Mapping wildfire susceptibility with the BURN-P3 simulation model

BURN-P3

MAPPING WILDFIRE SUSCEPTIBILITY WITH THE BURN-P3 SIMULATION MODEL

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ABSTRACT

To optimize strategic planning, resource management in fire-dominated ecosystems requires an understanding of the probability of wildfire occurring and spreading at different points on a landscape. This report describes an approach to evaluating wildfire susceptibility, or burn probability (BP), for fire-prone landscapes such as the boreal forest of North America. BURN-P3 (probability, prediction, and planning) is a landscape-level simulation model producing BP maps. The model combines deterministic fire growth based on the Canadian Fire Behavior Prediction System and spatial data for forest fuels and topography with probabilistic fire ignitions and spread events derived from historical fire and weather data. Model components include the location and frequency of ignitions, the rate at which fires escape initial attack and become large, the number of days on which each fire achieves significant spread, the fire weather conditions associated with these spread event days, and the deterministic fire spread. For a given landscape, BP is simulated for a single annual time step, or iteration, based on 500 to 1000 Monte Carlo simulations. A case study of the application of BURN-P3 was undertaken for a 15 × 10^6 ha boreal mixedwood area of central Saskatchewan. The BP values varied considerably within the study area. Regions with a high BP were highly localized (clustered distribution), largely because of the configuration and continuity of flammable forest fuels. These results highlight the importance of landscape features, such as lakes and recent burns, to wildfire susceptibility, and suggest that assessments based solely on stand-level characteristics may be inadequate.

RÉSUMÉ

Afin d’optimiser la planification stratégique, la gestion des ressources dans les écosystèmes dominés par le feu requiert une compréhension des probabilités d’allumage et de propagation des feux à différents endroits sur le territoire. Nous décrivons dans le présent rapport une méthode d’évaluation de la susceptibilité aux incendies de forêt, ou la probabilité de brûlage (PB), dans des paysages susceptibles aux feux, comme la forêt boréale de l’Amérique du Nord. BURN-P3 (probabilité, prédiction et planification) est un modèle de simulation à l’échelle du paysage qui produit des cartes de PB. Le modèle réunit, d’une part, des données déterministes de la propagation des feux basées sur la Méthode canadienne de prévision du comportement des incendies de forêt, ainsi que des données spatiales sur les combustibles forestiers et la topographie et, d’autre part, des incidences probabilistes d’allumages et de propagation des feux établies d’après des données historiques sur les conditions météorologiques et les feux. Les éléments du modèle incluent l’emplacement et la fréquence des allumages, le taux d’échappée des feux à l’attaque initiale, le nombre de jours pendant lesquels chaque feu se propage, les conditions météorologiques quotidiennes lorsque chacun de ces feux s'est propagé et les données déterministes de la propagation des feux. Pour un paysage donné, la PB est simulée pour une seule année, ou itération, reposant sur 500 à 1 000 simulations de Monte Carlo. Nous avons appliqué le modèle BURN-P3 à un secteur de la forêt boréale mixte de 15 ´ 106 ha du centre de la Saskatchewan. Les valeurs de PB variaient fortement à l'intérieur de la zone d'étude. Les secteurs montrant une PB élevée étaient faciles à localiser (distribution regroupée), principalement à cause de la composition et de la présence continue des combustibles forestiers inflammables. Ces résultats mettent en évidence l'importance des éléments du paysage, comme les lacs et les brûlis récents, quant à la susceptibilité aux incendies de forêt des différents secteurs, et suggèrent que les évaluations reposant uniquement sur les caractéristiques des peuplements peuvent être inadéquates.

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INTRODUCTION

In many boreal and mountain biomes, large stand-renewing wildfires represent the main forest disturbance. An understanding of the dynamics of these fire-prone ecosystems requires measurement of the recurrence and magnitude of this disturbance. In the boreal forest of Canada, for example, thousands of fires are reported every year, but a fraction of these fires (2–3%) account for virtually all (97%) of the area burned (Weber and Stocks 1998). Thus, a small proportion of fires produces most of the impact on the landscape; furthermore, while a given area might experience no or few large fires in some years, other years may be particularly severe. Fire regimes are not only highly variable over time, but they also vary in space. For example, estimates of fire cycles in large ecological units (e.g., ecozones) of the Canadian boreal forest vary dramatically (Stocks et al. 2003). Such variation also occurs at a smaller scale: marked spatial variation in the fire regime has indeed been observed for much smaller areas (e.g., $<10^6$ ha) (Bergeron 1991; Larsen 1997; Parisien and Sirois 2003).

