cells in between stations. As a rule of thumb, Turner and Lawson (1978) suggested that at distances of less than 40 km from a weather station, the FWI System values are highly reliable indicators of fire behavior, whereas beyond 160 km the FWI System values should be considered unreliable. In the current study area, the BPl ecozone had adequate weather station density, but the northern region of the province had very low coverage (Fig. 4). In fact, the interpolation process can be expected to yield highly reliable data for only about 40% of the study area (i.e., within 40 km of a weather station) (Fig. 4, histogram).

The two weather station types (EC and SE) account for additional discrepancies in the weather data, as they are located in very different settings and usually use different equipment. The

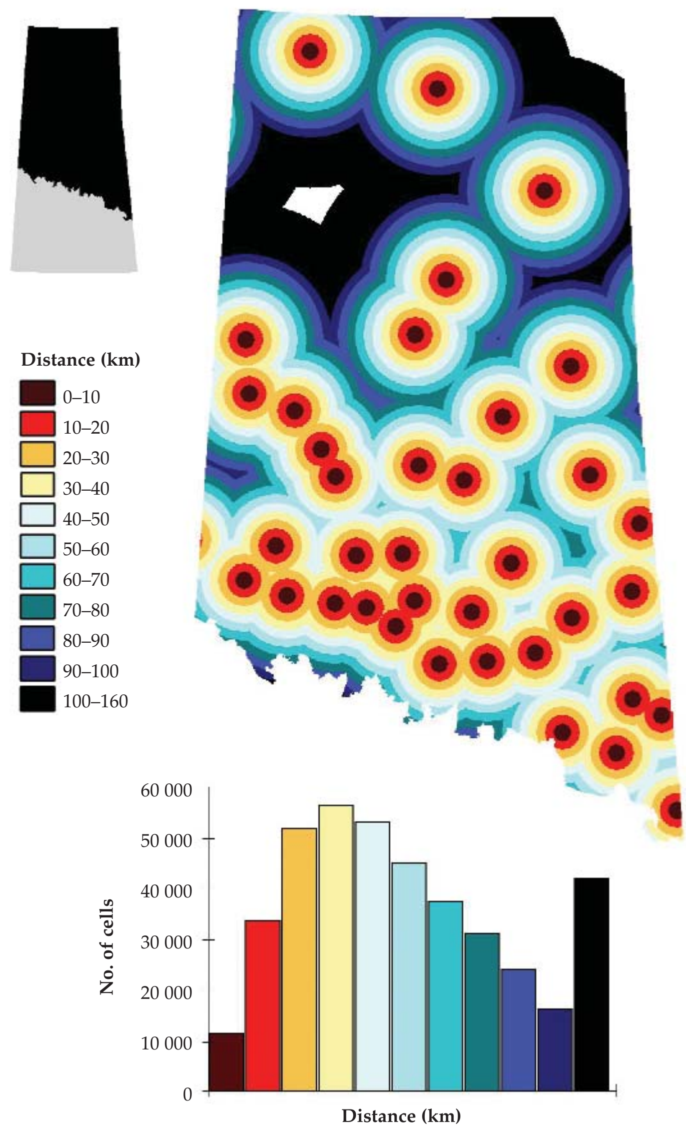


Figure 4. Distance to weather station and frequency histogram of number of cells per distance class (1 cell = 100 ha).

most significant difference is in wind speed, which is almost twice as high, on average, at the EC stations as at the SE stations. Kafka et al. (Kafka, V.; Parisien, M.A.; Hirsch, K.G.; Flannigan, M.D.; Todd, J.B. 2001. Climate change in the prairie provinces: assessing landscape fire behavior potential and evaluating fuel treatment as an adaptive strategy. Prairie Adaptation Research Cooperative. Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. Rep.) applied a correction (proposed by Silversides 1978) by doubling the daily wind speed values of the SE stations, but this overestimated fire danger potential at SE stations. Other problems arose because of station location. Fortunately, difference in elevation is rarely an issue in Saskatchewan; however, some weather stations are not representative of their surroundings. For example, some stations are located in river valleys, adjacent to lakes, or close to obstructions, such as buildings and roads. However, despite the many problems associated with these stations, weather data are invaluable for analyses of large-scale fire regimes.

Topography and Forest Fuels

The topography data set consisted of a digital elevation model (DEM) at 100-m resolution. In addition to elevation, aspect and slope were also derived from the DEM. Reliable forest fuels (i.e., vegetation) data were available for the commercial forest area, as well as for Prince Albert National Park (Fig. 5). The fuel types were classified according to the Canadian Fire Behavior Prediction (FBP) System, a subsystem of the CFFDRS (Forestry Canada Fire Danger Group 1992). The FBP System recognizes 17 fuel types, 7 of which apply in the study area. Data are stored as a raster grid at 100-m resolution. The fuels data originate from provincial forest inventory data, which were converted to FBP System fuel types according to

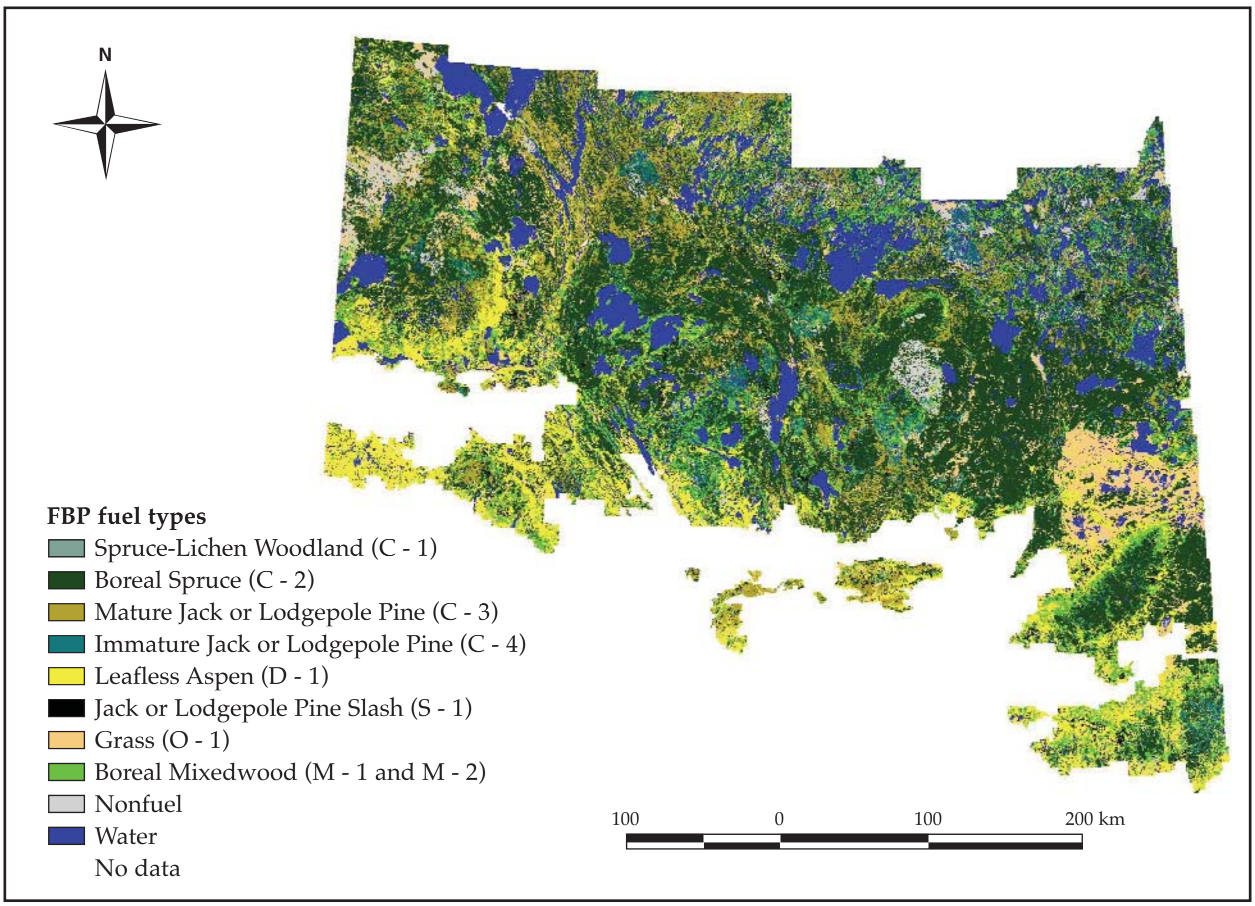


Figure 5. Canadian Forest Fire Behavior Prediction (FBP) System fuel types for the commercial forest of Saskatchewan and Prince Albert National Park.

a simple set of rules developed by CFS and SE. Inventory data from a wide span of years (1972 to 1996) were used to produce this grid; vegetation, and hence fuel types, were therefore expected to have changed in some areas because of natural succession, recent fires, and land use disturbances. Another problem was the absence of data for some vegetated areas ("no data" cells); however, these features represented a very small proportion of the landmass (<0.1%). This data set is being updated, a process that will accelerate in future through accessibility of high-resolution satellite imagery data.

A well-known shortcoming of the FBP System is that the limited number of fuel types can be unrepresentative of actual field variability. The Boreal Spruce fuel type, for example, is assigned to a wide range of boreal stands, ranging from well-drained upland sites to waterlogged muskeg, as in much of the MbL ecoregion, in which larger fires would typically occur in years of extreme droughts. The government of Alberta has attempted to circumvent this problem by creating the Crown Susceptibility Model (PFFC 2001), a model that accounts for more variables of stand structure, to further stratify the FBP System fuel types.

The DEM covers the entire province, whereas the fuels cover only the commercial forest. Analyses requiring fuel data were therefore performed only for the southern part of the study area.

Other Spatial Data

Lightning data for the period 1985 to 1999, excluding 1988 and 1990, for which data were unavailable, were also used in the analyses. From 1985 to 1998, the lightning data were collected from sensors operated by the province of Saskatchewan; after 1998 a new lightning detection system (LDS) was installed and operated by EC as the Canadian Lightning Detection Network. The data did not always include information on strike polarity or LCC (long continuous current) strikes, which are responsible for most lightning-caused ignitions. Furthermore, the LDS used before 1998 gathered poor location data and missed many lightning strikes. Because the reliability of the pre-1999 lightning data is suspect, this data set is of limited use and was used only to produce a lightning strike density grid. By contrast, the EC system offers more accurate detection, and the resulting data were therefore amenable to more refined analyses.

Various other geographic data were used in this study, including the study area boundaries (i.e., for ecological units) and specific data types appropriate for some of the analyses (e.g., information for roads, towns, lakes).

FIRE OCCURRENCE

Methods

Fire occurrence is defined as the number of fires in a given area over a given period of time (CIFFC 2000). The SE-FO data, summarized in a table of simple statistics, were used to analyze fire occurrence. Because the dates and locations of fires were included in this data set it was possible to identify seasonal and spatial patterns of fire occurrence. The temporal and spatial representations in this report are meant to complement each other. For the former, the numbers of human-caused and lightning-caused fires were tallied for each day of the calendar year (for all years). A smoothing technique known as the binomial expansion (Van Wagner 1988) was applied to better outline the trends of these results. Then, the magnitude and configuration of spatial patterns of fire occurrence were represented as density grids of 100-km^2 cells. A nearest-neighbor analysis (Cressie 1993) was then performed to evaluate whether human-caused and lightning-caused fire occurrence patterns were clustered ($R < 1$), random ($R = 1$), or uniform ($R > 1$) throughout the landscape.

The 100-km^2 cell density grids were also used to compare the lightning-caused fires with a lightning density map for 1985 to 1999 (excluding 1988 and 1990). The spatial correspondence between these two maps was assessed by plotting the average number of lighting fires per 10^5 ha by the density class of lighting strikes in the BPl ecozone. To explore the relation between lightning strikes and lightning-caused fires in forest vegetation, the two variables were compared by fuel type for a subset of the BPl ecozone for the year 1999. Finally, to define the relation between major infrastructures and fire occurrence, the proximity of human-caused fires to roads and towns in the BPl ecozone was quantified by defining buffers around these features.

Results and Discussion

Spatial and Temporal Patterns of Fire Occurrence

Distinct patterns of fire occurrence were observed for the various ecological units (Table 2), notably regarding the cause of ignition. In general, the proportion of human-caused fires decreased with increasing latitude, even though the number of smaller fires in the northern part of the province was likely underestimated.

In the BPl ecozone, the number of human-caused fires reached a well-defined peak in the spring and declined sharply in the summer, when lightning-caused fires increased (Fig. 6). The human-caused fires were highly clustered throughout the BPl ecozone for both the spring (nearest-neighbor analysis, $R = 0.60$, $p \leq 0.05$) and the summer ($R = 0.58$, $p \leq 0.05$). The vast majority of human-caused fires have occurred very close to towns and roads (Fig. 7). In fact, in the BPl ecozone 77% of reported fires ignited within a 5-km distance from roads and 36% within a 5-km distance from towns. When weighted by unit area, there were 6 and 27 times more fires in the buffers around roads and towns, respectively, than outside these 5-km buffers. However, fires near roads and towns rarely escape, as they are more readily detected and extinguished.

In the BTr ecoregion, human-caused fires occurred virtually everywhere across the farmland-forest interface and, interestingly, were almost as numerous in the forested (BTr-mod) as in the nonforested area (Table 2). However, large fires have burned less area in this ecoregion than in the other BPl ecoregions (see following section).

Table 2. Fire occurrence statistics by ecological unit from 1981 to 2000

	Ecozone			Ecoregion (within Boreal Plain)			
Variable	Boreal Plain	Boreal Shield	Taiga Shield	Boreal Transition	Boreal Transition modified	Mid-boreal Lowland	Mid-boreal Upland
Total no. of fires	8829	4720	683	2110	924	636	6080
Cause (%)							
Human	64.4	31.6	22.5	94.0	90.0	50.9	55.8
Lightning	35.4	68.4	77.5	6.0	10.0	49.1	44.2
Annual no. of fires							
Average ± SD	441 ± 147	236 ± 104	34 ± 23	106 ± 39	46 ± 16	32 ± 16	304 ± 110
Average per 10^6 ha ± SD	25 ± 8	13 ± 6	7 ± 5	20 ± 7	53 ± 18	15 ± 7	30 ± 11
Minimum	224	110	9	22	13	16	121
Maximum	769	464	91	187	82	83	502

Note: SD = standard deviation.

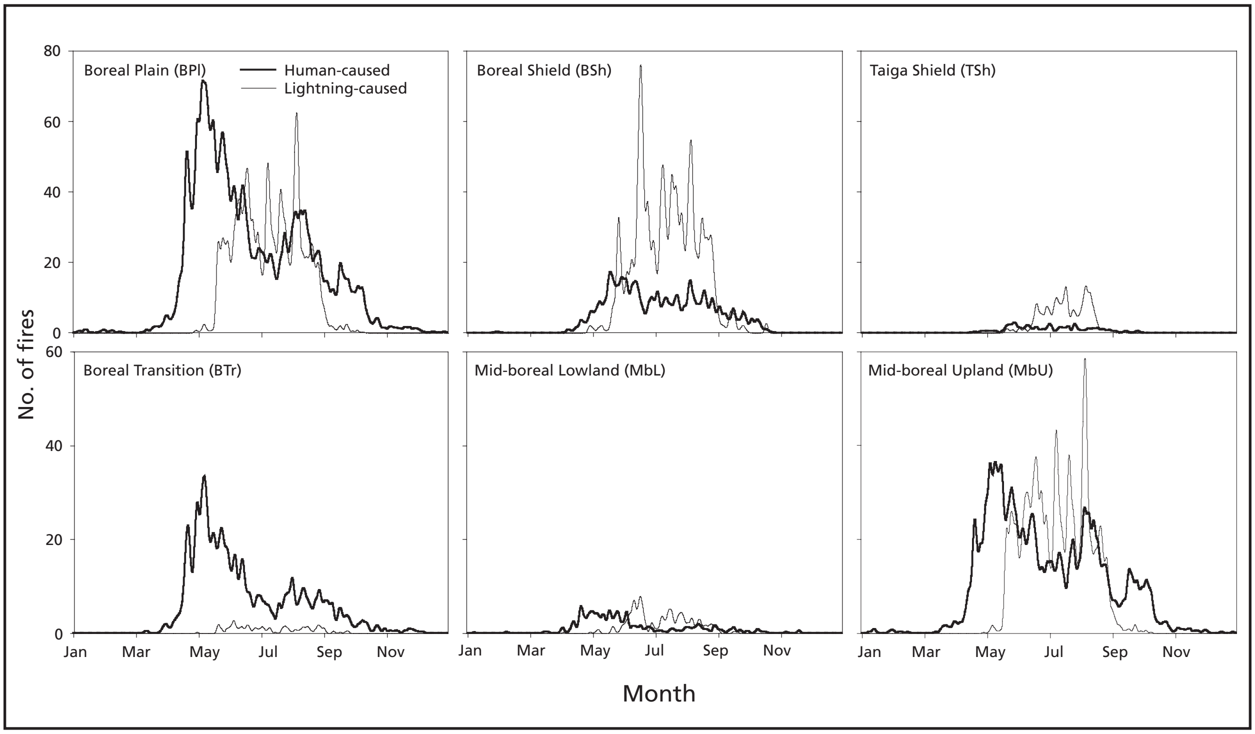


Figure 6. Number of reported fires per day for the Boreal Plain, Boreal Shield, and Taiga Shield ecozones and for the Boreal Transition, Mid-boreal Lowland, and Mid-boreal Upland ecoregions, from 1981 to 2000. The values have been subjected to a binomial smoothing of $n = 8$.

This is consistent with the findings of Pew and Larsen (2001), who documented an inverse relation between the number of human-caused ignitions and mean fire size on Vancouver Island, BC. They found that regions of low human-caused fire occurrence had more logging fires, which were much bigger than other types of human-caused fires (e.g., recreation, agriculture). The part of Saskatchewan that has the lowest number of fires, the northern part the BSh ecozone, is also the part where the area burned is the highest (Fig. 2). Many factors might explain this situation: poor detection of fires, drier conditions in the north (see Fire Climatology section), higher continuity in flammable fuels, and low suppression efforts.

Although the spatial extent of human-caused fires was very similar for spring and summer (Fig. 7), there was a northern shift in the magnitude of fire occurrence later in the year, with a notable increase near the BPl-BSh ecozone boundary. This shift was attributed primarily to the decrease in flammability of grassland and deciduous fuels, which are more prominent in the south, as the fuels green up. There may also be a seasonal change in the different types of human ignitions (*see* Appendix 2).

A marked seasonal pattern in lightning-caused fires was also observed, virtually all such fires occurring from June to August (Fig. 6). Contrary to human-caused fires, lightning-caused fires had a more regular, though still statistically clustered, spatial distribution for the spring (nearest-neighbor analysis, $R = 0.74$, $p \leq 0.05$) and the summer ($R = 0.79$, $p \leq 0.05$). Apart from previously discussed detection issues, it can be speculated that ignition processes differ substantially between ecological units, notably between the BPl and BSh ecozones, which have contrasting landforms that tend to support different vegetation types and soil organic matter (i.e., surface fuels). Therefore, the smoldering stage of ignition may differ by ecozone, thereby influencing ignition potential (Anderson 2000). For example, the consolidated bedrock of the BSh and TSh ecozones may support fuels that undergo more rapid changes in moisture than the BPl ecozone (Stocks 1975).

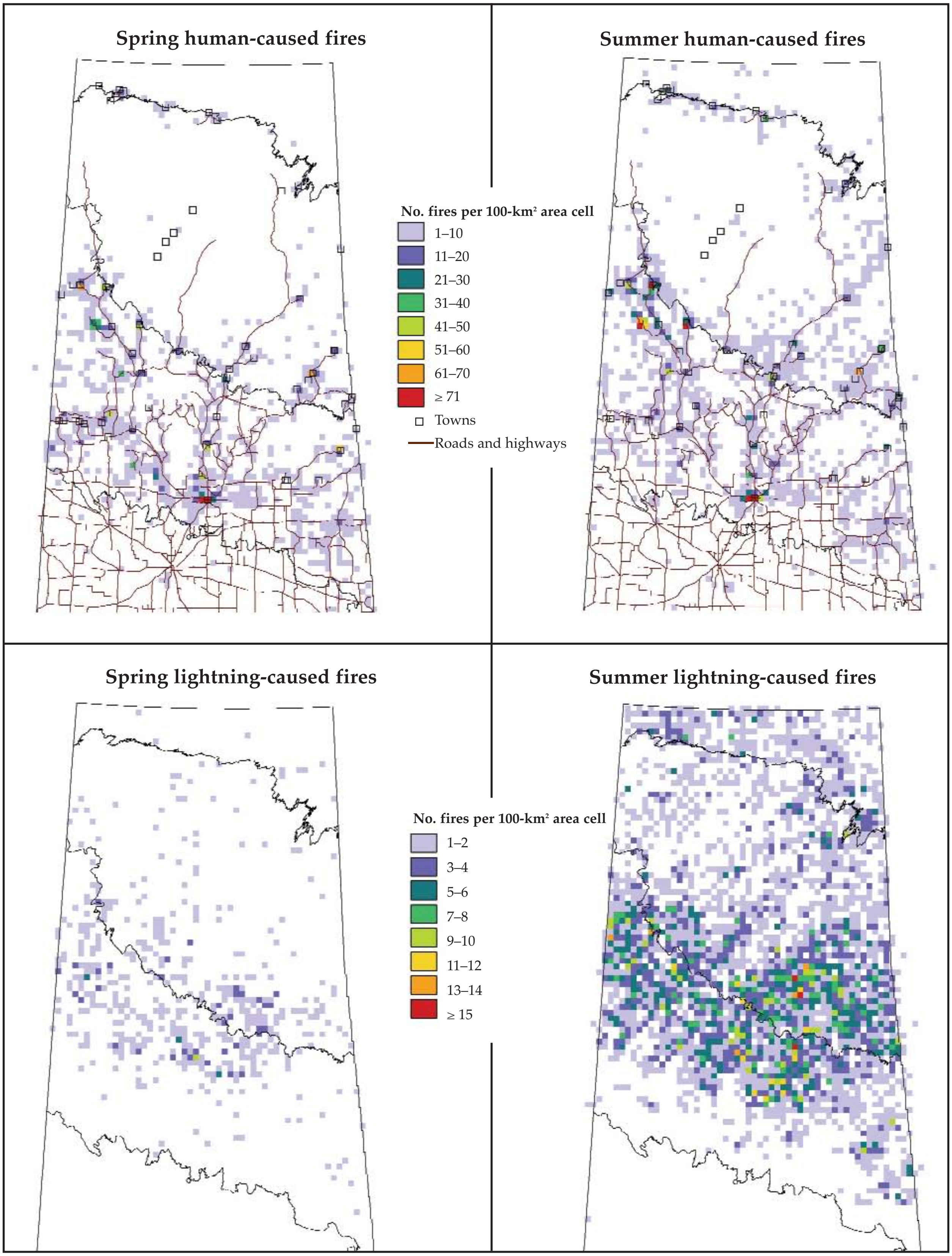


Figure 7. Density grids (100-km^2 cells) of the number of reported human-caused and lightning-caused fires in spring and summer, from 1981 to 2000.

Spatial Correspondence between Lightning Strikes and Lightning-Caused Fires

The ignition of lightning-caused fires is a function of many factors, including elevation, soils, vegetation type, and weather. These factors and their interactions explain much of the spatial variation in detectable fires (Flannigan and Wotton 1991; Wierzchowski et al. 2002). In the BPl ecozone, where most lightning detection occurs, there is a weak but slightly negative relation between lightning strike density and lightning-caused fires (Fig. 8, R^2 = 0.069, p = 0.07), as mapped in Figure 9. In Saskatchewan, more lightning strikes are associated with fewer fires because lightning is usually associated with rain,

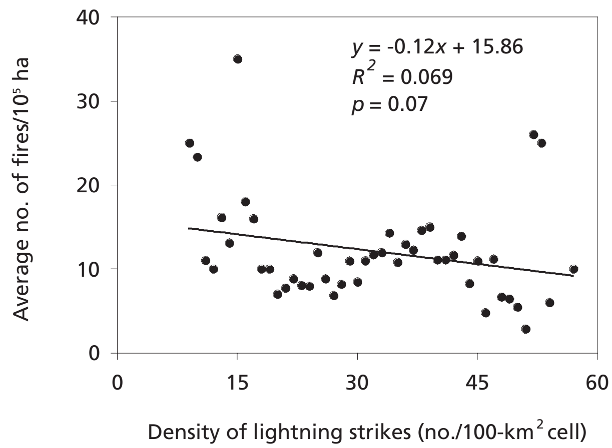


Figure 8. Average number of lightning-caused fires per 10^5 ha as a function of density of lightning strikes in 100-km^2 cells, from 1981 to 2000 (both data types excluding 1988 and 1990), as presented in Figure 9.

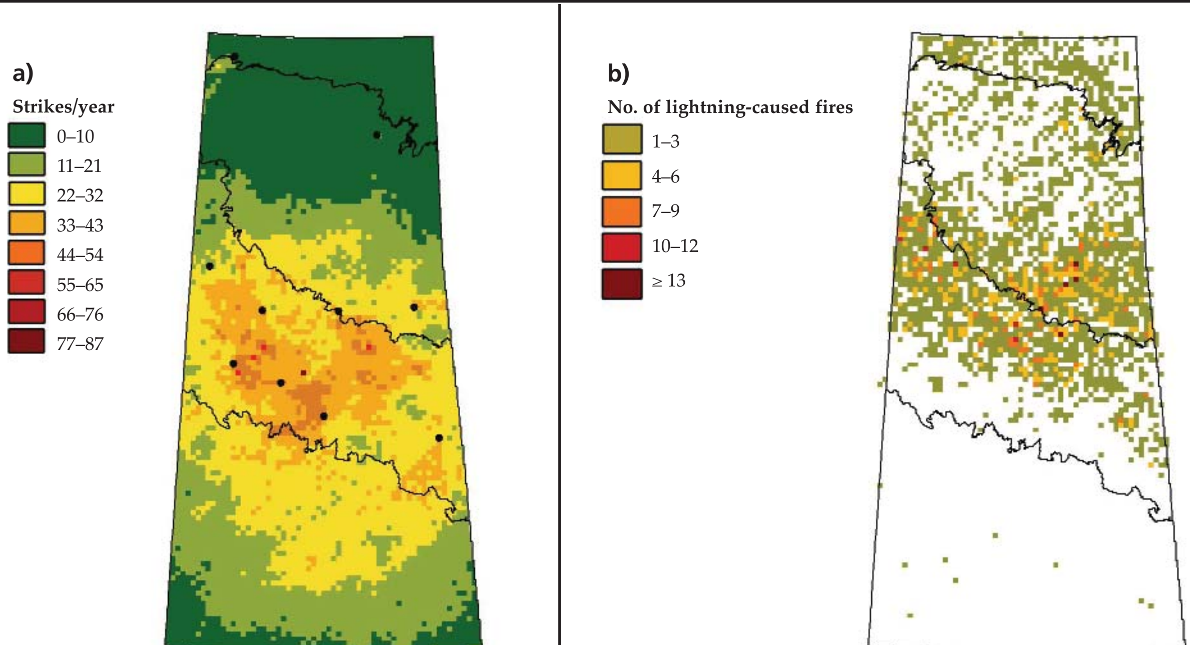


Figure 9. Density grids (100-km^2 cells) of (a) average lightning strikes per year from 1985 to 1999 and (b) reported lightning-caused fires, from 1981 to 2000 (both data types excluding 1988 and 1990). The black dots in Figure 9a represent provincial lightning detectors.

as reported by Anderson (1999), who observed fairly good correlations between lightning strike density and convective rainfall, according to data from three weather stations of the southern BPl ecozone. The results of this present analysis are consistent with those of Flannigan and Wotton (1991) and Podur et al. (2003) in Ontario, the latter of whom also failed to find an annual relation between lightning and fires. By contrast, in Alaska, Kasischke et al. (2002) identified a positive relation between lightning strike density and the area burned by lightning-caused fires. However, they also outlined the role of other factors, such as weather, elevation, aspect, and level of forest cover, and their complex interaction in explaining patterns of area burned. Preliminary analyses conducted by Podur et al. (2003) revealed a spatial correspondence between lightning-caused fires and lightning strikes in some parts of western Ontario during drought conditions, which suggests a need to explore this relation at a much finer temporal scale, with consideration of other factors promoting fire ignition and spread.

Lightning and Lighting-Caused Fires by FBP Fuel Type

A major factor driving lightning-caused ignitions in the western boreal forest is fuel type, for which drastically different rates of ignitions have been reported (Anderson and Englefield 2001; Cumming 2001). According to Cumming (2001), lightning-caused fires rarely, if ever, ignite in aspen stands, where much lightning activity occurs. In a section of the MbU, there were proportionally more lightning strikes than lightning-caused fires in the Leafless Aspen (D1) fuel type in 1999 (Table 3). By contrast, lightning-caused fires were proportionally higher in the Boreal Spruce (C2) and Boreal Mixedwood (M1, M2) fuel types, as reported by Anderson and Englefield (2001), who carried out a similar analysis for the entire SE-FO database. The results reported here should be interpreted with extreme caution, as there are many concerns pertaining to the quality of the data on fuel type and the spatial accuracy of the detection of lightning strikes and lightning-caused fires.

Table 3. Number of lightning strikes and detected lightning-caused fires by Forest Fire Behavior Prediction (FBP) System fuel type for a portion of the Boreal Plain ecozone in 1999[a]

FBP system fuel type	Area (ha)		No. of strikes		No. of lightning-caused fires		Ratio of fires to lightning strikes[b]
C2	2 731 583	(41.5)[a]	11 865	(41.2)	96	(52.5)	1.3
C3	943 902	(14.3)	4 115	(14.3)	26	(14.2)	1.0
C4	149 134	(2.3)	631	(2.2)	2	(1.1)	0.5
D1	621 947	(9.4)	2 839	(9.8)	8	(4.4)	0.4
S1	55 377	(0.8)	262	(0.9)	1	(0.6)	0.6
O1	573 413	(8.7)	2 561	(8.9)	11	(6.0)	0.7
M1, M2	501 901	(7.6)	2 111	(7.3)	22	(12.0)	1.6
Nonfuel	215 709	(3.3)	908	(3.1)	2	(1.1)	0.4
Total	6 585 024		28 831		183		

[a]Percentages in parantheses. The percentages do not add up to 100% because some fires and lightning strikes were reported over water.
[b]On the basis of percentages of total.
Note: C2 = Boreal Spruce, C3 = Mature Jack or Lodgepole Pine, C4 = Immature Jack or Lodgepole Pine, D1 = Leafless and Green Aspen, S1 = Jack or Lodgepole Pine Splash, O1 = Grass, M1 and M2 = Boreal Mixedwood (Leafless and Green).

Methods

The data sets for large fires (LFDB, FFCS) were used for analyses of area burned, as these had much more reliable data on fire size than the SE-FO database. It is also typical to use only large fires in analyses of area burned in the boreal forest because they are responsible for most of the area burned (97% to 98% in Saskatchewan). The FFCS was used in all cases where cause and timing information was not required. The area of the polygons was recalculated in ArcView GIS (1999). The LFDB points were used for the remaining analyses.

First, the number of large fires and the area burned were determined on a yearly basis for the entire study areas, as well as by ecological unit. Then, to quantify the uncertainty in area burned, 95% confidence intervals were computed for the average annual area burned for each ecological unit.

Fire cycle, defined as the number of years required to burn an area equal to the size of the study area, was calculated by two methods: the reciprocal of the average percent annual area burned, as described by Heinselman (1973), and a maximum likelihood estimator (MLE) survival analysis (Johnson and Gutsell 1994; Reed et al. 1998). The latter method provides an estimate of the mean rate of area burned. The areas in the data set that have not burned are considered censored (i.e., open-ended) because it is likely that they will eventually burn. Censoring was taken into account in these analyses. Both methods are valid and thoroughly documented; therefore, no further explanation will be provided here. The major difference between them is that the survival analysis can provide error bounds to the fire cycle estimates. However, because of the high variability of the rather limited data set (56 years) the bounds calculated here were too wide to be of any use.

The number of large fires, as well as the area burned, was plotted as a function of size class to examine the fire size distribution of the ecological units. These distributions were standardized by relative proportions and compared statistically by means of a Kolmogorov-Smirnov test (Zar 1998). The month of ignition was also used to assess the seasonal patterns of large fires by cause, whereas a nearest-neighbor analysis was performed to evaluate the clustering of these fires (LFDB data).

Results and Discussion

Annual Area Burned

As typically observed in boreal biomes, the vast majority of fires in Saskatchewan are of small to moderate size, as observed from the fire size classification of the SE-FO database. In the BPl ecozone, for example, 78% of reported fires are <1 ha, 97% are <100 ha, and over 99% are <1000 ha. Although fires <1000 ha represent a small fraction of the area burned (about 3%), they are of concern because of potential loss of timber, threat to communities, and potential to escape and become large fires.

In Saskatchewan for the period 1945 to 2000, there were on average 18 large fires (≥1000 ha) per year, burning 270 000 ha annually (Fig. 10). Significant interannual variability was observed for both the numbers of large fires and the corresponding area burned. In some years no large fires have been recorded, whereas in other years, such as 1970, 1980, 1981, 1994, and 1995, fires have burned in excess of 10^6 ha. The interannual variability in area burned was generally greater than the variability in the number of fires, as expressed by the coefficients of variation. Annual numbers of fires and area burned were nevertheless strongly correlated for the entire study area (Pearson correlation, $R = 0.90$, $p < 0.01$), as well as for each ecological unit ($R \geq 0.66$, $p < 0.01$).

During some severe fire years, fires were widespread throughout the province, whereas in other years, they were highly localized, as reported for other parts of North America (Foster 1983; Payette et al. 1989; Rollins et al. 2001; Bothwell et al. 2004). In Saskatchewan, this variability translated into a general clustering of both human-caused and lightning-caused large fires (nearest-neighbor analysis, $R < 1$, $p \leq 0.05$). The large fires in 1980 and 1981, for example, burned disproportionately more in the two northern ecozones. Conversely, some important fire years have affected only a fraction of the

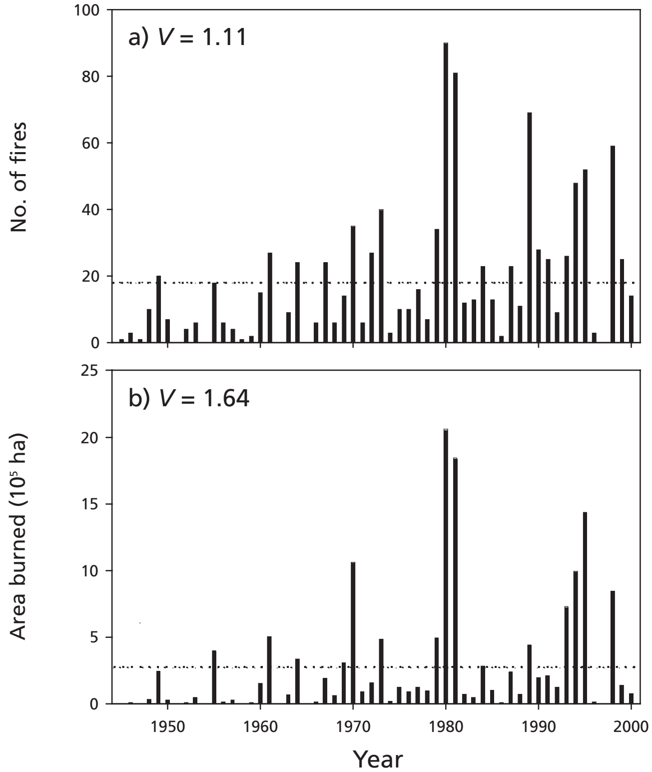


Figure 10. (a) Number of large fires (≥1000 ha) and (b) total area burned per year, from 1945 to 2000, for the entire study area. The dashed lines represent the mean values. *V* = coefficient of variation (standard deviation/mean).

territory, such as 1995 in the MbU ecoregion, when just four fires burned approximately 700 000 ha, and 1991, when 79% of the 214 588 ha burned in Saskatchewan was in the TSh ecozone. A few or even a single large fire—as was the case in the BPl ecozone in 1998—can therefore account for a severe fire year.

The number of and area burned by large fires thus differed significantly between ecozones (Fig. 11) and ecoregions (Fig. 12). Most of the large fires and also most of the area burned occurred in the northern ecozones, BSh and TSh combined, and the majority of large fires in the BPl ecozone occurred in the MbU ecoregion. Per unit area, the northern ecozones experienced significantly more large fires (Kruskall-Wallis test with a pairwise Wilcoxon sign test, $p = 0.048$): 0.27, 0.60, and 0.89 fires per 10^6 ha, for the BPl, BSh, and TSh ecozones, respectively. While the differences in percent annual area burned between ecozones were marked (0.38%, 1.01%, 0.88% for the BPl, BSh, and TSh ecozones, respectively; Table 4) they were not statistically different according to a Kruskall-Wallis test. Apart from contrasts in human land use, the southern and northern parts of the boreal forest of Saskatchewan have generally different forest landscapes, notably in terms of vegetation, physiography, and climate. However, fire also shapes these landscapes. Differences in the fire regimes between the northern and southern parts of the Prince Albert National Park area, for example, produced contrasting mosaics of stand types and ages (Weir et al. 2000). It is logical that different fire regimes would boast different forest mosaics, and vice versa, considering the tight relation between forest vegetation and forest fires since the end of the last ice age (Ritchie 1987; Payette 1993). Different physiographic units may also contribute to fire regime differences through contrasting topography (Engelmark 1987) and landscape configuration (Bergeron 1991; Wardle et al. 2003).

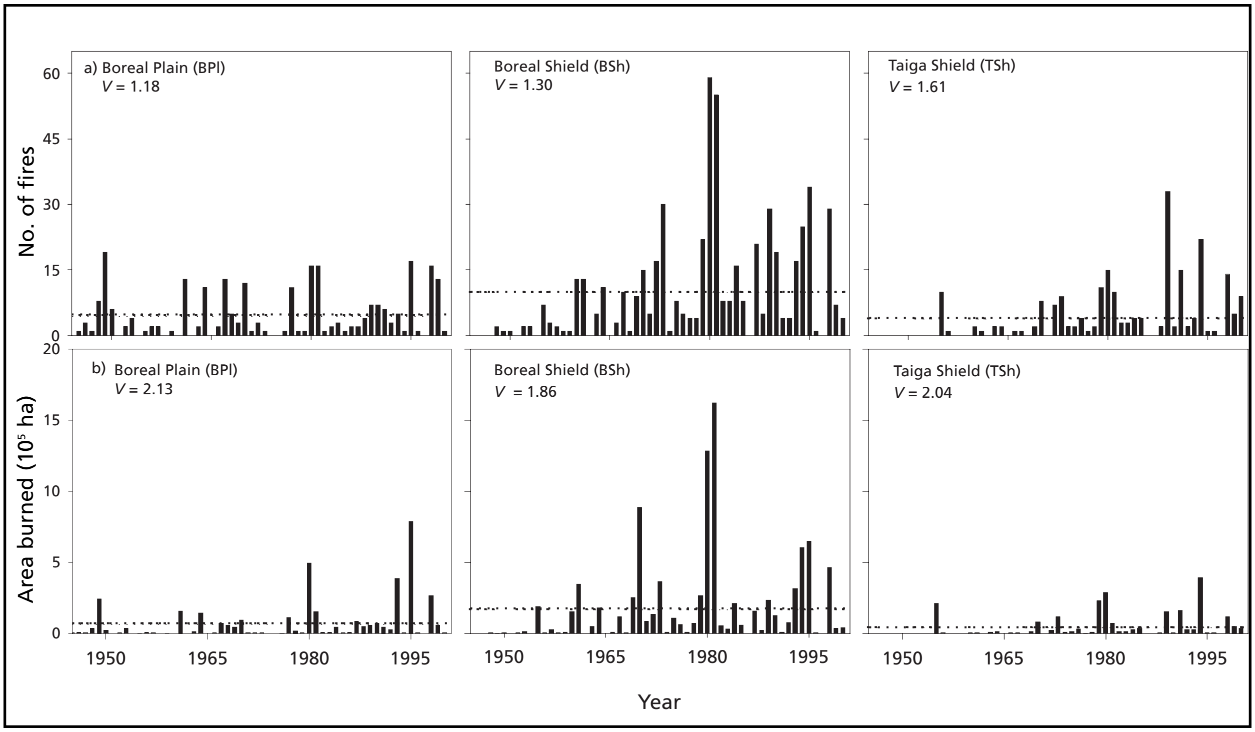


Figure 11. (a) Number of large fires (≥1000 ha) and (b) area burned by large fires per year for the Boreal Plain, Boreal Shield, and Taiga Shield ecozones, from 1945 to 2000. The dashed lines represent the mean values. *V* = coefficient of variation (standard deviation/mean).