In any case, documented spatial contrasts in fire regimes are often difficult to explain and interpret. For example, in the boreal mixedwood of Canada, conifer-dominated areas are more susceptible to fire spread than areas where deciduous stands are common (Cumming 2001b). However, over large areas, some sectors with certain vegetation simply burn more often than others with similar vegetation. Greater frequency of burning in some areas is likely a consequence of several factors: a higher frequency of fire-conducive weather, more ignitions, lower levels of landscape fragmentation, or less successful fire suppression. Current knowledge makes it possible to predict where a fire will spread according to factors that are known to affect fire behavior (e.g., vegetation, weather, and topography); however, there is considerable uncertainty about which areas of the landscape will be affected by fires over long periods (e.g., years). Predicting wildfire susceptibility, or burn probability (BP), over large areas involves predicting the ignition and spread of multiple fires.

This report describes a tool for producing spatially explicit estimates of wildfire susceptibility. A landscape-level Monte Carlo simulation modeling approach is used, which combines deterministic fire growth modeling of individual fires with probabilistic fire ignition, spread event days (days of significant fires spread), and fire weather. The resulting approach, called BURN-P3 (probability, prediction, and planning), allows users to apply these concepts to a large fire-prone area and thus to map wildfire susceptibility, expressed as BP, for a given year. BURN-P3 is meant to be a flexible, user-friendly tool that relies on the user's knowledge of the fire regime that is being assessed. Although it was initially designed as a strategic planning tool for the Saskatchewan Environment fire management agency, BP mapping may also be useful for land-use planning, as well as forest fire research applications. This report includes the documentation for the foundation of BURN-P3 and a case study for a large (15×10^6 ha) boreal mixedwood area of Saskatchewan to demonstrate the BURN-P3 approach and to identify its strengths and weaknesses.

STUDY AREA

The area for the case study, 15×10^6 ha in central Saskatchewan, covered four ecoregions (ESWG 1995) and comprised commercial forestland, provincial parkland, and Prince Albert National Park (Fig. 1). A 25-km buffer zone was added to the periphery of the study area to eliminate edge effects on the BP maps.

Most of the study area lies in the Boreal Plain ecozone, which contains three ecoregions (Fig. 1): the Boreal Transition, the Mid-boreal Lowland, and the Mid-boreal Upland. The Boreal Plain ecozone is a generally flat to rolling plain, with a large proportion (25% to 50%) of its area covered by wetlands. The study area also includes the Churchill River Upland ecoregion, which is part of the Boreal Shield ecozone (ESWG 1995). The Boreal Shield ecozone lies on the Precambrian Shield, and its landscape is characterized by alternating rolling hills and wetlands with numerous lakes. The main conifers of the study area are white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), and tamarack (*Larix laricina* (Du Roi) K. Koch). The deciduous component is mainly represented by trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marsh.). Although the deciduous component is more important in the southern part of the study area, the central and northern parts are dominated by conifers.

The strongly continental climate in the study area is characterized by long, cold winters and short, cool summers. The 1971 to 2000 climate normals for the La Ronge weather station (55°09′N, 105°16′W), located approximately in the middle of the study area, indicate a range in monthly mean temperatures from –20.4°C for January to 17.2°C for July (Environment Canada 2003). The mean total annual precipitation, which occurs mostly as rain, ranges from 400 to 500 mm, reaching its maximum during the summer months. Prolonged drought during the spring and summer occurs relatively frequently and promotes the ignition and spread of large, high-intensity wildfires. In fact, this part of the boreal forest experiences some of the shortest fire cycles in Canada (Stocks et al. 2003).