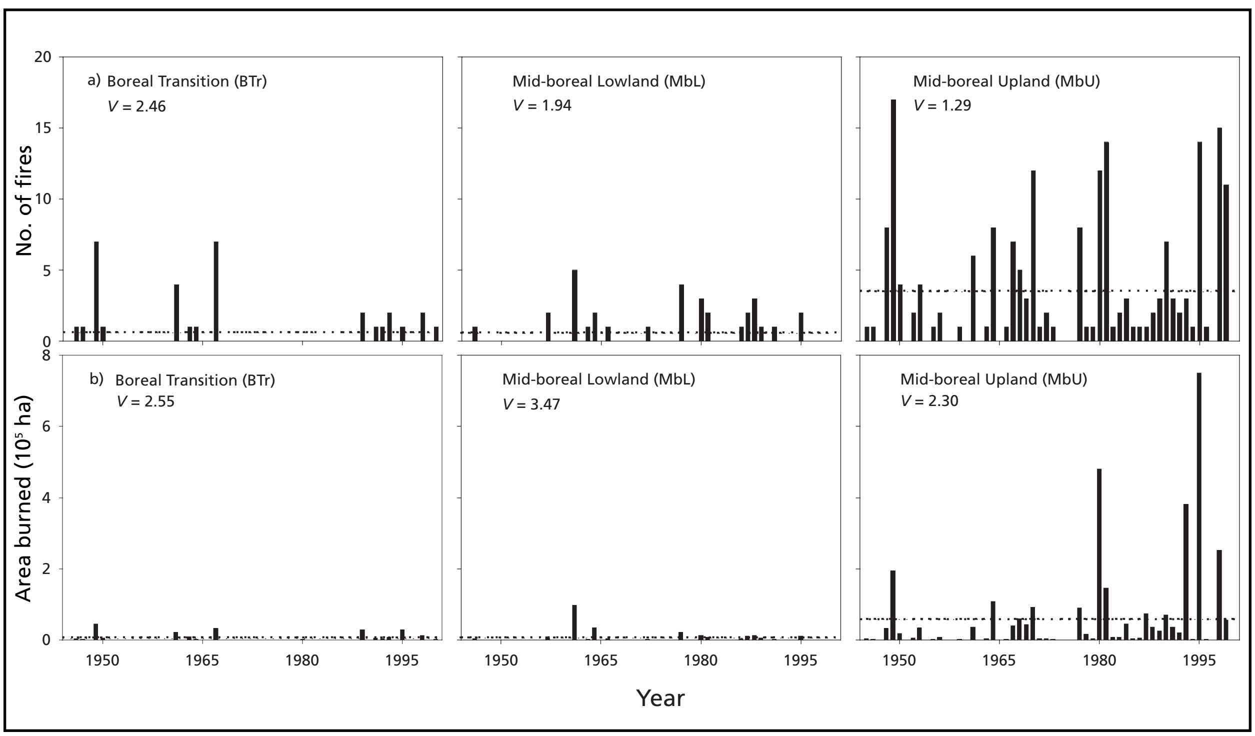


Figure 12. (a) Number of large fires (≥1000 ha) and (b) area burned by year for the Boreal Transition, Mid-boreal Lowland, and Mid-boreal Upland ecoregions, from 1945 to 2000. The dashed lines represent the mean values. *V* = coefficient of variation (standard deviation/mean).

Table 4. Fire statistics for large fires (≥200 ha) by ecological unit[a]

Variable	Ecozone			Ecoregion (within Boreal Plain)			
	Boreal Plain	Boreal Shield	Taiga Shield	Boreal Transition	Boreal Transition modified	Mid-boreal Lowland	Mid-boreal Upland
Cause of fire (%)							
Human	52.50	6.10	3.60	87.90	84.80	52.00	38.70
Lightning	40.80	75.60	78.30	12.10	15.20	40.00	52.20
Unknown	6.70	17.30	18.20	0	0	8.00	9.10
Annual no. of fires/10^6 ha	1.50	3.34	4.88	0.73	5.17	1.70	2.17
Annual area burned ± CL (%)	0.38 ± 0.21	1.01 ± 0.50	0.88 ± 0.48	0.07 ± 0.05	0.34 ± 0.25	0.19 ± 0.18	0.59 ± 0.37
Estimated fire cycle (years)							
Heinselman method	263	99	114	1488	292	517	169
MLE survival analysis method	288	104	112	2723	423	669	169

[a]The proportions by cause were calculated from the Canadian Forest Service Large Fire Database for fires from 1950 to 1998, whereas the other statistics were calculated from Saskatchewan fire polygon data from 1945 to 2000.
Note: CL = upper and lower confidence limits at $p \leq 0.05$, MLE = maximum likelihood estimator.

Humans have undoubtedly had an effect on the number of and area burned by large fires, notably through their fragmentation and use of the forest (Johnson et al. 1998; Weir et al. 2000). Consequently, proportions of human-caused and lightning-caused large fires vary between ecological units (Table 4). While most large fires in the BPl ecozone were ignited by humans (52.5%), the opposite was true for the BSh and TSh ecozones. In the BPl ecozone, the largest proportion of human-caused fires was, by far, in the BTr ecoregion. The large fires of this ecoregion were most often spring fires that ignited in the cured (matted) grasses and subsequently escaped. However, less flammable forest fuel types and heavy fragmentation kept the BTr fires small, and hence the area burned was low.

Possible Teleconnections

Marsden (1982) showed that for lightning-caused fires in the American Northwest, the severe fire years (which he called "temporal clumps") were distributed randomly in time. Somewhat contradictory to this pattern, other studies have reported a teleconnection—a linkage between weather anomalies occurring in widely separated areas of the world—linking area burned to regularly occurring climate phenomena. Flannigan et al. (1999) described a teleconnection between annual area burned in Canada and anomalies in the surface temperature of the Pacific Ocean; this teleconnection is particularly strong for western Canada. In the boreal forest of Alaska, Hess et al. (2002) found a correlation between high fire years and El Niño years, which typically had warmer and drier conditions. Other studies have presented evidence of a similar relation between area burned and El Niño (Swetnam and Betancourt 1990; Donnegan et al. 2001; Kitzberger et al. 2001), but this teleconnection has not been documented for the Canadian boreal forest. However, cyclic patterns in drought conditions in the Canadian prairie provinces have been reported, notably in relation to El Niño (Bonsal and Lawford 1999).

Fire Cycle

The fire cycle, calculated from area burned, summarizes a considerable amount of information and is readily understood by fire managers and ecologists alike. These values are often used by forest managers to determine a reserve factor, the percent of annual area of the forested landmass that is lost to fire, for timber supply calculations. Furthermore, many ecologists and forest managers attempting to emulate the rate of natural disturbance with harvesting use the fire cycle as a benchmark.

For the BPl, BSh, and TSh ecozones, the calculated fire cycles were 263, 99, and 114 years, respectively, according to the Heinselman method and 288, 104, and 112 years according to the MLE survival analysis method. The calculations of fire cycle by ecoregion confirmed spatial variations in the fire regime within large geographic units such as ecozones. The very long fire cycle calculated for the BTr ecoregion (1488 years according to the Heinselman method) is misleading, as most of this ecoregion has been converted to farmland over the past century. The BTr-modified fire cycle of 292 years (Heinselman method) is thus a more meaningful estimate for the BTr, since it was calculated on the basis of the actual forest boundary. In any case, these fire cycle estimates differ from those calculated by Weir et al. (2000) for the Prince Albert National Park region (15 to 1745 years, depending on the time period), and Andison (Andison, D.W. 1998. Age-class distributions and fire cycles on the Mistik FMLA. Bandaloop Landscape-Ecosystems, Coal Creek Canyon, CO. Unpubl. Rep.) for part of the western BPl ecozone (33 to 55 years). However, those studies used stand origin maps and different methods of calculating the fire cycle.

For ecozones, the relative difference in fire cycle values calculated by the two methods was low (<10%), but it was much greater for some ecoregions. The two methods generally yield similar results when the data sets cover long periods or the burn rates are high (Lesieur et al. 2002), but discrepancies are to be expected when these conditions are not met. Therefore, the shorter fire cycle estimates produced here are much more reliable than the longer ones. It is because of this inherent variability that fire cycle estimates must be interpreted with caution, as indicated by the large confidence intervals for annual area burned (49.5% to 95% of the mean for ecozones and ecoregions) (Table 4). The 95% confidence intervals produced from the MLE survival analysis were too wide to be meaningful, further exemplifying the high variability of the dataset. Using a stand origin map, Johnson and Gutsell (1994) claimed that a data set two or three times the length of the fire cycle is required to provide an adequate estimate of this statistic, but this aspect has not been explored for polygon data, such as those presented here.

Temporal Change in Area Burned

A general increase in area burned was apparent for the second half of the dataset (1970 to 2000): the area burned was 2.7, 4.8, and 6.0 times greater than for the period 1945 to 1969 for the BPl, BSh, and TSh ecozones, respectively (Fig. 11). This increase may be partly a result of data quality, as many large fires are possibly unreported for the first half of the data set. In Alberta, for example, the largest fire ever reported, the Chinchaga Lake fire of 1950 (Murphy and Tymstra 1986), was absent from the fire records until very recently. That said, no attempt was made to statistically compare the burn rates of different periods ("epochs"), as described in Reed et al. (1998). Some authors (Rogeau 1998; Lertzman et al. 1998; Armstrong 1999) question whether it is possible to detect long-term changes in area burned on the basis of annual area burned, given the extreme interannual variability in this phenomenon. In any case, the frequency of severe fire seasons seems to be increasing in many parts of Canada. According to some studies, this increase is probably a consequence of climate change (Flannigan et al. 1998), whereby periods of extreme fire weather recur more often. Although undocumented, there is also a potential effect of an increase in fuel load because of lack of disturbance (i.e., successful fire suppression) in some regions.

The increase in area burned was not as marked in the BPl ecozone. The fire regime in that ecozone could be considered the least “natural,” as land-use activities (e.g., agriculture, urban sprawl, forest fragmentation from forestry operations) have drastically changed parts of the landscape (Johnson et al. 1998; Fitzsimmons 2001). Also, humans might have had a strong impact by providing artificially high ignition rates in localized areas (i.e., near human infrastructure) and by actively suppressing fires. In the southern part of the BPl ecozone, Weir and Johnson (1998) documented a marked historical change in forest composition related to fires that escaped during past logging and noted that these fires decreased the abundance of white spruce at the expense of trembling aspen and jack pine.

Optimal Spatial Scale of Study

Spatial variations in the fire regime were evident within each ecological unit. However, such variation cannot be easily detected with a limited data set, as areas that have not burned in 56 years are not necessarily less susceptible to burning. Furthermore, it is likely that fire regimes change through time and are thus unstable over the long term. This instability, which could be viewed as a dynamic equilibrium (Baker 1989b), would make it difficult to identify a steady state in the fire regime, if such a thing exists. For example, in a 400 000 ha area of Minnesota, Baker (1989a) reported that the forest could not reach a steady state, largely because of heterogeneity in the fire regime and the environment. This inherent instability, coupled with the short period of the data set, makes it essential to fully assess and recognize the area-specific variability of disturbances and not rely solely on mean values that are subject to drastic change. For example, one very large fire in a small area could easily halve the fire cycle estimate in a short data set.

There is therefore a trade-off between the accuracy of the estimates of fire statistics and the representation of spatial variation in the fire regime: larger areas will produce estimates of fire statistics with lower statistical error but will overlook spatial variations. It is clear from the results reported here that to adequately describe spatial and temporal patterns in the fire regime, more than one scale must be considered. The size of ecozones and ecoregions were deemed adequate for these analyses. Although ecological units smaller than ecoregions, called ecodistricts, do exist, they would represent an inappropriate spatial scale for most analyses of this study. Johnson and Gutsell (1994) proposed as a rule of thumb that study areas for fire history studies should be at least three times as large as the sum of area burned in the year in which the most area had been burned. In other words, for areas with similar burn rates, the shorter the time frame, the larger the area required for analysis. Although rules of thumb have worked well in the past and generally make sense, the use of spatial statistical techniques that measure contagion (e.g., spatial autocorrelation, Ripley's *K*; Cressie 1993) hold promise, in that they could provide a more objective evaluation of the effect of scale on fire statistics.

Fire Size Distribution

In Saskatchewan from 1945 to 2000, as typically observed in the boreal forest, there was a near-exponential decrease in the number of fires as a function of fire size (Fig. 13). Of all fires ≥200 ha, 31% were ≥10 000 ha and 6% were ≥50 000 ha; however, these fires were responsible for 84% and 71% of the area burned, respectively. In fact, a single large fire can easily dwarf the area burned of a very large number of small fires. It is therefore these large fires that are the most influential in defining landscape configuration and affecting landscape-level population dynamics of plants and animals. In the boreal forest of Minnesota, Heinselman (1973) found that where the occurrence of large fires was greatly reduced, partly as a result of fire suppression, important vegetation changes occurred. Wein and Moore (1979) reported that, in Nova Scotia, the virtual elimination of large fires in the recent past caused the fire cycle to increase from 200 to >1000 years. Of course, large fires are not likely to be eliminated from the Saskatchewan landscape in the near future, but a sustained increase in the length of the fire cycle over time could lead to important changes in vegetation patterns (Overpeck et al. 1990).

The size-class distribution of fires revealed further differences between ecological units. For

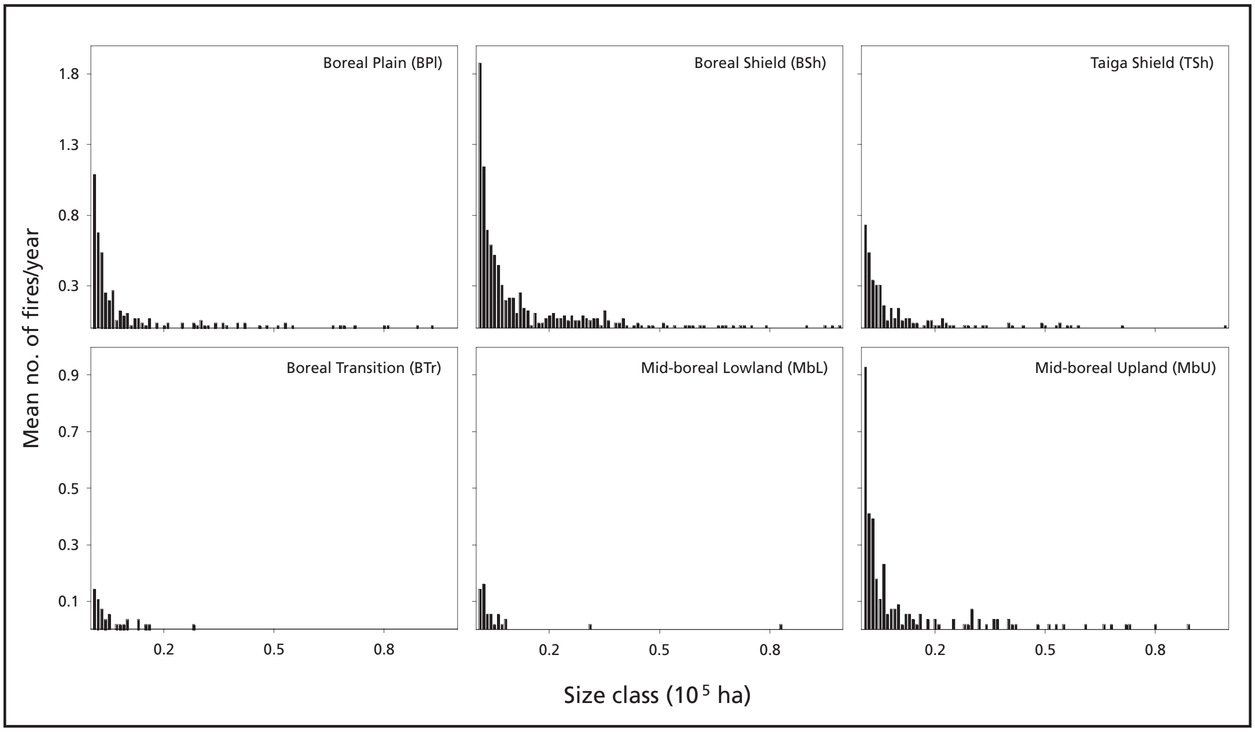


Figure 13. Mean number of large fires (≥1000 ha) per year per 1000-ha size class for the Boreal Plain, Boreal Shield, and Taiga Shield ecozones and for the Boreal Transition, Mid-boreal Upland, and Mid-boreal Lowland ecoregions, from 1945 to 2000. The *x*-axis has been limited to fires <100 000 ha although bigger fires did occur in the study area.

instance, even though the TSh and the BSh ecozones had a similar mean annual area burned per unit area, very large fires were proportionally more prominent in the BSh ecozone. In fact, the shape of the TSh ecozone size-class distribution was significantly different from that of the BSh ecozone (Fig. 13; two-sample Kolmogorov-Smirnov test, $p = 0.006$), but not from that of the BPl, an ecozone that also experienced proportionally fewer very large fires than the BSh ecozone. Fuel discontinuity on the landscape might also explain why the BPl and TSh ecozones experienced proportionally fewer very large fires than the BSh ecozone. Forest fragmentation and large expanses of the deciduous (D1) fuel type in some parts of the BPl ecozone might be comparable to the discontinuity created by lakes, wetlands, and areas of exposed rock in the TSh ecozone.

In parallel, Payette et al. (1989) found pronounced differences in fire size across a latitudinal transect in northern Quebec, mainly because of climate and vegetation gradients. Fires of the forested tundra, which has a highly discontinuous forest cover, were much smaller. Rollins et al. (2002) reported that a lack of fuel continuity was the most important constraint to area burned in one of their two study areas in the western United States. Niklasson and Granström (2000) claimed a counteracting effect of the number and size of large fires: in areas where many large fires commonly occur, there is an increase in the probability of a fire stopping at the boundary of a recent burn. This was likely exemplified in parts of the BSh ecozone, especially given that the burn rates were much higher than the ones reported by Niklasson and Granström (2000).

Seasonal Trends of Large Fires

Distinct seasonal patterns of large fire occurrence by cause were observed for ecozones (Fig. 14) and ecoregions (Fig. 15) of Saskatchewan. Although a few large fires have occurred from November to March, virtually all large fires burn between April and October, the bulk of them during the months of May through August.

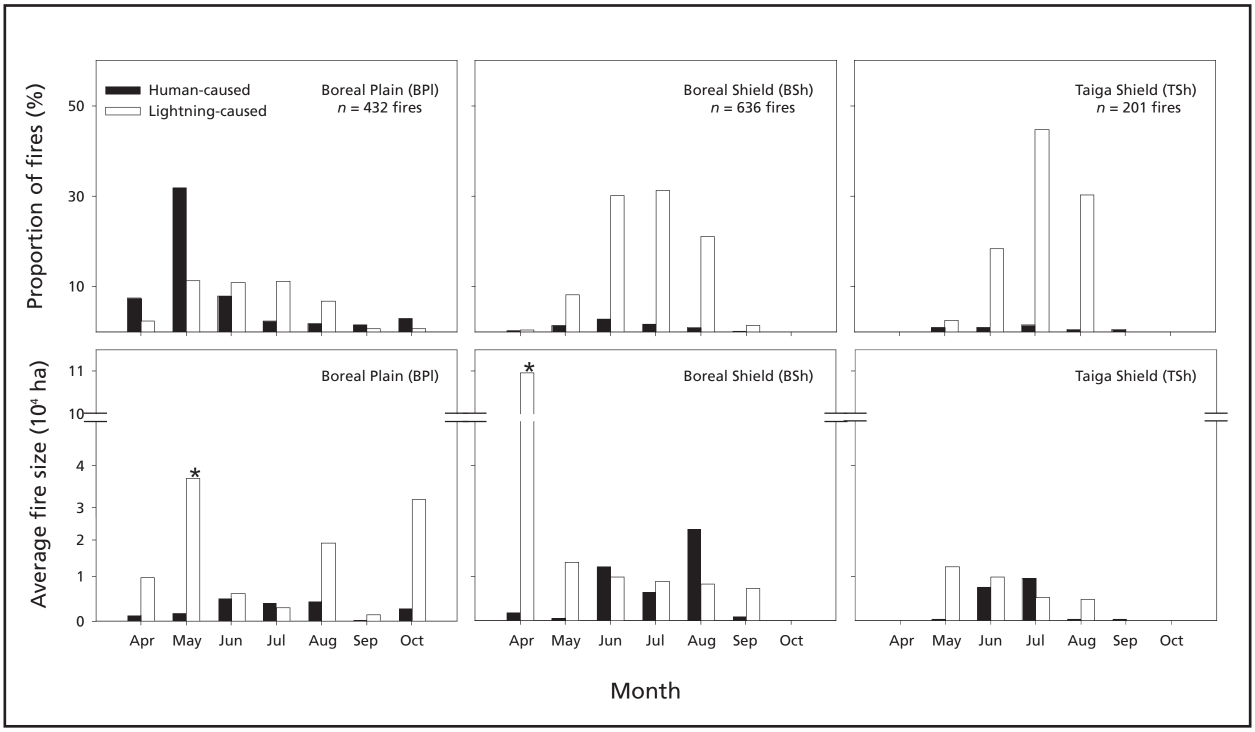


Figure 14. Monthly proportion and average size of fires ≥200 ha, from 1950 to 1998, for human-caused and lightning-caused fires by ecozone. Asterisk indicates unrepresentative average size because only a few fires were used in the calculations.

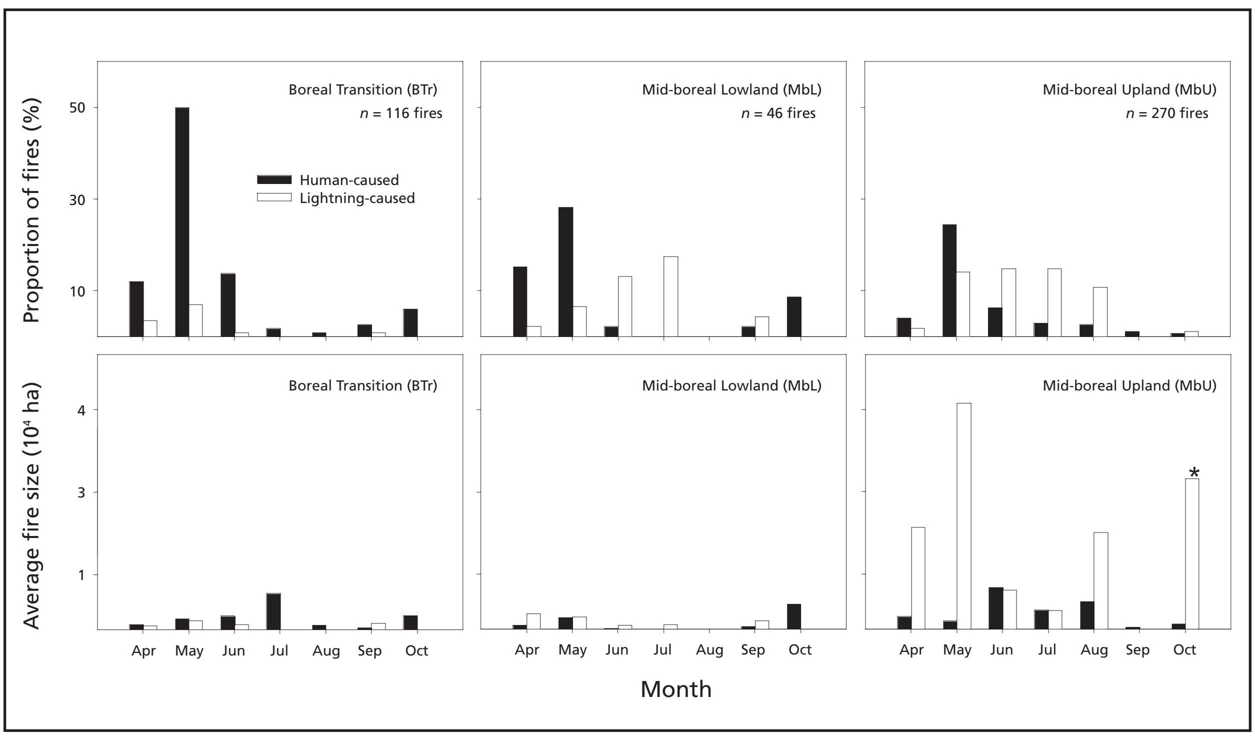


Figure 15. Monthly proportion and average size of fires ≥200 ha, from 1950 to 1998, for human-caused and lightning-caused fires by ecoregion. Asterisk indicates unrepresentative average size because only a few fires were used in the calculations.

Toward the north, the fire season is shorter, which increases the fraction of large fires occurring in June, July, and August (Fig. 14). Unlike the situation in the BSh and TSh ecozones, many large fires in the BPl ecozone are of human origin, most of these occurring in spring. Furthermore, human presence is often associated with fuels that are volatile in the spring, such as grass, which are in turn associated with land suitable for agriculture. Humans are also a major cause of fires igniting in aspen stands before green-up, whereas few lightning-caused fires ignite in these stands (Cumming 2001). The greening effect of aspen and grass (fuel types O1a, O1b), both much more prominent in the south, lead to the belief that even without human influence there would be proportionally more spring fires in the BPl ecozone than in the northern ecozones, but the extent of this trend is impossible to determine.

In the BPl ecozone, lightning-caused spring fires were on average much larger than human-caused fires (Fig. 14). A single lightning storm can cause multiple, almost simultaneous ignitions (up to 30 or even 40); these fires may be in remote areas, in which case they are less likely to be contained by initial-attack crews. Although the difference in average fire size between lightning-caused and human-caused fires was considerable in the spring, particularly in the BPl ecozone, this difference was much reduced in the summer. It could be that summer fires that escape initial attack are simply more difficult to control, perhaps because of the higher frequency of prolonged drought, regardless of fire location. However, although spring fires may be less intense, they can burn through more continuous fuels (i.e., before green-up), which could explain why lightning-caused fires are on average larger in spring than in summer.

Within the ecoregions of the BPl ecozone, human-caused large fires clearly dominated in the BTr ecoregion throughout the fire season, whereas they were mostly concentrated in the spring for the MbL and MbU ecoregions (Fig. 15). Oddly, no large fires were recorded in August in the MbL, but these were infrequent throughout the year in this ecoregion. The disproportionately high average size of May lightning fires in the MbU (41 000 ha) might be analogous to the observations of Wein and Moore (1977, 1979) for New Brunswick and Nova Scotia. They proposed that, although most May fires are small, some burn considerable areas because the rapid drying of the exposed forest floor fuels (i.e., before green-up) promotes rapid spread.

FIRE CLIMATOLOGY

Methods

Percentile Maps

Maps were created for each weather and FWI System variable with the 80th and 95th percentile values from 1990 to 2001. A percentile is a value below which lies that fraction of the data, expressed on a scale of 0 to 100. For example, if the 80th percentile value for temperature is 19ºC, 80% of the days had a temperature of 19ºC or less and 20% of the days were warmer than 19ºC. Percentiles are useful when working with large data sets because they indicate the frequency with which a given value will occur. High percentile values were chosen because of their relevance to forest fires; the mean and lower percentile values are of little significance, as fires usually ignite and spread on the days with the most extreme fire weather conditions.

The weather data sets were separated into two seasons: spring (May) and summer (June to August). Although officially part of the fire season, the fall period was not considered, because large fires seldom occur in Saskatchewan after August. For each season, the percentile values were computed for each weather station with a program written in the C programming language. The percentile maps were produced with the Spatial Fire Management System (sFMS) (Englefield et al. 2000), an ArcView GIS (1999) application that calculates and interpolates the components of the FWI and FBP systems across the landscape from point data (i.e., weather stations). Data were interpolated according to the inverse distance weight method with an exponent of 2 (Flannigan and Wotton 1989). For each grid cell, the interpolation used the six closest stations; however, stations further away have less influence because of the distance-squared weighting scheme. An elevation adjustment was applied to temperature and relative humidity to the interpolated values by the sFMS.

Wind Direction and Dominant Direction of Burning

Because dominant wind direction at noon LST was not always included in the fire weather data set, this variable was determined for a subset of 16 stations selected on the basis of spatial coverage and quality of data. Wind roses (circular plots showing wind direction frequencies) for these stations were produced with the fire climatology module of sFMS and were represented spatially on a map of Saskatchewan. Wind roses were built for the average dominant wind direction (i.e., normal), as well as for days of extreme fire weather conditions, based on 90th percentile FWI values. Intuitively, the latter would be more meaningful from a fire science perspective, as fires are expected to spread more under more severe fire weather conditions.

To determine the dominant burning direction of large fires, the longest possible line inside each fire polygon was fitted, and the bearing of that line was calculated with the Longest Possible Line version 1.3 Avenue script (ESRI 2003). Fire polygons that intersected with ecological unit boundaries were discarded to avoid bias. The bearings were classified in four general directions (N–S, NE–SW, E–W, SE–NW). However, because only the fire polygons are provided, it is impossible to know in which direction the fire actually burned (e.g., a N–S bearing could be a fire that burned from the north or from the south). These results, also represented as wind roses, were visually compared with the climatology results to verify if fires burn more often during conditions of average or severe fire weather.

Rainfall

Detailed patterns of rainfall were assessed using data from the same weather stations as for wind direction. These analyses were not represented spatially because of their high level of detail; however, they could be linked to the weather station map (Fig. 3).

To identify the seasonal distribution of rainfall, the average amount of rain per week from 1990 to 2001 was plotted for the period May to September. Also calculated in these analyses were the seasonal average rainfall values and the average number of days that had ≤0.5 mm of rain, which corresponds to the wetting phase for the FFMC (i.e., FFMC is only affected with rainfall beyond this value). This representation of data allowed depiction not only of total rainfall but also of the timing and, indirectly, the approximate frequency of average rainfall.

Results and Discussion

Wildfires are tightly linked to weather, as well as its long-term trends, which constitute climate. Propagation of individual fires is highly dependent on meteorological conditions, which has prompted the development of weather-based fire danger rating systems throughout the world. Fire weather is of particular concern to fire managers because, unlike vegetation and topography, it varies considerably on a daily basis. On a much larger time scale (decades to millennia), trends in climate are also strongly related to the sum of the fires occurring in an area (i.e., the fire regime) (Clark 1988; Swetnam 1993). Fire climatology can therefore be viewed as the relative likelihood of recurrence of certain fire weather conditions. Of course, fire climatology is useful only when other factors affecting fire regime are considered. However, it also provides a measure of fire danger that is independent of other factors, such as vegetation and human influence, and thus allows speculation on the role of fire weather where all other factors are constant.

The interactions among climate, fire, and vegetation are difficult to untangle. Hogg (1994), for example, stated that at the southern edge of the western boreal forest, conifer regeneration is hindered by moisture limitations. This may promote higher fire frequency, thereby preventing conifers from attaining sexual maturity. In the boreal mixedwood, this moisture deficiency may cause negative feedback, whereby more fires would promote aspen regeneration, thereby leading to a decrease in landscape flammability (Peterson and Peterson 1992; de Groot et al. 2003).

Fire Weather Mapping

Maps are presented for 80th and 95th percentiles of all weather observations, as well as all FWI System components (Figs. 16a to 16h). It is recognized that these maps are subject to several biases, most relating directly to the data (e.g., weather station type, unrepresentative location) and others to the calculation method (e.g., shortcomings of interpolation). However, if interpreted with caution, they are generally useful in presenting spatial patterns at a very coarse resolution (i.e., 100 km^2). Furthermore, because the FWI System components were computed solely from weather observations, these maps can be useful in evaluating potential fire danger independent of human influence, unlike the large fire and fire occurrence data. There is also a large discrepancy in data quality between the southern and northern parts of the forested area: the data for the southern part are fairly reliable, but the data for the northern part are definitely not reliable, as there can be hundreds of kilometers between weather stations (Fig. 4). Therefore, the northern data should be used only to provide a crude estimate of spatial patterns of fire weather.

As in most parts of Canada, Saskatchewan had a generally decreasing gradient in temperature with increasing latitude for the period of analysis (Fig. 16a). There was also a north-south pattern in rainfall (Fig. 16c), with dry conditions in the south (prairie), a maximum near the center of the boreal forest, and a decline further north. There was a generally decreasing northward gradient of fire danger, as exemplified by the FWI (Fig. 16j) and the DSR (Fig. 16k). Although this fire danger gradient was sharp in the spring, it was greatly attenuated or even disappeared in the summer for most fire weather components. The FWI System fuel moisture codes (FFMC, DMC, and DC) (Fig. 16e to Fig. 16g) also exemplified seasonal changes: the spring latitudinal gradient disappeared in the summer and was actually reversed for DMC, although this was mostly due to data from the northernmost station, Uranium City (Fig. 3).

Despite Saskatchewan's relatively flat landscape, elevation has a slight effect on fire danger in the province, in that it affects temperature (Fig. 16a) and relative humidity (Fig. 16b). Relative humidity and wind direction, in particular, may be subject to biases, as many weather stations are adjacent to large lakes (Fig. 3) or are positioned in unrepresentative topography (e.g., ridges, river valleys). As noted earlier, data biases are particularly important in the case of wind speed, as wind values are disproportionately high at the EC stations. The EC stations in the BPl ecozone are responsible for "hot spots" on the wind speed maps, which also account for increases in wind-driven fire behavior indexes, the ISI (Fig. 16i) and the FWI (Fig. 16j). These results are therefore skewed near the weather stations, but this effect is lessened between them, as results are interpolated from the six closest stations. Even though interpolation provides an adequate estimate for most weather observations (Flannigan and Wotton 1989), rainfall is unreliable where stations are sparse because it is highly spatially variable over short distances.

Fire Climatology and Fire Occurrence

How strong is the actual relation between fire occurrence and the FWI System components? Using the same fire occurrence and weather databases as in this study, Anderson and Englefield (2001) used the FWI and FBP system components to evaluate the conditions under which fires are reported in Saskatchewan. They found that fires ignited mostly when values for the FWI System components were high and that the described relations approximated a logistic (i.e., threshold) function. They also found that lightning-caused fires generally occurred under higher DMC and DC values than human-caused fires, which may illustrate the importance of the smoldering stage for the former fire type. Using the US fire danger rating system BEHAVE, Andrews et al. (2003) also found good relations between fire weather and fire occurrence; however, they reported that there might be high regional specificity in terms of the strength of the relation, as well as the main factors driving it.

Fire Climatology and Area Burned

High DMC, DC, and BUI values, often resulting from drought conditions later in the fire season, are associated with combustion of deep organic layers, whereas high FFMC and ISI values usually translate into ease of ignition and faster rates of spread (de Groot 1988). Figure 16 shows apparent east–west gradients for FFMC, DC, BUI, and ISI. Therefore, according to these results, fires would on average be more intense and slow-burning in the western part of Saskatchewan, whereas less-intense, faster-burning fires would occur in the eastern part. These gradients could be due in part to the previously mentioned limitations of the data set but might also result from continental effects. For instance, the Rocky Mountain air mass, which has an important effect

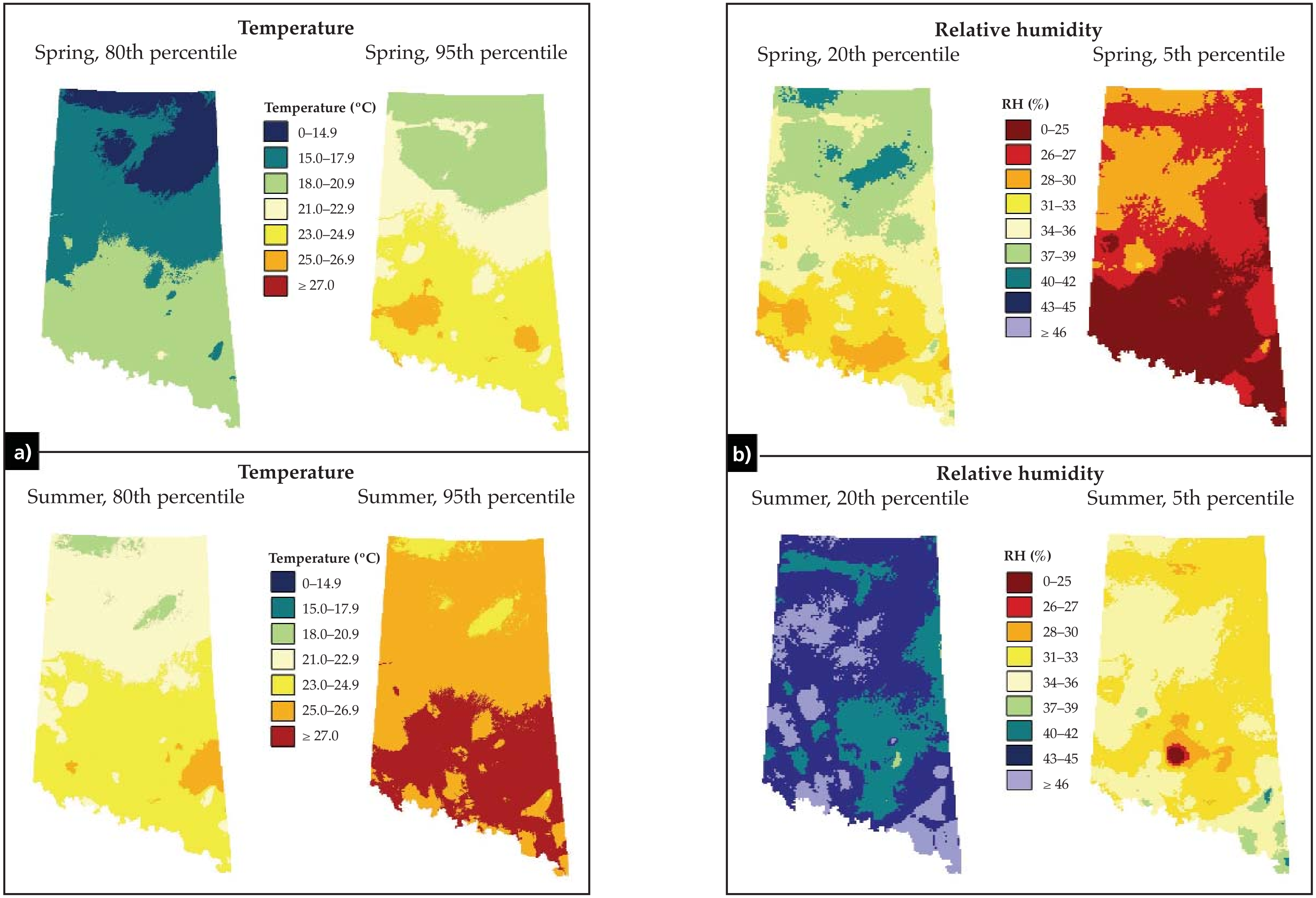
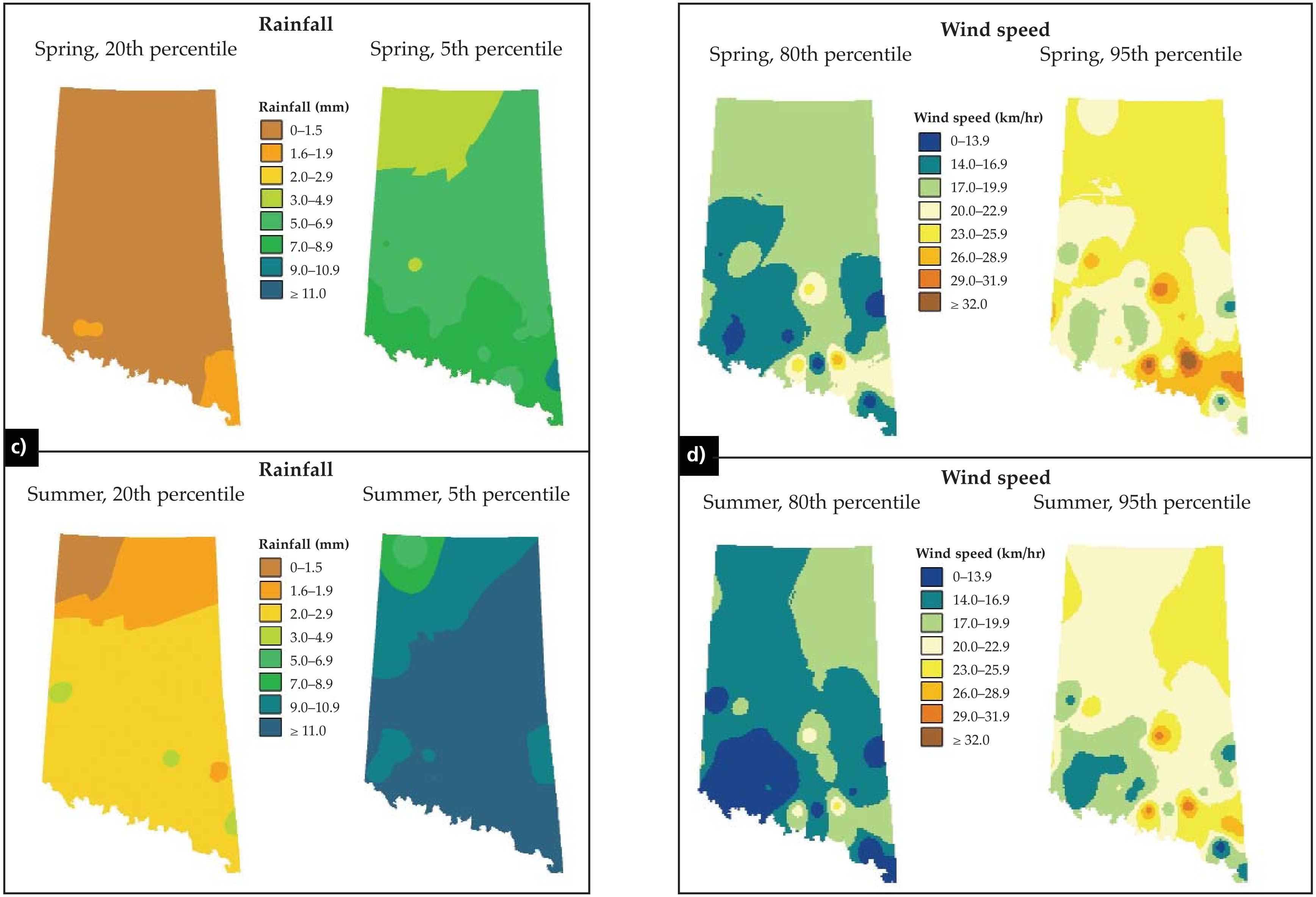


Figure 16. Interpolated 80th and 95th percentile values for noon weather observations and Fire Weather Index System codes and indices for spring and summer, from 1990 to 2001. For relative humidity (RH) and rainfall, the percentiles are reversed, because high values are associated with less extreme fire weather conditions. FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, BUI = Buildup Index, ISI = Initial Spread Index, FWI = Fire Weather Index, DSR = Danger Severity Rating.