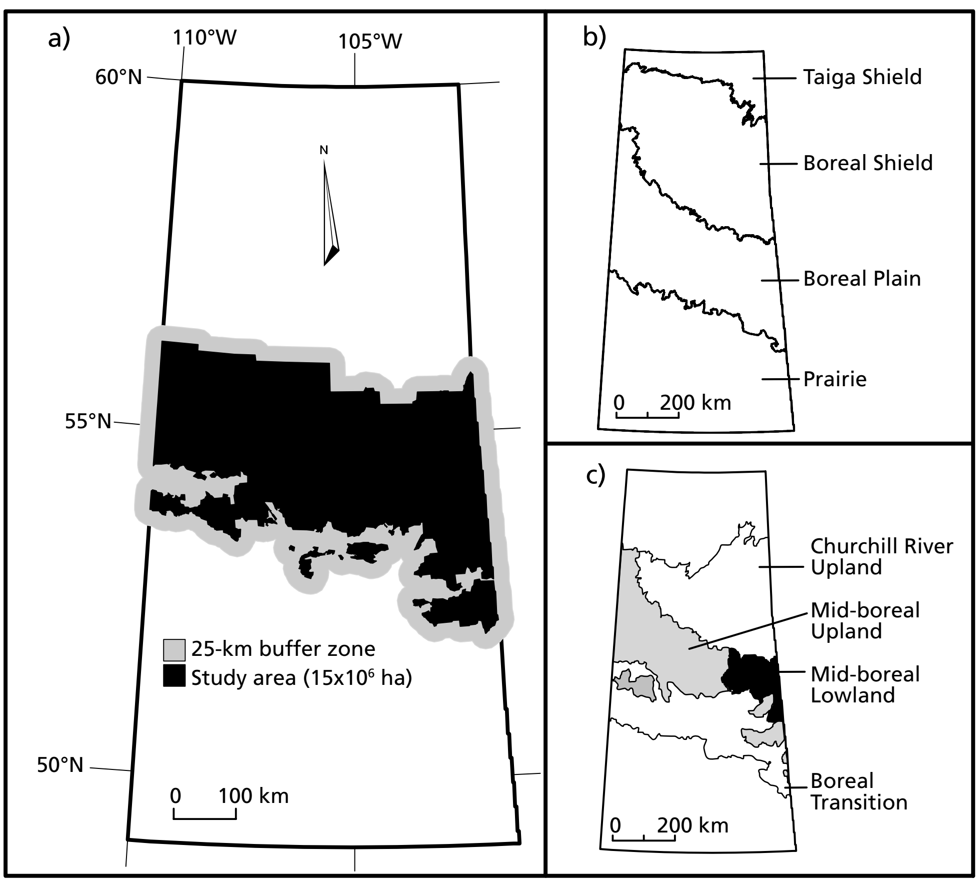

Figure 1. The study area in central Saskatchewan (a), the ecozones of Saskatchewan (b), and the ecoregions covered by the study area (c) (ESWG 1995).

Source Data

The source data used in the BURN-P3 case study are described in Table 1, and further specifications are given below. A more thorough description of the databases used was provided by Parisien et al. (2004).

Fire databases

There are two basic types of fire databases in Canada: fire occurrence databases and large fire databases. Fire occurrence data represent the presumed point of origin of all reported fires, regardless of the size of the fire. The vast majority of fires are small (<10 ha), and overall they represent a small fraction of total area burned (<2–3%). Although fire occurrence databases are useful for measuring fire frequency (the number of fires for a given period and geographic area) and depicting historical ignition patterns, they generally do not provide a reliable measure of area burned. The latter statistic is much better addressed by large fire databases, which are derived from mapped fire perimeters. However, because these databases contain data only for large fires (≥200 ha), they usually represent a small percentage (<5%) of all reported fires.

In this report, fires of at least 200 ha are considered escaped fires, fires that have escaped initial attack and have burned a large area. This is a reasonable assumption, because the entire study area is within a primary protection zone for fire suppression, where all reported wildfires undergo initial attack. In the study area, fires ≥200 ha have, by far, the most impact in terms of area burned, being responsible for over 97% of the area burned by all fires (Parisien et al. 2004). BURN-P3 does not explicitly model fire-suppression effects, but assumes that once a fire has escaped initial attack, suppression activities cannot significantly reduce its spread. In BURN-P3, fire suppression can be modeled implicitly through thoughtful input to the modules.

For this case study, the last two decades of fire data were used because the number and spatial patterns of fires are likely to have changed over longer time periods, fire occurrence data for the entire study area are available only since 1981, and the suppression capacity is assumed to have been relatively constant over this period. The period of data used for BURN-P3 represents a trade-off: the data must span a period that is long enough to adequately capture spatial and temporal variability, but not so long that it ignores changes in the data (e.g., changes in human-caused spatial ignition patterns and climate change). Because 200 ha is the cutoff size for fires in the Canadian Forest Service (CFS) large fire database (Stocks et al. 2003), it was convenient to use this value as the minimum fire size for the study.