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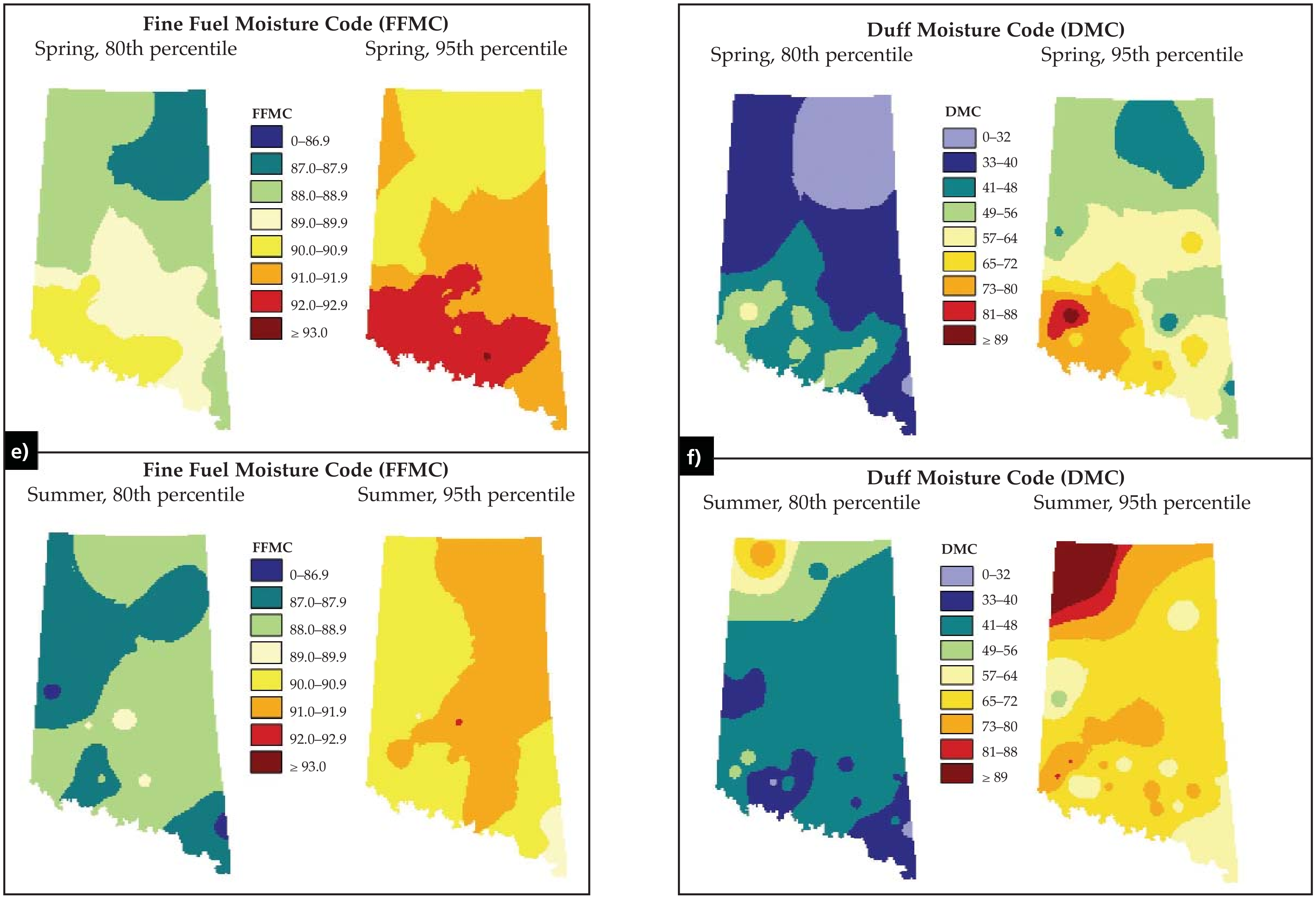

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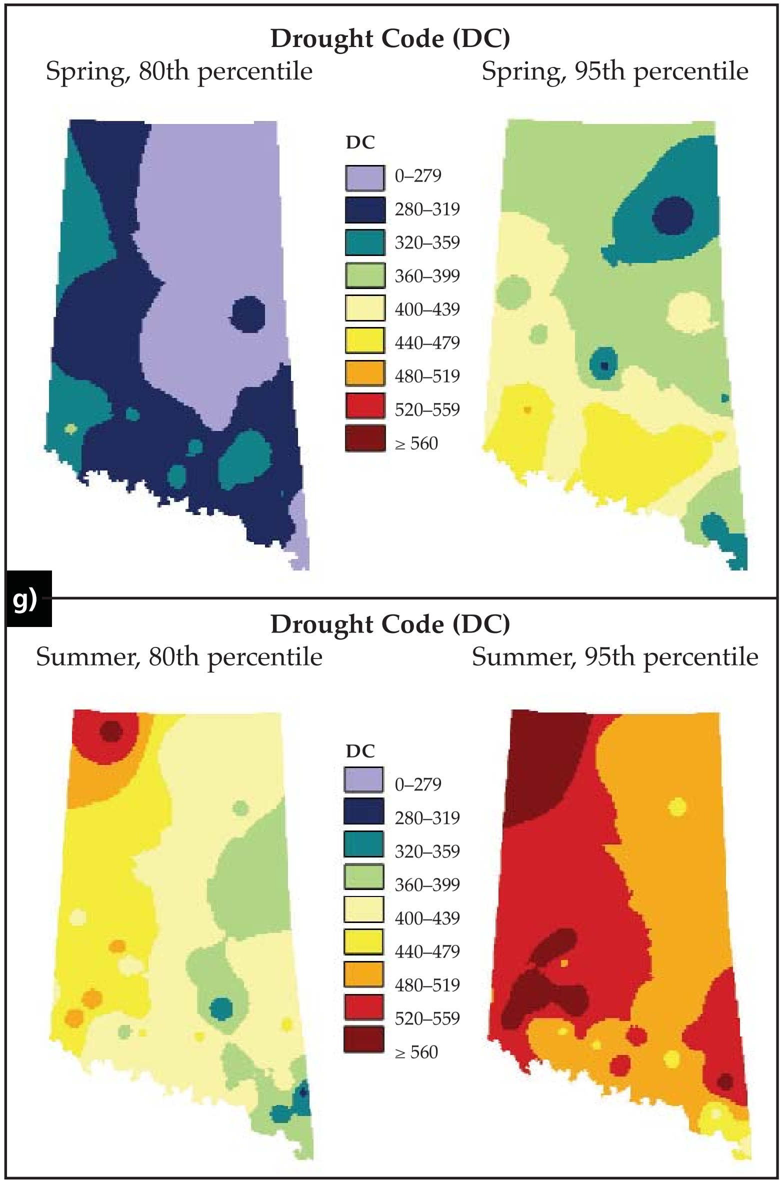

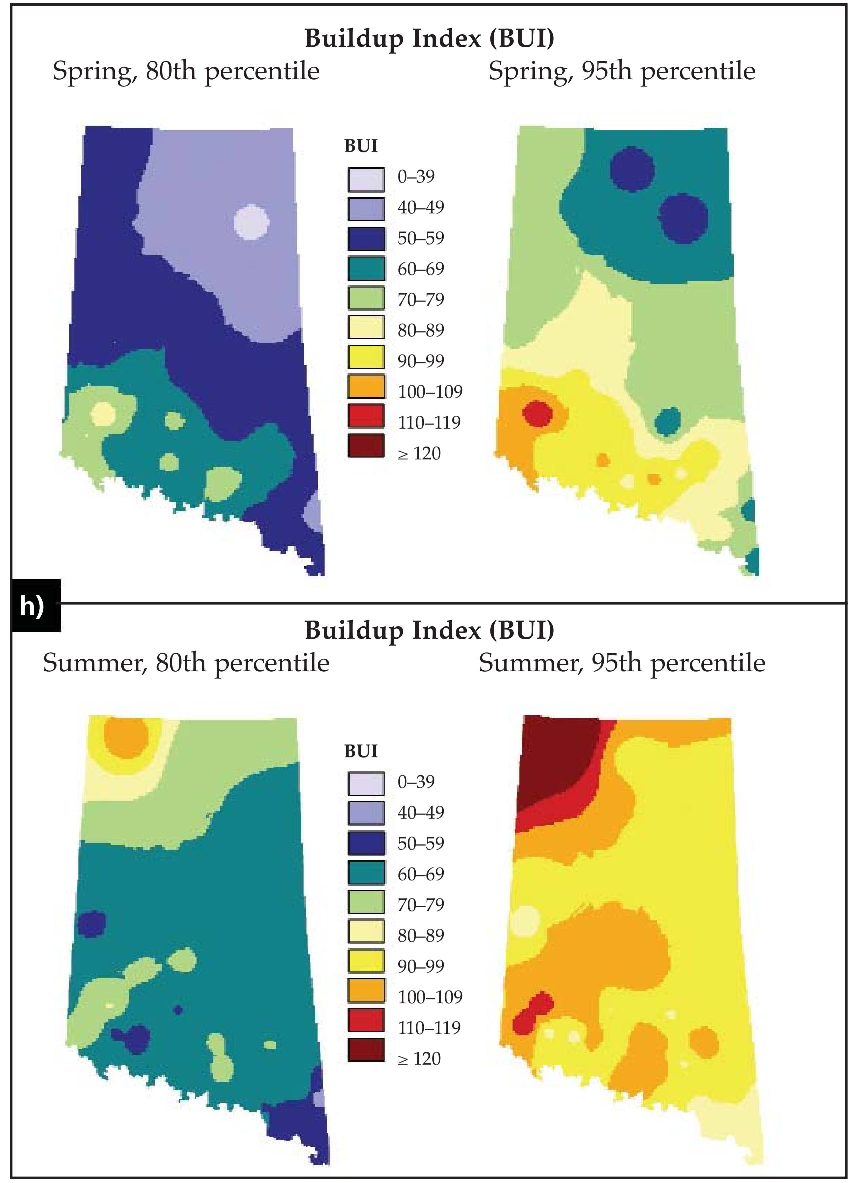

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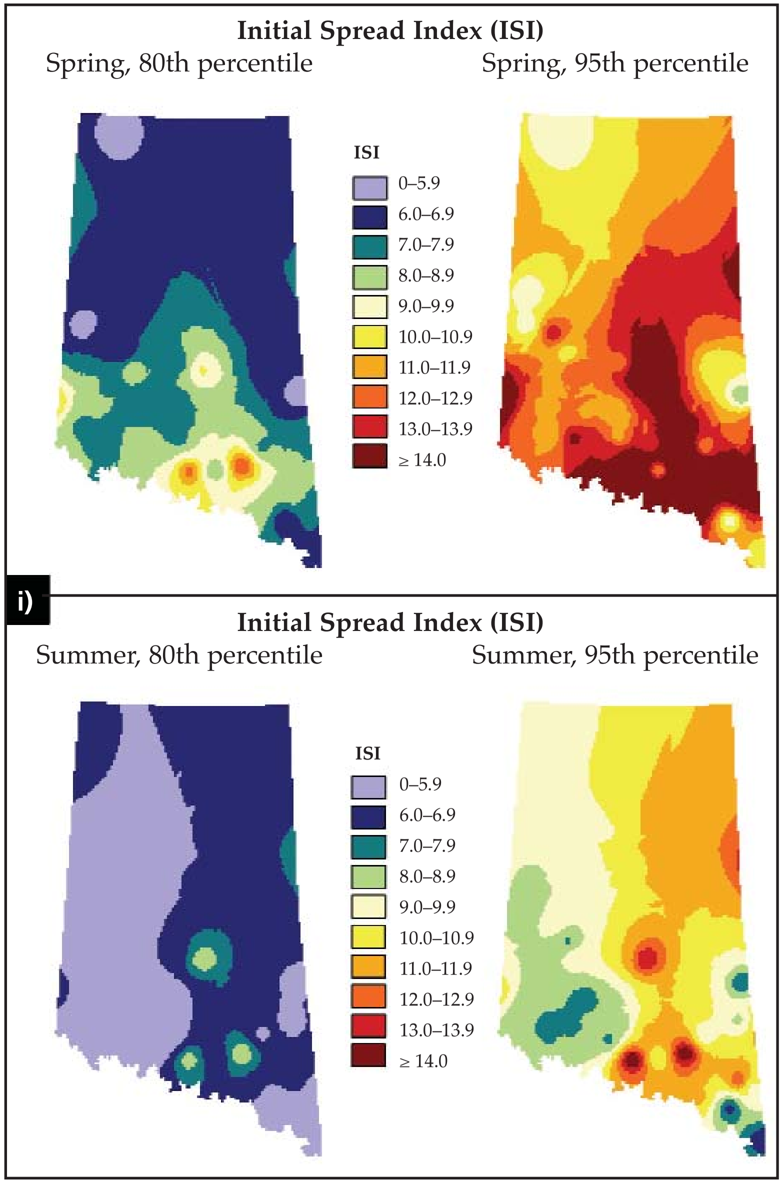

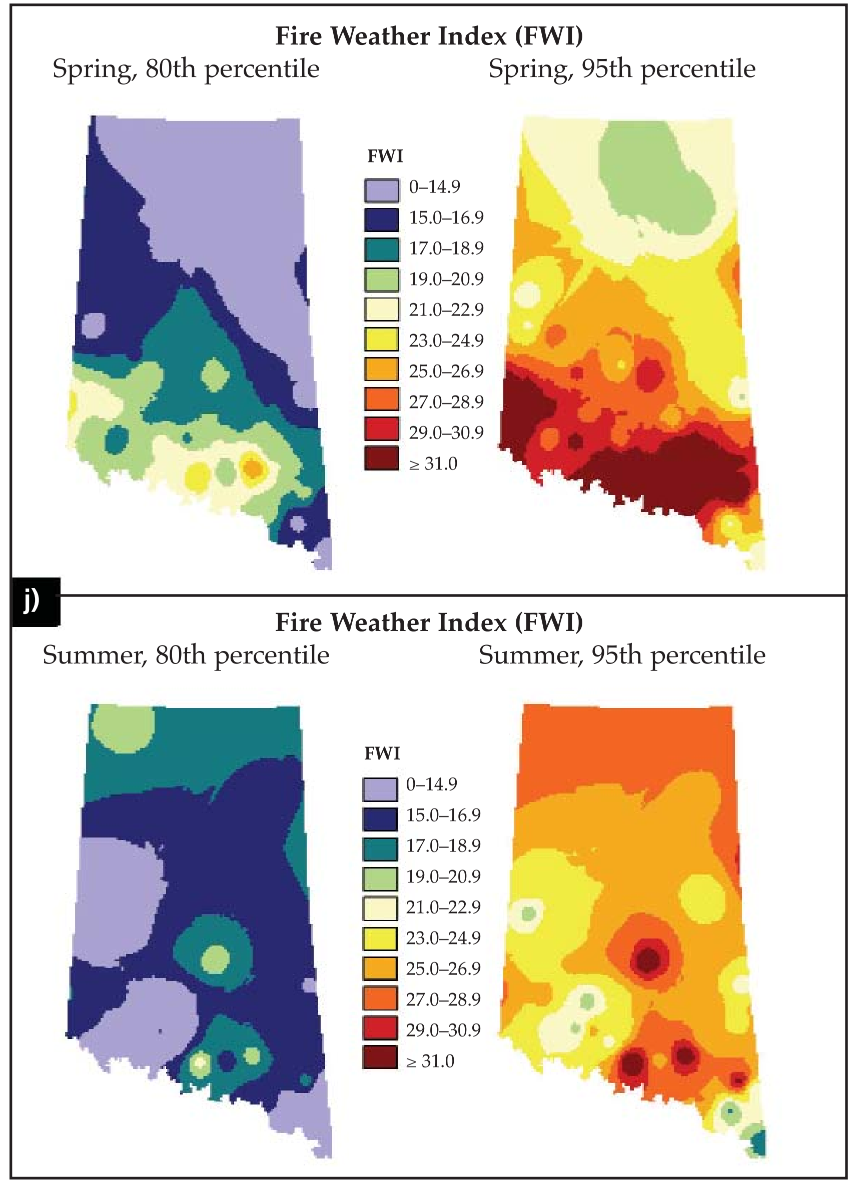

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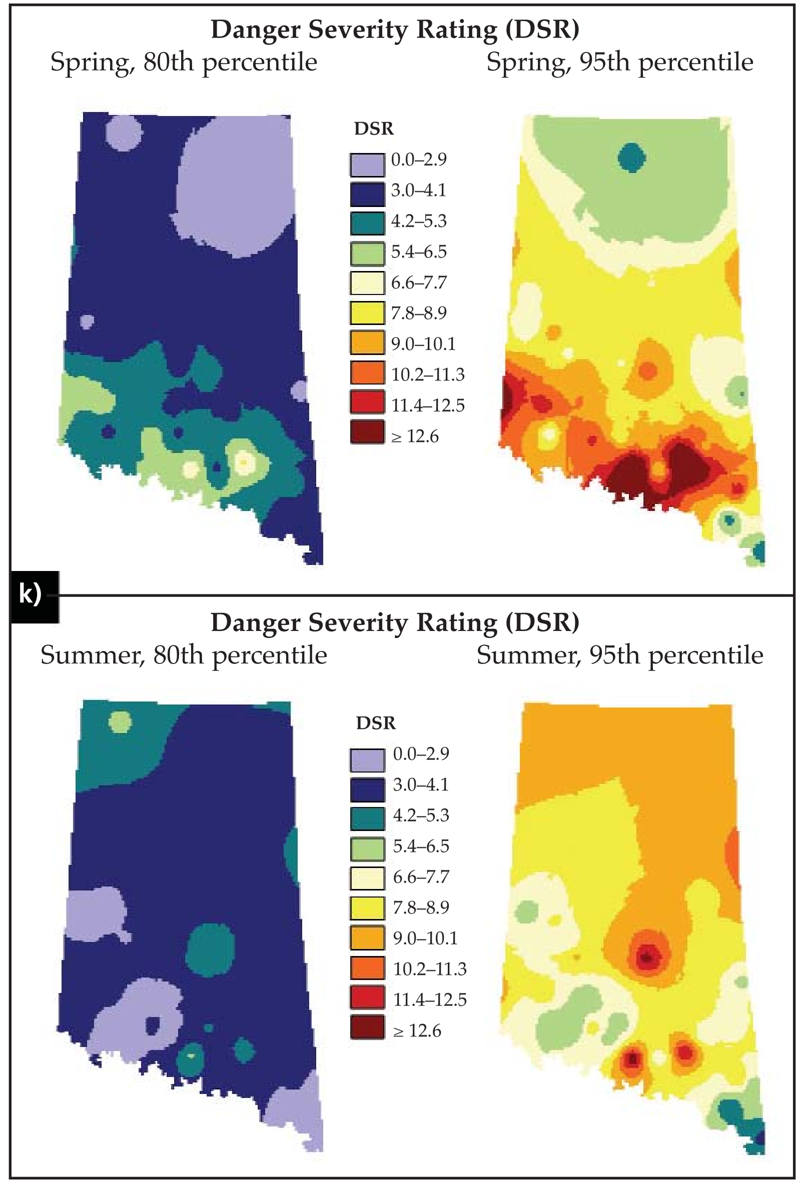

Figure 16. (Concluded)

in southern Saskatchewan, decreases to a minimum in the northeastern corner of the province (Trewartha 1966). The Hudson Bay has an impact during the fire season through moisture input and also has an influence on the storm track, but its overall climatic effect on Saskatchewan is probably marginal (Langley 1972; Mike Flannigan, Canadian Forest Service, July 2002, discussion, personal communication).

FWI System codes and indices generally perform well for describing daily fire danger (Turner 1973; Stocks 1974; Kiil et al. 1977) and also explain much of the variance in area burned per province (Harrington et al. 1983), the best predictors being monthly mean and extreme DMC values, as well as DSR values. Human-caused fires also correlate well with the FWI System moisture codes (Todd and Kourtz 1991). Strong relations have been observed between lightning-caused ignitions and FFMC (Nash and Johnson 1996) and DMC (Flannigan and Wotton 1991; Anderson and Englefield 2001).

Indeed, the trends in overall fire danger in this study, as described by the FWI and the DSR, were consistent with sections of high area burned: large spring fires were confined to the southern part of the province, whereas large fires occurred throughout the province in the summer. Unfortunately, accurate spatial patterns of fire danger could not be depicted in the north because of lack of weather data for this area. Even in the BPl ecozone, where the density of weather stations is high, the maps do not show higher potential fire danger in the MbU ecoregion, where most of the large fires have occurred. These spatial variations in the fire regime are partly due to the different proportions of flammable fuels in the different ecoregions of the BPl ecozone (Table 5). Examining the relative proportion of FBP fuel types provides a quick and easy method of evaluating general fire danger in a given area. The MbU ecoregion is covered by large areas of the most flammable fuel types, Boreal Spruce (C2) and Immature Jack or Lodgepole Pine. The fuel types common in the BTr ecoregion, such as Grass (O1-a, O1-b) and Aspen (D1, D2), may experience many spring fires but will rarely support large fires in the summer, after green-up has occurred. While the MbL ecoregion stands encompass a high proportion of the C2 fuel type, these lie mostly in wet areas and are largely unrepresentative of this fuel type in terms of flammability.

Table 5. Area (% of total) covered by Fire Behavior Prediction (FBP) System fuel types for the Boreal Transition, Mid-boreal Lowland, and Mid-boreal Upland ecoregions[a]

Fuel type	Boreal Transition	Mid-Boreal Lowland	Mid-boreal Upland
C2	4.9	53.3	41.5
C3	2.1	3.8	9.9
C4	0.2	1.1	1.8
D1	18.4	6.3	14.8
S1	0.4	0.5	0.9
O1	63.0	21.8	8.1
M1, M2	8.7	4.0	11.5
Nonfuel	0.3	1.0	2.4

[a]These proportions were obtained from the Saskatchewan Environment FBP System fuel type grid and are not fully representative of current fuel types.

Note: C2 = Boreal Spruce, C3 = Mature Jack or Lodgepole Pine, C4 = Immature Jack or Lodgepole Pine, D1 = Leafless and Green Aspen, S1 = Jack or Lodgepole Pine Splash, O1 = Grass, M1 and M2 = Boreal Mixedwood (Leafless and Green). Values sum to < 100 because of water bodies.

Wind Direction and Dominant Direction of Burning

Wind direction is another important weather variable, as it largely determines the orientation of fire spread and therefore influences the forest mosaic. Although winds vary on a daily basis, a dominant wind direction often prevails. In Saskatchewan, the dominant wind direction changes considerably from one region to another (Fig. 17), although some weather stations are not representative of the region in which they are located. Stations near large lakes, such as Southend, are evidently subject to a lake breeze effect. However, such effects are important from a fire danger perspective, as they can greatly influence the local fire regime (Parisien and Sirois 2003). The winds associated with extreme fire danger conditions, as represented by the 90th percentile FWI, were often highly divergent from the average direction. Winds at the Collins Bay station, for example, blew most frequently from the northeast in the spring. However, under extreme fire danger conditions the most dominant direction was, by far, the south. The winds occurring on those days were also much stronger than average, because wind speed is highly correlated with the drying of fuels and hence with fire danger.

In Alberta, wind gusts, which are presumably responsible for many large fire runs, usually have a strong westerly and northwesterly component (Flesch and Wilson 1993), but this variable could not be assessed for Saskatchewan. The general direction of burning reveals distinct patterns among ecozones and ecoregions (Fig. 18), although the sample size was insufficient for the latter. While the dominant spread directions in the BPl ecozone were clearly N–S and SE–NW, the pattern was almost opposite in the northern ecozones, where the NE–SW direction prevailed. NE–SW fires in the BPl ecozone were on average longer (19.6 km) than the N–S (16.8 km), E–W (17.9 km), and SE–NW (15.9 km) directions. This pattern was not observed in the other ecozones, but the shortest fire distance did correspond to the lowest frequency of direction for all ecozones. This direction–distance relation could be due to the fact that strong winds driving fire spread ahead of a cold front suddenly shift perpendicularly on passage of the front, whereupon the flank of the fire becomes the front.

Seasonal Patterns of Rainfall

Large fire years are generally related to decreases in average rainfall, as observed by Stocks and Walker (1973), who studied the seasonal fire weather for four catastrophic fires occurring in different years in Ontario. Using 48 years of data, Flannigan and Harrington (1988) found that area burned in Canada was significantly related to rainfall frequency but not to rainfall amount. Other studies have demonstrated that the occurrence and behavior of large fires are largely influenced by seasonal patterns of rainfall and drought (Stocks 1974; Lawson 2002), and Carcaillet and Richard (2000) found that this was true throughout the Holocene. The seasonality of precipitation makes it possible for fires to burn in wet years, as reported by Rollins et al. (2001) for New Mexico, where the largest and third-largest fires of the 20th century occurred in two of the wettest years of the century.

Given the level of detail, the seasonal patterns of rainfall throughout the study area (Fig. 19) can provide further insight into spatial variations in the fire regime. These analyses revealed that the three northernmost weather stations, Uranium City, Fort Chipewyan, and Stony Rapids, were among the four stations that recorded the least precipitation. These stations generally had drier springs; for example, Uranium City had on average less than half of the spring rainfall of most other stations. Although the total precipitation did not vary much overall, somewhat contrasting temporal patterns of rainfall were observed throughout the province. Some stations, such as Buffalo Hills, Little Bear Lake, and Prince Albert, recorded considerably wetter first halves of the fire season, whereas the opposite was observed for other stations, concentrated in the northern half of the study area (e.g., Stony Rapids, Collins Bay, Key Lake). No trends were observed in the number of days without rain (Fig. 19); it is then presumably the timing of weekly rainfall amounts, which also approximates rainfall frequency, that has the strongest effect on spatial variations in the fire regime. Perhaps an analysis of the consecutive number of days without rain would have provided a more complete picture but, unfortunately, this could not be easily carried out for this study.

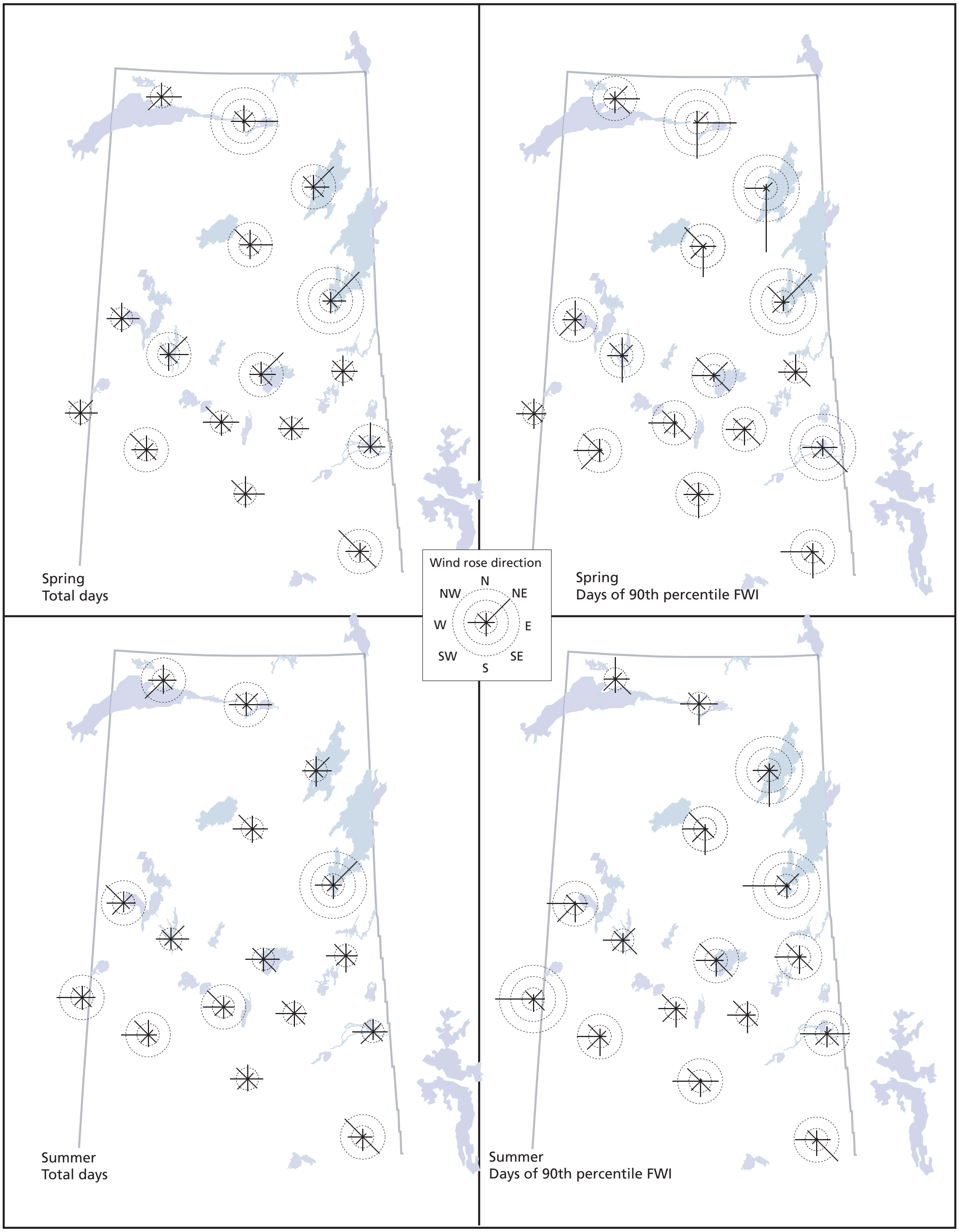

Figure 17. Frequency of occurrence of wind directions for a subset of 16 weather stations. The length of the bars represents the frequency (%), whereas the concentric rings represent 10% increments in frequency. Gray areas represent large lakes.

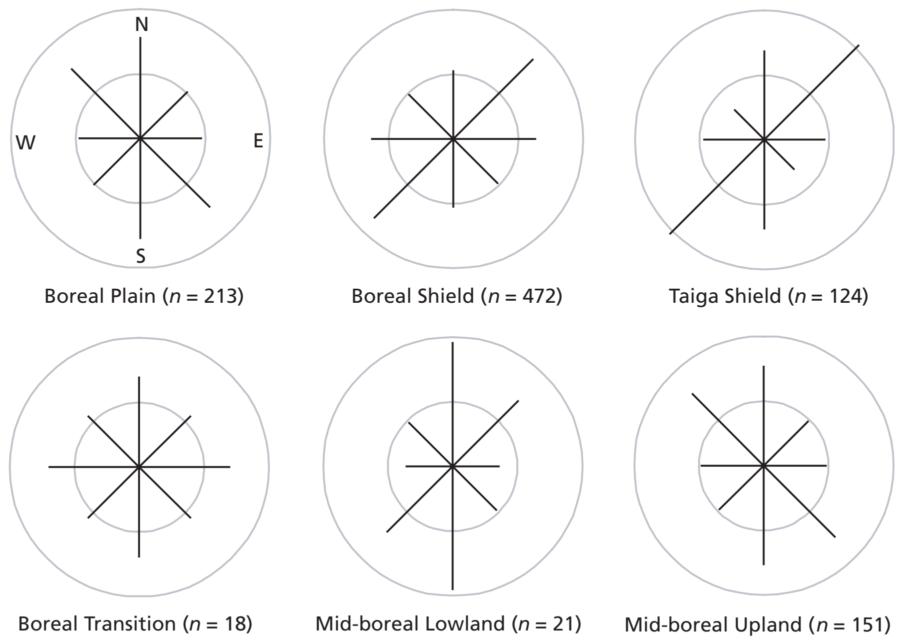

Figure 18. The dominant direction of fire spread for fires ≥200 ha contained entirely within the boundaries of the six ecological units, from 1945 to 2000. The concentric rings represent 10% increments in frequency. Diametric lines are of equal length because it is impossible to determine from which side the fire was burning on the basis of the polygon data.

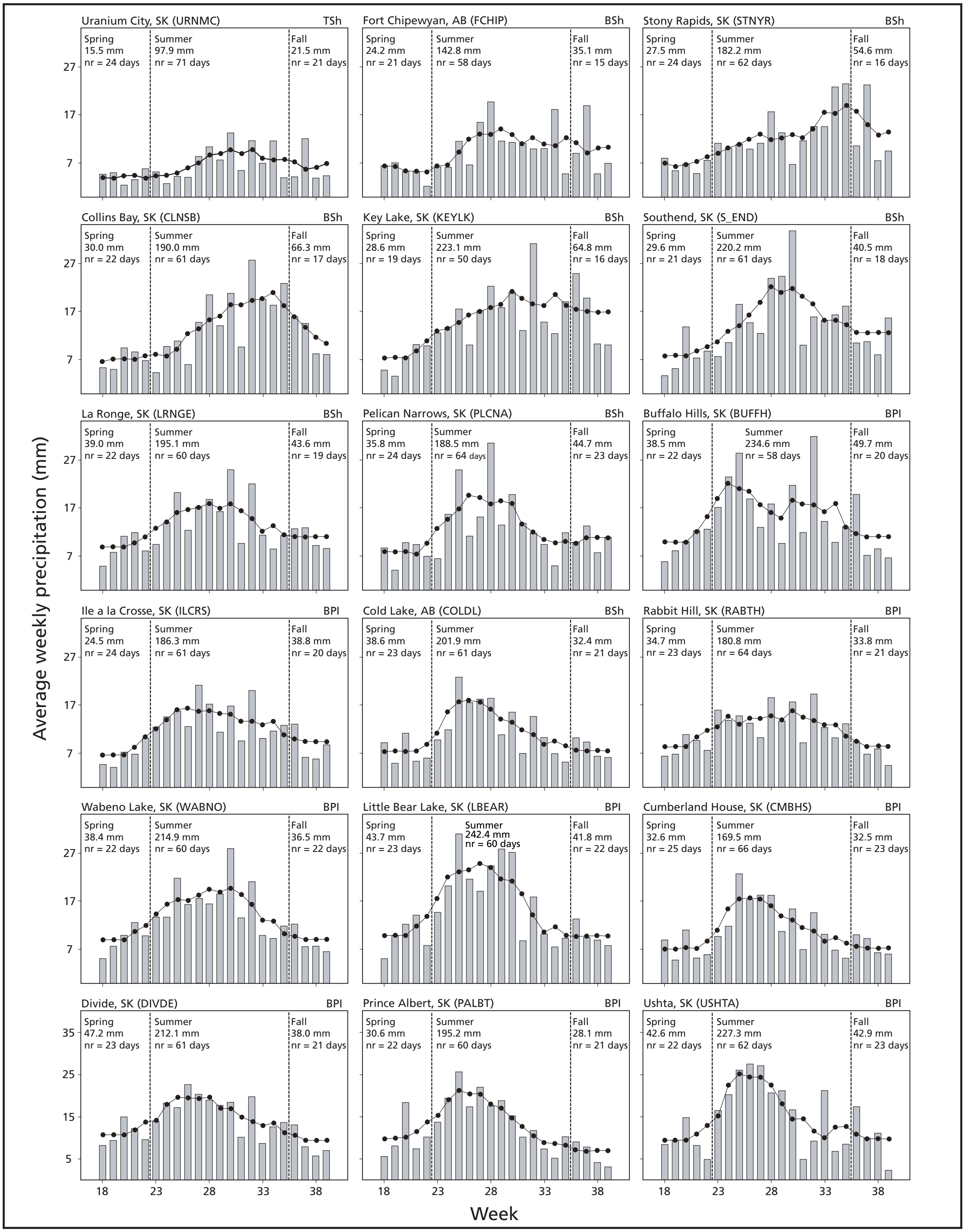

Figure 19. Average precipitation per week from May to September for a subset of weather stations of the Taiga Shield (TSh), Boreal Shield (BSh), and Boreal Plain (BPl) ecozones (1990–2001). nr = average number of days in a season where rain ≤0.5 mm. The connected black circles represent a moving average based on the average of each value with the neighboring value on each side.

Methods

Maps of head fire intensity (HFI), in kilowatts per meter were produced to spatially assess potential fire behavior. HFI is a primary component of the FBP System (Forestry Canada Fire Danger Group 1992), which provides quantitative measures of fire behavior for 17 fuel types. Weather, fuels, and topography data are required for calculation of its components. Although the FBP System provides many other measures of fire behavior, such as rate of spread and crown fraction burned, HFI is the most comprehensive, as it can be linked to fire behavior characteristics (Alexander et al. 1991; Stocks and Hartley 1995; Hirsch 1996), effectiveness of fire suppression (Hirsch et al. 1998), and fire effects (e.g., Stocks 1987, 1989; Arseneault 2001). To a certain degree, HFI can also be related to fire severity, both in terms of duff consumption and crown fraction burned, because total fuel consumption is a required input for calculation of fire intensity (described by Byram [1959]).

HFI maps from a previous Saskatchewan study (Kafka, V.; Parisien, M.A.; Hirsch, K.G.; Flannigan, M.D.; Todd, J.B. 2001. Climate change in the prairie provinces: assessing landscape fire behavior potential and evaluating fuel treatment as an adaptive strategy. Prairie Adaptation Research Cooperative. Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. Rep.) were used for the present study. The earlier maps were prepared with sFMS but only for the commercial forest area of the province, as that was the only area with reliable fuels data at the time of analysis. The method of percentile calculation for these maps differed from the method used to produce the weather and FWI System maps for the present study. For the latter maps, percentiles were calculated for the individual components, a method known as individual percentile calculations. The HFI requires three weather-based components for its calculation: wind speed, FFMC, and BUI, which must be considered jointly in the percentile calculation. Thus, individual percentiles for these components cannot be used to determine a given percentile value of HFI. For example, at the Hudson Bay weather station from 1990 to 2001, the 80th percentile values for wind speed, FFMC, and BUI were 22, 88, and 64.4 km/h, respectively. However, these conditions were equaled or exceeded on the same day (joint probability) only 0.02% of the time in the current data set for the same period. When considered jointly, therefore, these components actually represent the 99.98th percentile. To circumvent this problem, a joint percentile method was developed (Kafka, V.; Parisien, M.A.; Hirsch, K.G.; Flannigan, M.D.; Todd, J.B. 2001. Climate change in the prairie provinces: assessing landscape fire behavior potential and evaluating fuel treatment as an adaptive strategy. Prairie Adaptation Research Cooperative. Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. Rep.), whereby all days were ranked according to their FWI values. Then, the days for specific percentiles (80th and 95th) were selected from the FWI values, and the wind speed, FFMC, and BUI of the selected days were used. For example, the 80th percentile FWI of the Hudson Bay station for the entire fire season from 1990 to 2001 was 17.1. For that day, the wind speed, FFMC, and BUI values were 19, 87.8, and 40.6, respectively. A true 80th percentile for HFI could then be calculated from these three values.