Although escaped fires may remain active for periods of weeks to months, they usually achieve most of their spread in one to several days. The days over which fires have burned a significant proportion of their final size are called spread event days. A database of fire progression, mapped daily, was created for 130 escaped fires that occurred in Saskatchewan from 1991 to 2000. This database was used specifically for the purpose of modeling spread event days in BURN-P3 and represents reliable data from daily forest fire reports in Saskatchewan. Here, a spread event day is defined as a day when the fire achieved ≥4% of its final size. This percentage is an approximation of the fraction of days when burning conditions were likely to exceed fire suppression capabilities (M. A. Parisien, unpublished results).

Forest Fuels

In BURN-P3, vegetation must be represented as a fuel type, as defined by the Canadian Fire Behavior Prediction (FBP) System (FCFDG 1992) (Fig. 2). The FBP System is a subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS) producing quantitative fire behavior outputs, such as rate of spread, head fire intensity (HFI), and crown fraction burned, which are routinely used by fire management agencies to predict fire behavior. The FBP System outputs are computed for given fire weather inputs, FBP System fuel types (i.e., vegetation), and topographic conditions. This system categorizes vegetation into 16 fuel types, 7 of which are represented in the Saskatchewan boreal forest (Table 2). In the FBP System, the coniferous fuel types, C-2 (Boreal Spruce) in particular, produce more severe fire behavior than the deciduous and mixedwood fuel types.

Table 1. Data types used in the Saskatchewan BURN-P3 case study[a]

Data type	Description	Source[b]	Period covered[c]	Format[d]	Data quality	Use in BURN-P3
Fire occurrence	Point of origin for all reported fires ($n \approx$ 20 000)	SE	1981–2002	Tabular Georeferenced attributes (e.g., cause, date)	Very good Contains most reported fires of the study area	Ignition grids
Escaped fires[e]	Location and area burned by escaped fires (≥200 ha) (n = 1 014 fires)	SE CFS	1981–2002	GIS[f] polygons (SE) Tabular (CFS) Georeferenced attributes (CFS)	Good Inaccuracies in area burned	Distribution of number of escaped fires Escaped fire rates Validation of BURN-P3 outputs
Spread event days[g]	Number of days for which fires burned ≥4% of final size for fires ≥200 ha (n = 130 fires)	SE	1991–2000	Tabular Attributes (e.g., date, daily area burned)	Acceptable Daily area burned often a coarse approximation	Distribution of spread event days
Fire weather	Daily noon LST[h] weather records from weather stations and FWI System[i] fuel moisture codes and fire behavior indices	SE EC	1990–2002	Tabular	Very good Discrepancies between SE and EC weather because of weather station location and equipment	Fire weather list
Ecosystem classification	Ecological units (ecozones, ecoregions, and ecodistricts) from ESWG (1995)	NRCan	NA[j]	Polygons	Excellent for this use in Saskatchewan	Fire statistics on an ecoregion basis Delimitation of weather zones
Forest fuels[k]	FBP[l] System fuel types	SE PANP USGS AVHRR	1965–2003 1968 1992–1993 1992–1993	Raster grids Derived from vegetation data (air photos, forest inventory, and satellite imagery)	Highly variable throughout the study area No recent updates for some areas	Fuels grid

[a]Full description of data types in Parisien et al. (2004).
[b]SE = Saskatchewan Environment, CFS = Canadian Forest Service, EC = Environment Canada, NRCan = Natural Resources Canada, PANP = Prince Albert National Park, USGS = United States Geological Survey, AVHRR = Advanced Very High Resolution Radiometer.
[c]Only the fire periods used in BURN-P3 are listed.
[d]Only the attributes used in BURN-P3 are listed.
[e]The size threshold of 200 ha was selected to represent escaped fires because this value represents the minimum area burned by fires in the existing databases.
[f]GIS = Geographic information system.
[g]The selection threshold of ≥4% of the final fire size is an approximation of the proportion of days with head fire intensity values ≥4 000 kW/m (i.e., when fire weather conditions become problematic in fire suppression).
[h]LST = Local Standard Time.
[i]FWI = Fire Weather Index.
[j]NA = not applicable.
[k]Better-quality fuel data from high-resolution (i.e., 30 m) satellite imagery now exists for the study area.
[l]FBP = Fire Behavior Prediction.