Results and Discussion

The integration of fuels and topography data allowed the HFI maps for the 80th and 95th percentile conditions (Fig. 20) to depict higher-resolution patterns of potential fire behavior than the weather and FWI System maps (Fig. 16). In areas where the weather conditions were similar and the changes in topography minimal, variation in fire behavior patterns was largely a function of fuels. In fact, the most extreme areas of fire behavior potential corresponded largely to the large expanses of C2 fuels in both percentile conditions. Given their high HFI values, these areas are expected to pose a problem to fire suppression at least 5% of the time (95th percentile). In addition, in the spring and summer, 38% and 23% of the study area, respectively, can be expected to experience fires burning in conditions far beyond any possible direct attack (HFI > 30 000 kW/m).

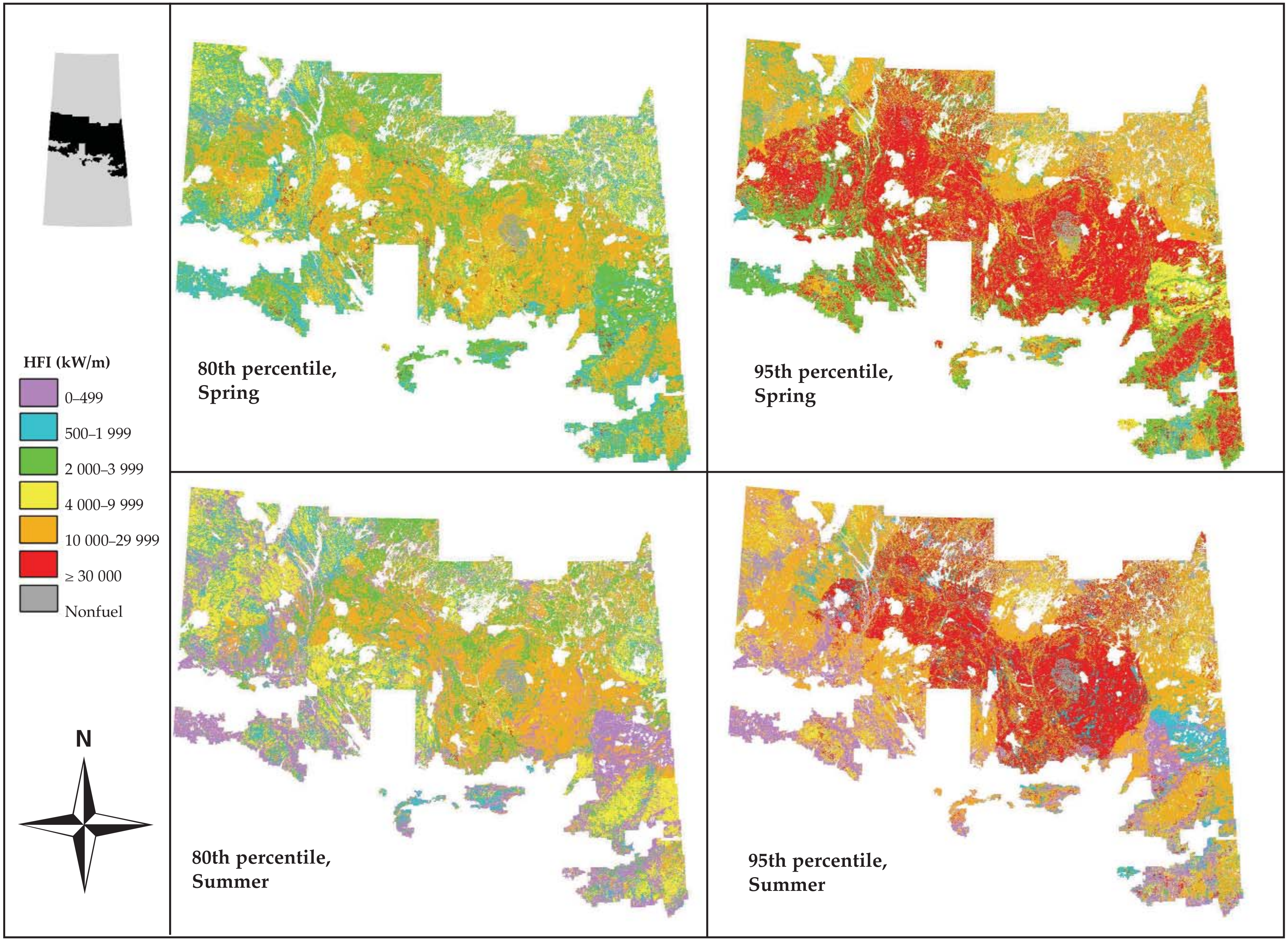

Figure 20. Head fire intensity (HFI) for the 80th and 95th percentiles for spring and summer, from 1990 to 1999 (from Kafka, V.G.; Parisien, M.A.; Hirsch, K.G.; Flannigan, M.D.; Todd, J.B. 2001. Climate change in the prairie provinces: assessing landscape fire behavior potential and evaluating fuel treatment as an adaptive strategy. Prairie Adaptation Research Cooperative. Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. Rep).

Kafka et al. (Kafka, V.; Parisien, M.A.; Hirsch, K.G.; Flannigan, M.D.; Todd, J.B. 2001. Climate change in the prairie provinces: assessing landscape fire behavior potential and evaluating fuel treatment as an adaptive strategy. Prairie Adaptation Research Cooperative. Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. Rep.) claimed that, from a fire-suppression perspective, it is perhaps more appropriate to look at the relative change from one set of percentile conditions to the next. Large fires occurring in Boreal Spruce (C2) fuel type, for example, would exhibit extreme fire behavior (e.g., HFI > 10 000 kW/m) for both the 80th and 95th percentile conditions, whereas the Mature Jack or Lodgepole Pine (C3) fuel type would attain extreme fire behavior potential only under 95th percentile conditions. In other words, the C2 fuel type is a problem for fire suppression at least 15% of the time, whereas the C3 fuel type will start exceeding suppression capabilities only during the most extreme fire danger conditions.

The green-up of deciduous species and the regrowth of grass cover caused regions with high proportions of Aspen (D1 and D2) and Grass (O1) fuel types to experience a marked decrease in potential HFI from spring to summer. A decrease in HFI in the more flammable fuel types was also observed as the fire season progressed, largely because of decreased wind speeds in some regions (Kafka, V.; Parisien, M.A.; Hirsch, K.G.; Flannigan, M.D.; Todd, J.B. 2001. Climate change in the prairie provinces: assessing landscape fire behavior potential and evaluating fuel treatment as an adaptive strategy. Prairie Adaptation Research Cooperative. Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. Rep.). However, the HFI maps are also subject to inaccuracies, as they use weather data and FWI System components as inputs. Admittedly, some uncertainty looms over the absolute values of HFI, but the methods used were consistent and therefore comparison between percentiles, seasons, and different regions is possible. A method that considerably reduces the inaccuracies of the HFI calculations, the daily method, is described in Kafka et al. (2000). That method could not be used here because it was too computationally intensive.

KNOWLEDGE GAPS AND FUTURE RESEARCH

This section briefly outlines the potential needs for research related to large-scale fire regime analyses. These needs stem from the data analysis and interpretation of the results and are intended only as suggestions.

Although the constraints related to data collection are accepted, the foremost and most obvious suggestion to stimulate and improve future fire regime studies is to increase and enhance the quality of fire data sets. Given that they are more reliable, longer data sets would enable better analysis and, more important, would decrease the uncertainty (error) of the analyses. The establishment of more weather stations in Saskatchewan, for example, would provide much more reliable maps of fire weather, for both daily tactical planning and the fire climatology analyses used in long-term planning.

A specific area of concern in terms of data quality pertains to the lightning data. Despite some studies relating lighting strikes to fire occurrence (e.g., Flannigan and Wotton 1991; Wierzchowski et al. 2002), many aspects of the relation between lighting and forest fires remain largely undocumented for the boreal forest, as outlined by Podur et al. (2002). Further research might examine the spatial correspondence of lightning and fires as a function of the timing of fire weather events (e.g., drought) or the effect of positive and negative strikes or LCC strikes. Furthermore, more accurate lightning data could allow better evaluation of the effect of factors such as vegetation and topography on lightning ignitions, which would in turn help to improve existing lightning-caused fire occurrence prediction models (Kourtz and Todd 1991; Anderson 2002).

Combining fire weather data and forest fire data also holds enormous promise in understanding the factors that drive fire occurrence and, just as important, fire spread. Some studies have documented the conditions under which fires are reported (Meisner 1993;

Anderson and Englefield 2001; Andrews et al. 2003), but to the authors' knowledge none have thoroughly examined fire weather during days of high fire propagation. In parallel, an analysis of drought events could verify what conditions are responsible for bad fire seasons.

However important it is to know when fires ignite and burn, it is also crucial to assess what they burn. This latter topic has been partly addressed by the fire behavior observations used to create the CFFDRS (Van Wagner 1987; Forestry Canada Fire Danger Group 1992) and, more recently, by the work of Cumming (2001) in the western boreal forest of Canada. However, a more detailed analysis could help to determine the long-term effects of vegetation and topographic factors on area burned over the long term. Similarly, it would be interesting to assess the interactions between fires and other disturbances, such as insect outbreaks, as these are generally poorly understood in the boreal forest, despite some recent attention (e.g., Fleming et al. 2002; Bebi et al. 2003).

Finally, to optimize large-scale fire regime analyses, it has become clear that the effect of spatial scale on the different fire regime components (e.g., fire occurrence, area burned, season) should be evaluated. The use of spatial statistical techniques for detailed analysis of individual fire metrics, as well as landscape-level metrics (e.g., clustering, connectivity), would provide valuable insight in identifying an optimal scale of analysis.

CONCLUSIONS

This study has attempted to provide a detailed large-scale assessment of the fire regime of Saskatchewan. Despite data biases that cannot be ignored, the methods were sound and the analyses conservative enough for the results to be safely interpreted and grounds to be laid for further fire regime studies. In addition, these results might be useful for the physical or ecological modeling of fire or as part of succession modeling.

How landscape fire statistics vary among areas, as well as within an area, is of prime concern to forest managers. From a sustainable management viewpoint, these spatial variations in the fire regime must be considered in management strategies, as forests differ considerably under different fire cycles (Bergeron and Dansereau 1993; Larsen and MacDonald 1998; Parisien and Sirois 2003). Furthermore, despite increased fire suppression efforts, some regions are inherently at greater risk of large fires than others. In Saskatchewan, these regions of high risk are mostly concentrated in parts of the Precambrian Shield ecozones. If the commercial forest limit is extended into the BSh ecozone as projected, forest and fire managers should expect a high likelihood of very large fires. In addition, fires in this area could potentially occur under different conditions and might exhibit different fire behavior than the ones occurring to the south, in the BPl ecozone.

Results from this study provide pertinent fire information and increase understanding of broad-scale fire regimes. Although fire specialists have by far the most in-depth knowledge of the fire regime in their own work locations, this study can be used to compare one region with another. At the provincial scale, the information presented here can also help fire managers in their decisions to build infrastructure, such as bases and lookout towers. Perhaps the most useful tool is the combination of fire climatology and fire behavior potential (HFI) maps. These types of maps complement one another nicely: the climatology maps evaluate coarse patterns of fire behavior characteristics independent of land use, human intervention, and vegetation, whereas the HFI maps are largely fuel-driven and more useful at a local scale. At any rate, the analyses presented in this report must be considered jointly to obtain the clearest picture of the fire regime; no single analysis encompasses all components of the fire regime.

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LITERATURE CITED

Alexander, M.E. 1982. Calculating spring Drought Code starting values in the Prairie provinces and Northwest Territories. Environ. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. For. Manage. Note 12.

Alexander, M.E.; Stocks, B.J.; Lawson, B.D. 1991. Fire behavior in black spruce-lichen woodland: the Porter Lake project. Can. For. Serv., North. For. Cent., Edmonton, AB. Inf. Rep. NOR-X-310.

Anderson, K.R. 1999. Predicting convective rainfall amounts from lightning flash density. Pages 116-168 *in* Proceedings of the 20th Conference on Severe Local Storms, Orlando, Florida, 11–15 September 1999. Am. Meteorol. Soc., Boston, MA.

Anderson, K.R. 2000. Incorporating smoldering into fire growth modelling. Pages 31-36 *in* Proceedings of the 3rd Symposium on Fire and Forest Meteorology, Long Beach, California, 10–12 January 2000. Am. Meteorol. Soc., Boston, MA.

Anderson, K.R. 2002. A model to predict lightning-caused fire occurrences. Int. J. Wildland Fire 11:163–172.

Anderson, K.R.; Englefield, P. 2001. Quantile characteristics of forest fires in Saskatchewan. Pages 9-16 *in* Proceedings of the 4th Symposium on Fire and Forest Meteorology, Reno, Nevada, 13–15 November 2001. Am. Meteorol. Soc., Boston, MA.

Andison, D.W. 2003. Disturbance events on foothills and mountain landscapes of Alberta. Part I. Bandaloop Landscape-Ecosystem Services, Belcarra, BC. Alberta Foothills Disturbance Ecology Research Series, Rep. 5.

Andrews, P.L.; Loftsgaarden, D.O.; Bradshaw, L.S. 2003. Evaluation of fire danger rating indexes using logistic regression and percentile analysis. Int. J. Wildland Fire 12:213–226.

ArcView GIS. 1999. ArcView GIS version 3.2. Environmental Systems Research Institute. Redlands, CA.

Armstrong, G.W. 1999. A stochastic characterisation of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. Can. J. For. Res. 29:424–433.

Arseneault, D. 2001. Impact of fire behavior on postfire forest development in a homogeneous boreal landscape. Can. J. For. Res. 31:1367–1374.

Baker, W.L. 1989a. Effect of scale and spatial heterogeneity on fire interval distributions. Can. J. For. Res. 19:700–706.

Baker, W.L. 1989b. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. Ecology 7:181–194.

Bebi, P.; Kulakowski, D.; Veblen, T.T. 2003. Interactions between fire and spruce beetles in a subalpine Rocky Mountain forest landscape. Ecology 84:362–371.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72:1980–1992.

Bergeron, Y.; Dansereau, P.-R. 1993. Predicting the composition of Canadian southern boreal forest in different fire cycles. J. Veg. Sci. 4:827–832.

Bergeron, Y.; Harvey, B.; Leduc, A.; Gauthier, S. 1999. Forest management guidelines based on natural disturbance dynamics: stand- and forest-level considerations. For. Chron. 75:49–54.

Bergeron, Y.; Leduc, A.; Harvey, B.D.; Gauthier, S. 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fenn. 36:81–95.

Bessie, W.C.; Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76:747–762.

Bonsal, B.R.; Lawford, R.G. 1999. Teleconnections between El Niño and La Niña events and summer extended dry spells on the Canadian Prairies. Int. J. Climatol. 19:1445–1458.

Bothwell, P.M.; de Groot, W.J.; Dubé, D.E.; Chowns, T.; Carlsson, D.H.; Stefner, C.N. 2004. Fire regimes in Nahanni National Park and the Mackenzie Bison Sanctuary, Northwest Territories, Canada. *In* R.T. Engstrom and W.J. de Groot, eds. Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Kananaskis, Alberta, 15–18 October 2001.Fire in temperate, boreal and montane ecosystems. Tall Timbers Research Station, Tallahassee, FL. In press.

Boychuk, D.; Martell, D.L. 1996. A multistage stochastic programming model for sustainable forest-level timber supply under risk of fire. For. Sci. 42:10–26.

Byram, G.M. 1959. Combustion of forest fuels. Pages 61–89 *in* K.P. Davis, ed. Forest fire: control and use. McGraw-Hill Book Co., New York, NY.

(CIFFC) Canadian Interagency Forest Fire Centre. 2000. The glossary of forest fire management terms.Winnipeg, MB.

Canadian Standards Association. 1996. A sustainable forest management system: guidance document. CSA Standard CAN/CSA-Z809–96: environmental technology: a national standard. Etobicoke, ON.

Carcaillet, C.; Richard, P.J.H. 2000. Holocene changes in seasonal precipitation highlighted by fire incidence in eastern Canada. Clim. Dynam. 16:549–559.

Cissel, J.H.; Swanson, F.J.; Weisberg, P.J. 1999. Landscape management using historical fire regimes: Blue River, Oregon. Ecol. Appl. 9:1217–1231.

Clark, J.S. 1988. Effect of climate change on fire regimes in northwestern Minnesota. Nature 334:233–235.

Cressie, N.A.C. 1993. Statistics for spatial data. Wiley, New York, NY.

Cumming, S.G. 2001. Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? Ecol. Appl. 11:97–110.

De Groot, W.J. 1988. Interpreting the Canadian Forest Fire Weather Index (FWI) System. Pages 3–14 in K.G. Hirsch, ed. Proceedings of the 4th Central Region Fire Weather Committee Scientific and Technical Seminar, Winnipeg, Manitoba, 4 April 1987. Can. For. Serv., Edmonton, AB. Study NOR-36-03-1, File Rep. 3.

De Groot, W.J.; Bothwell, P.M.; Carlsson, D.H.; Logan, K. 2003. Simulating the effects of future fire regimes on western Canadian boreal forests. J. Veg. Sci. 14:355–364.

Donnegan, J.A.; Veblen, T.T.; Sibold, J.S. 2001. Climatic and human influences on fire history in Pike National Forest, central Colorado. Can. J. For. Res. 31:1526–1539.

Eberhart, K.E.; Woodard, P.M. 1987. Distribution of residual vegetation associated with large fires in Alberta. Can. J. For. Res. 17:1207–1212.

Engelmark, O. 1987. Fire history correlations to forest type and topography in northern Sweden. Ann. Bot. Fenn. 24:317–324.

Englefield, P.; Lee, B.S.; Suddaby, R.M. 2000. Spatial Fire Management System. *In* Proceedings of the 20th International ESRI User Conference, San Diego, California, 26–30 June 2000. Environmental Systems Research Institute, San Diego, CA. Paper No. 489.

Environment Canada. 1986. The 1961–1990 Canadian climate normals atlas. Environ. Can., Atmos. Environ. Serv., Downsview, ON.

(ESRI) Environmental Systems Research Institute. 2003. Search ArcScripts [on-line]. Accessed on 14 July 2004. <http://arcscripts.esri.com/>.

(ESWG) Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agric. Agri-Food Can., Res. Br., Cent. Land Biol. Resour. Res.; Environ. Can., State Environ. Dir., Ecozone Anal. Br., Ottawa/Hull.

Fitzsimmons, M. 2001. Effects of deforestation and reforestation on landscape spatial structure in boreal Saskatchewan, Canada. For. Ecol. Manage. 174:577–592.

Flannigan, M.D.; Bergeron, Y.; Engelmark, O.; Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. J. Veg. Sci. 9:469–476.

Flannigan, M.D.; Harrington, J.B. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). J. Appl. Meteorol. 27:441–452.

Flannigan, M.D.; Todd, J.B.; Wotton, B.M.; Stocks, B.J.; Skinner, W.R.; Martell, D.L. 2000. Pacific sea surface temperatures and their relation to area burned in Canada. *In* Proceedings of the 3rd Symposium on Fire and Forest

Meteorology, Long Beach, California, 10–12 January 1999. Am. Meteorol. Soc., Boston, MA.

Flannigan, M.D.; Wotton, B.M. 1989. A study of interpolation methods for forest fire danger rating in Canada. Can. J. For. Res. 18:1059–1066.

Flannigan, M.D.; Wotton, B.M. 1991. Lightning-ignited forest fires in northwestern Ontario. Can. J. For. Res. 21:277–287.