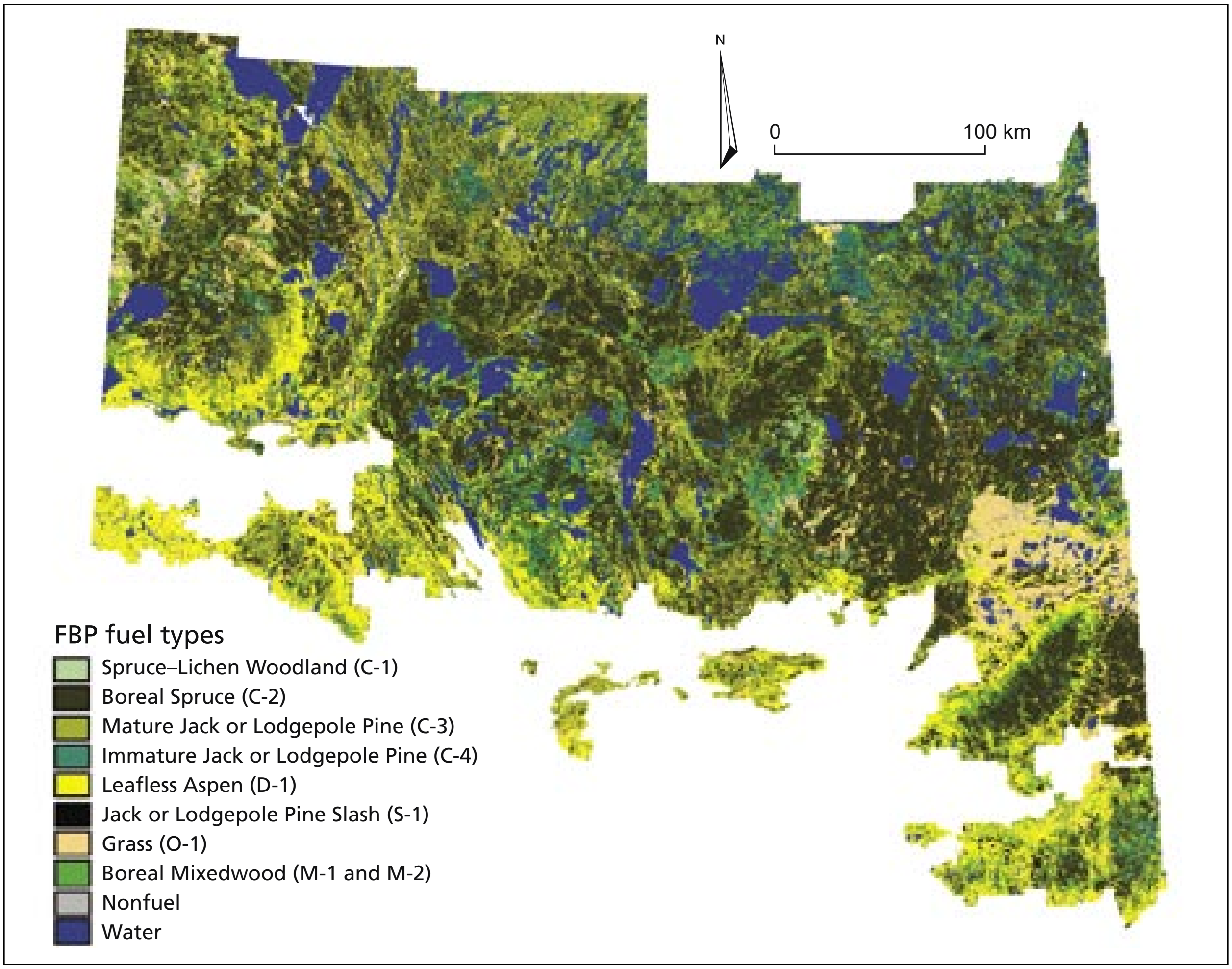

Figure 2. Fuel types of the Canadian Fire Behavior Prediction System (FBP) in the study area.