Fleming, R.A.; Candau, J.-N.; McAlpine, R.S. 2002. Landscape-scale analysis of interactions between insect defoliation and forest fire in central Canada. Clim. Change 55:251–272.

Flesch, T.K.; Wilson, J.D. 1993. Extreme value analysis of wind gusts in Alberta. For. Can., North. For. Cent., Edmonton, AB., and Alta. For. Serv., For. Lands Wildl., Edmonton, AB. Can.-Alta. Partnership Agree. For. 107.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can., Ottawa, ON. Inf. Rep. ST-X-3.

Foster, D.R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. Can. J. Bot. 61:2459–2471.

Galindo-Leal, C.; Bunnell, F.L. 1995. Ecosystem management: implications and opportunities of a new paradigm. For. Chron. 71:601–606.

Harrington, J.B.; Flannigan, M.D.; Van Wagner, C.E. 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada 1953–80. Can. For. Serv., Petawawa Nat. For. Inst., Petawawa, ON. Inf. Rep. PI-X-25.

Harvey, B.; Leduc, A.; Gauthier, S.; Bergeron, Y. 2002. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. For. Ecol. Manage. 155: 369–385.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quat. Res. 3:329–382.

Heinselman, M.L. 1978. Fire in wilderness ecosystems. Pages 249–278 *in* J.C. Hendee, G.H. Stankey, and R.C. Lucas, eds. Wilderness management. US Dep. Agric. For. Serv., Washington, DC, Misc. Publ. 1365.

Helms, J.A. 1979. Positive effects of prescribed burning on wildfire intensities. Fire Manage. Notes 40:10–13.

Hély, C.; Flannigan, M.D.; Bergeron, Y.; McRae, D.J. 2001. Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two fire behavior prediction systems. Can. J. For. Res. 31:430–441.

Hess, J.C.; Scott, C.A.; Hufford, G.L.; Fleming, M.D. 2002. El Niño and its impact on fire weather conditions in Alaska. Int. J. Wildland Fire 10:1–13.

Hirsch, K.G. 1996. Canadian Forest Fire Behavior Prediction (FBP) System: user's guide. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. Spec. Rep. 7.

Hirsch, K.G.; Corey, P.N.; Martell, D.L. 1998. Using expert judgment to model initial attack fire crew effectiveness. For. Sci. 44:539–549.

Hirsch, K.G.; Kafka, V.; Tymstra, C.; McAlpine, R.; Hawkes, B.; Stegehuis, H.; Quintilio, S.; Gauthier, S.; Peck, K. 2001. Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. For. Chron. 77:1–7.

Hogg, E.H. 1994. Climate and the southern limit of the western Canadian boreal forest. Can. J. For. Res. 24:1835–1845.

Hunter, M.L., Jr. 1993. Natural fire regimes as spatial models for managing boreal forests. Biol. Conserv. 65:115–120.

Johnson, E.A.; Gutsell, S.L. 1994. Fire frequency models, methods and interpretations. Adv. Ecol. Res. 25:239–287.

Johnson, E.A.; Miyanishi, K.; Weir, J.M.H. 1998. Wildfires in the western Canadian boreal forest: landscape patterns and ecosystem management. J. Veg. Sci. 9:603–610.

Johnson, E.A.; Wowchuk, D.R. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. Can. J. For. Res. 23:1213–1222.

Johnson, K.N.; Sessions, S.; Franklin, J.F. 1996. Initial results from simulation of alternative forest management strategies for two national forests of the Sierra Nevada. Pages 175–216 *in* Sierra Nevada Ecosystem Project: final report to Congress, Addendum. University of California, Centers for Water and Wildland Resources, Davis, CA.

Kafka, V.; Tymstra, C.; Hirsch, K.G.; Flannigan, M.D. 2000. Assessing fire behavior potential: a comparative analysis of two spatial techniques. Pages 113–122 *in* L.F. Neuenschwander and K.C. Ryan, eds. Proceedings of the symposium of the Joint Fire Science Conference and Workshop: Crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management, Boise, Idaho, 15–17 June 1999. University of Idaho, Moscow, ID; International Association of Wildland Fire, Fairfield, WA.

Kasischke, E.S.; Williams, D.; Barry, D. 2002. Analysis of the patterns of large fires in the boreal forest region of Alaska. Int. J. Wildland Fire 11:131–144.

Kiil, A.D.; Miyagawa, R.S.; Quintilia, D. 1977. Calibration and performance of the Canadian Fire Weather Index in Alberta. Environ. Can., Can. For. Serv., North. For. Res. Cent., Inf. Rep. NOR-X-173.

Kitzberger, T.; Swetnam, T.W.; Veblen, T.T. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Global Ecol. Biogeogr. 10:315–326.

Kourtz, P.; Todd, B. 1991. Predicting the daily occurrence of lightning-caused forest fires. For. Can., Petawawa Natl. For. Inst., Chalk River, ON. Inf. Rep. PI-X-112.

Langley, R.W. 1972. The climate of the prairie provinces. Dep. Environ., Atmos. Environ. Serv., Ottawa, ON. Climatol. Stud. No. 13.

Larsen, C.P.S.; MacDonald, G.M. 1998. An 840-year record of fire and vegetation in a boreal white spruce forest. Ecology 79:106–118.

Lawson, B.D. 2002. The Chisholm fire behavior documentation. Alta. Sustain. Resour. Dev., For. Protect. Div., Edmonton, AB. Accessed on 14 July 2004. <http://www3.gov.ab.ca/srd/forests/chisholm/pdfs/Section2.pdf>.

Lertzman, K.; Fall, J.; Dorner, B. 1998. Three kinds of heterogeneity in fire regimes: at the crossroads of fire history and landscape ecology. Northwest Sci. 72:4–23.

Lesieur, D.; Gauthier, S.; Bergeron, Y. 2002. Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. Can. J. For. Res. 32:1996–2009.

Marsden, M.A. 1982. A statistical analysis of the frequency of lightning-caused forest fires. Environ. Manage. 14:149–159.

McAlpine, R.S.; Hirsch, K.G. 1999. An overview of LEOPARDS: the level of protection analysis system. For. Chron. 75:615–621.

Meisner, B.N. 1993. Correlation of National Fire Danger Rating System indices and weather data with fire reports. For. Fire Lab., Pac. Southwest Res. Stn., US Dep. Agric., For. Serv., Riverside, CA. Final Rep., Interagency Agreement No. R500A20021.

Murphy, P.J.; Tymstra, C. 1986. The 1950 Chinchaga River fire in the Peace River region of British Columbia/Alberta: preliminary results of simulating forward speed and distances. Pages 20–30 *in* M.E. Alexander, ed. Proceedings of the 3rd Western Region Fire Weather Committee Scientific and Technical Seminar, Edmonton, Alberta, February 1986. Can. For. Serv., North. For. Cent., Edmonton, AB. Study NOR-5-05.

Nash, C.H.; Johnson, E.A. 1996. Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. Can. J. For. Res. 26:1859–1874.

Niklasson, M.; Granström, A. 2000. Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81:1484–1499.

Overpeck, J.T.; Rind, D.; Goldberg, R. 1990. Climate-induced changes in forest disturbance and vegetation. Nature 343:51–53.

Parisien, M.A.; Sirois, L. 2003. Distribution and dynamics of tree species across a fire frequency gradient in the James Bay region of Québec. Can. J. For. Res. 33:243–256.

Payette, S. 1993. The range limit of boreal tree species in Québec-Labrador: an ecological and palaeoecological interpretation. Rev. Palaeobot. Palynol. 79:7–30.

Payette, S.; Morneau, C.; Sirois, L.; Desponts, M. 1989. Recent fire history of the northern Québec biomes. Ecology 70:656–673.

Peterson, E.B.; Peterson, N.M. 1992. Ecology, management, and use of aspen and balsam poplar in the prairie provinces, Canada. For. Can., Northwest Reg., North. For. Cent., Edmonton, AB. Spec. Rep. 1.

Pew, K.L.; Larsen, C.P.S. 2001. GIS analysis of spatial and temporal patterns of human-caused wildfires in the temperate rain forest of Vancouver Island, Canada. For. Ecol. Manage. 140:1–18.

Podur, J.; Martell, D.L.; Knight, K. 2003. Statistical quality control analysis of forest fire activity in Canada. Can. J. For. Res. 32:195–205.

(PFFC) Provincial Forest Fire Centre. 2001. Crowning susceptibility model (CroSuM) application user guide. Version 1.1 (draft). Alta. Sustain. Resour. Dev., For. Protect. Div., Edmonton AB. Accessed on 14 July 2004. <http://www3.gov.ab.ca/srd/wildfires/fpd/pwf_fs_tools.cfm>.

Reed, W.J.; Errico, D. 1986. Optimal harvest scheduling at the forest level in the presence of the risk of fire. Can. J. For. Res. 16:266–278.

Reed, W.J.; Larsen, C.P.S.; Johnson, E.A.; MacDonald, G.M. 1998. Estimation of temporal variations in historical fire frequency from time-since-fire map data. For. Sci. 44:465–475.

Ritchie, J.C. 1987. Postglacial vegetation of Canada. Cambridge Univ. Pr., Cambridge, UK.

Rogeau, M.-P.; Woodard, P.M.; Feunekes, U. 1998. Landscape disturbance modelling. Pages 461–466 *in* Proc. 13th Conference on Fire and Forest Meterology, 27–31 October 1996. Lorne, Australia.

Rollins, M.G.; Morgan, P.; Swetnam, T. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecol. 17:539–557.

Rollins, M.G.; Swetnam, T.W.; Morgan, P. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Can. J. For. Res. 31:2107–2123.

Saskatchewan Environment. 2002. Saskatchewan fire and forest insect and disease policy development fact sheet 8: Wildland fire and fire operations [on-line]. Regina, SK. Accessed on 14 July 2004. <http://www.se.gov.sk.ca/fire/insect-disease/FACT8.htm>.

Silversides, R.H. 1978. Forest and airport wind speeds. Atmos. Ocean 16:293–299.

Skinner, W.R.; Stocks, B.J.; Martell D.L.; Bonsal, B.; Shabbar, A. 1999. The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. Theor. Appl. Climatol. 63:89–105.

Stocks, B.J. 1974. Wildfires and the Fire Weather Index system in Ontario. Can. Dep. Environ., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, ON. Inf. Rep. O-X-213.

Stocks, B.J. 1975. The 1974 wildfire situation in Northwestern Ontario. Can. Dep. Environ., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, ON. Inf. Rep. O-X-232.

Stocks, B.J. 1987. Fire behavior in immature jack pine. Can. J. For. Res. 17:80–86.

Stocks, B.J. 1989. Fire behavior in mature jack pine. Can. J. For. Res.19:783–790.

Stocks, B.J.; Hartley, G.R. 1995. Fire behavior in three jack pine fuel complexes. Can. For. Serv., Great Lakes For. Cent., Sault Ste. Marie, ON. Poster with text.

Stocks, B.J.; Mason, J.A.; Todd, J.B.; Bosch, E.M.; Wotton, B.M.; Amiro, B.D.; Flannigan, M.D.; Hirsch K.G.; Logan, K.A.; Martell, D.L.; Skinner, W.R. 2002. Large forest fires in Canada, 1959–1997. J. Geophys. Res. 108(D1): FFR5-1 to FFR5-12.

Stocks, B.J.; Walker, J.D. 1973. Climatic conditions before and during four significant forest fire situations in Ontario. Can. Dep. Environ., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, ON. Inf. Rep. O-X-187.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262:885–889.

Swetnam, T.W.; Betancourt, J.L. 1990. Fire–southern oscillation relations in the southwestern United States. Science 249:1017–1020.

Todd, J.B.; Kourtz, P.H. 1991. Predicting the daily occurrence of human-caused forest fires. For. Can., Petawawa Natl. For. Inst., Chalk River, ON. Inf. Rep. PI-X-103.

Trewartha, G.T. 1966. The earth's problem climates. Univ. Wisconsin Pr., Madison, WI.

Turner, J.A. 1973. A fire load index for British Columbia. Can. Dep. Environ., Can. For. Serv., Pac. For. Res. Cent., Victoria, BC. Inf. Rep. BC-X-80.

Turner, J.A.; Lawson, B.D. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Can. Dep. Fish Environ., Can. For. Serv., Pac. For. Res. Cent., Victoria, BC. Inf. Rep. BC-X-177.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, ON. For. Tech. Rep. 35.

Van Wagner, C.E. 1988. The historical pattern of annual burned area in Canada. For. Chron. 64:182–185.

Wardle, D.A.; Hörnberg, G.; Zackrisson, O.; Kalela-Brundin, M.; Coomes, D.A. 2003. Long-term effects of wildfire on ecosystem properties across an island area gradient. Science 300:972–975.

Weatherspoon, C.P.; Sinner, C.N. 1996. Landscape-level strategies for forest fuel management. Pages 1471–1492 *in* Sierra Nevada Ecosystem Project: final report to Congress, Vol. 2. Assessments and scientific basis for management options. University of California, Centers for Water and Wildland Resources, Davis, CA.

Weber, M.G.; Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environ. Rev. 5:145–166.

Weber, M.G.; Stocks, B.J. 1998. Forest fires and sustainability in the boreal forests of Canada. Ambio 27:545–550.

Wein, R.W.; Moore, J.M. 1977. Fire history and rotations in the New Brunswick Acadian Forest. Can. J. For. Res. 7:285–294.

Wein, R.W.; Moore, J.M. 1979. Fire history and recent fire rotation periods in the Nova Scotia Acadian Forest. Can. J. For. Res. 9:166–178.

Weir, J.M.H.; Johnson, E.A. 1998. Effects of escaped settlement fires and logging on forest composition in the mixedwood boreal forest. Can. J. For. Res. 28:459–467.

Weir, J.M.H.; Johnson, E.A.; Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecol. Appl. 10:1162–1177.

Wierzchowski, J.; Heathcott, M.; Flannigan, M.D. 2002. Lightning and lightning fire, central cordillera, Canada. Int. J. Wildland Fire 11:41–51.

Zar, J.H. 1998. Biostatistical analysis. Prentice-Hall, Upper Saddle River, NJ.

APPENDIXES

Appendix 1. Coordinates of weather stations in and around the study area

Station name	Station ID	Operator	Latitude	Longitude	Elevation (m)
Big River, SK	B_RVR	SE	53.7950	–106.9886	518
Beauval, SK	BEAUV	SE	55.1536	–107.6089	434
Besnard Lake, SK	BSNRD	SE	55.3006	–106.0983	403
Buffalo Hills, SK	BUFFH	SE	55.9806	–109.2958	676
Buffalo Narrows, SK	BUFFN	EC	55.8333	–108.4333	440
Collins Bay, SK	CLNSB	EC	58.1833	–103.6833	408
Cumberland House, SK	CMBHS	SE	53.9522	–102.2639	266
Candle Lake, SK	CNDLK	SE	53.7653	–105.1200	510
Cold Lake, AB	COLDL	EC	54.4167	–110.2833	541
Cookson, SK	COOKS	SE	53.6022	–106.4553	525
Creighton, SK	CRETN	SE	54.6531	–102.0811	304
Divide, SK	DIVDE	SE	53.8850	–108.4072	716
Duck Mountain, SK	DUCKM	SE	51.6358	–101.6392	609
EB Campbell, SK	EBCAM	SE	53.6886	–103.3394	312
Fort Chipewyan, AB	FCHIP	EC	58.7667	–111.1167	232
Fort à la Corne, SK	FLCRN	SE	53.2483	–104.8417	495
Fort McMurray, AB	FMCMY	EC	56.6500	–111.2167	323
Greenwater Park, SK	G_WTR	SE	52.4928	–103.5556	579
Hudson Bay, SK	HDSNB	EC	52.8167	–102.3167	358
Ile a la Crosse, SK	ILCRS	SE	55.4394	–107.8983	419
Key Lake, SK	KEYLK	EC	57.2500	–105.6167	511
La Loche, SK	LALCH	SE	56.5483	–109.4178	449
Little Bear Lake, SK	LBEAR	SE	54.2747	–104.4153	678
Loon Lake, SK	LOONL	SE	54.0258	–109.1847	586
La Ronge, SK	LRNGE	EC	55.1500	–105.2667	373
Lynn Lake, MB	LYNNL	EC	56.8667	–101.0667	356
Mackenzie Falls, SK	MCKNZ	SE	56.6672	–106.2061	549
Maclennan Lake, SK	MCLNN	SE	55.8167	–104.5508	479
Meadow Lake Park, SK	MLPRK	SE	54.4061	–108.6428	480
Nipawin, SK	NIPWN	EC	53.3333	–104.0083	371
Prince Albert, SK	PALBT	EC	53.2167	–105.6833	428
Pelican Narrows, SK	PLCNA	SE	55.1889	–102.9450	335
Porcupine Hills, SK	PRCPN	SE	52.6317	–101.8283	807
Rabbit Hill, SK	RABTH	SE	54.3392	–107.1953	579
Southend, SK	S_END	EC	56.3333	–103.2500	341
Stony Rapids, SK	STNYR	EC	59.2500	–105.8333	245
The Pas, MB	THPAS	EC	53.9667	–101.1000	271
Uranium City, SK	URNMC	EC	59.6000	–108.4833	318
Ushta, SK	USHTA	SE	52.2611	–102.6361	594
Vimy, SK	VIMY	SE	53.8275	–107.5472	632
Wabeno Lake, SK	WABNO	SE	54.3736	–106.3656	571
Waskesiu, SK	WASKS	SE	53.8817	–106.1275	533

Note: SE = Saskatchewan Environment, EC = Environment Canada.

Appendix 2. Percent of detected fires by various human causes as recorded in the Saskatchewan Environment fire occurrence database from 1981 to 2000[a]

	Ecozone			Ecoregion				Protection zone	
Cause	BPI (n = 5702)	BSh (n = 1491)	TSh (n = 154)	BTr (n = 1984)	BTr-mod (n = 832)	MbL (n = 324)	Mbu (n = 3393)	Full response zone (n = 5364)	Modified response zone (n = 533)
Automobile or vehicle	1.5	0.6	0.0	1.3	1.4	1.2	1.7	1.4	0.4
Berry picker	1.2	0.9	0.0	0.3	0.2	0.6	1.8	1.4	0.2
Camper	18.6	16.0	12.3	41.7	53.1	4.3	6.5	15.8	11.3
Children with matches	5.0	16.8	8.4	1.8	0.8	6.2	6.8	8.3	10.5
Commercial fisherman	0.2	2.2	0.7	0.0	0.0	0.3	0.3	0.7	1.7
Fisherman	1.4	16.6	24.0	0.4	0.4	4.0	1.7	4.0	26.5
Forest industry	2.0	0.5	0.0	1.9	3.1	1.5	2.0	1.9	0.6
Garbage dump	5.3	5.7	9.1	4.6	4.0	5.3	5.7	5.1	8.4
Hunter	3.0	2.8	4.6	2.2	4.3	6.5	3.2	3.5	3.9
Incendiary materials	21.4	7.1	6.5	4.7	5.7	11.7	32.0	23.3	5.3
Landowner	10.4	3.6	5.2	15.9	6.5	15.1	6.7	5.0	4.1
Military activities	0.5	0.0	0.0	0.0	0.0	0.0	0.8	0.5	0.0
Mining activities	0.0	0.9	0.7	0.0	0.0	0.3	0.0	0.2	0.9
Other	5.6	5.5	4.6	3.9	4.3	12.7	5.9	5.9	6.2
Power line	2.3	2.8	3.3	1.8	1.1	2.8	2.5	2.4	1.1
Railroad	0.8	0.0	0.0	1.2	0.8	4.6	0.2	0.5	0.0
Road construction	0.3	0.2	0.0	0.2	0.0	0.3	0.3	0.2	0.4
Structure	0.4	0.7	3.3	0.3	0.1	0.0	0.6	0.5	1.7
Trapper	1.1	1.3	1.3	0.2	0.5	5.3	1.2	1.4	1.9
Unknown recreation	6.6	6.4	13.0	7.8	8.4	4.6	6.1	6.5	8.3
Unknown residential	12.0	9.1	3.3	9.8	5.2	12.7	13.9	11.5	6.8

[a]The number of fires per ecological unit is indicated in parentheses under the unit name.
Note: BPI = Boreal Plain, BSh = Boreal Shield, Tsh = Taiga Shield, BTr = Boreal Transition, BTr-mod = Boreal Transition modified, MbL = Mid-boreal Lowland, MbU = Mid-boreal Upland.