The FBP fuels of the study area were represented on a raster grid with a cell size of 300 m. This resolution, derived from the original resolution of 100 m, was used because of limitations on computation time. The fuel data were derived from different sources corresponding to slightly different time periods but not preceding 1965 (Table 1). Therefore, these data should be interpreted as an approximate depiction of the current forest fuels of the study area.

The distribution of fuels varies considerably from one ecoregion to another (Table 3). The Boreal Transition ecoregion is dominated by the Leafless Aspen (D-1) fuel type, which is much less flammable after green-up in the spring. The same pattern holds for the Grass (O-1a, O-1b) fuel type: the biomass is mostly dead, or cured, grass early in the growing season and green standing grass during the summer months. Unfortunately, the O-1 designation in the Boreal Transition ecoregions is generally an unrealistic representation of fuel type, because most of the area classified as O-1 is in fact agricultural land (i.e., cropland, pastures). From a fire behavior perspective, farmland is not nearly as flammable as the true O-1 fuel type. The other three ecoregions are mostly conifer-dominated. However, there can be considerable variation within a single fuel type; for example, much of the C-2 fuel type in the Mid-boreal Lowland contains lowland spruce stands, which are usually less flammable than upland spruce stands. In this area, the C-2 fuel type tends to overestimate all aspects of fire behavior. The Churchill River Upland has a higher proportion of nonfuel material (i.e., exposed rock) and open water, which is typical of Canadian Shield physiography.

Table 2. Description of fuel types of the Canadian Forest Fire Behavior Prediction System in the study area

Name	Designation	Key characteristics
Boreal Spruce	C-2	Moderately well stocked Black spruce tree crowns extending to or near the ground Labrador tea a dominant ground cover Deep organic layer
Mature Jack or Lodgepole Pine	C-3	Fully stocked (1 000–2 000 stems/ha) mature trees Live crown well above the surface fuels Herbs and shrubs sparse
Immature Jack or Lodgepole Pine	C-4	Pure, dense stands (10 000–30 000 stems/ha) of immature trees Continuous vertical and horizontal fuel continuity Large quantity of standing dead understory Heavy dead and downed fuel loading
Leafless Aspen	D-1	Pure, semimature, moderately well-stocked stands Ladder fuels absent Well-developed shrub layer Continuous leaf litter
Jack or Lodgepole Pine Slash	S-1	Continuous slash from mature jack or lodgepole pine stands Slash is usually 1–2 years old, retaining up to 50% of its foliage
Boreal Mixedwood	M-1, M-2	Moderately well-stocked stands of boreal coniferous and deciduous species, leafless (M-1) or green (M-2) Conifer crowns may extend to or near the ground Moderate shrub and herb layer Coniferous-deciduous composition influences fire behavior
Grass	O-1a, O-1b	Continuous grass cover, matted (O-1a) or standing (O-1b) Fuel loading and percent cured influences fire behavior

Source: Hirsch (1996).

Table 3. Distribution (%) of Fire Behavior Prediction System fuel types, by ecoregion[a]

Fuel type[b]	Boreal Transition	Mid-boreal Lowland	Mid-boreal Upland	Churchill River Upland
C-2	17.4	54.9	39.6	27.2
C-3	12.4	3.8	12.2	16.1
C-4	1.0	1.2	2.4	1.9
D-1	38.0	5.5	14.1	4.3
S-1	2.2	0.5	1.1	0.2
O-1a, O-1b	13.2	21.4	7.6	2.9
M-1, M-2	11.3	3.5	9.2	12.6
Nonfuel	1.3	0.9	3.2	7.1
Water	3.2	8.3	10.7	27.8

[a]The 25-km buffer area is not included.
[b]Fuel types are those defined in Hirsch (1996); see Table 2 in the current report for definitions of these fuel types.

BURN-P3 Framework

BURN-P3 is designed to simulate the ignition and growth of large (≥200 ha) escaped fires because these large fires are responsible for most of the total area burned in Canada. Exclusion of the more numerous small fires greatly simplifies the BURN-P3 approach.

BURN-P3 has three submodels or modules: the ignitions module, the burning conditions module, and the fire growth module (Fig. 3). The first two modules are probabilistic and can be derived from historical databases, whereas the fire growth module represents the deterministic aspect of the model. "Deterministic" means that a specific set of inputs always produces the same outputs; this determinism exists because this module is based on empirical equations of fire spread in the FBP System. Conversely, "probabilistic" means that a specific set of inputs can yield a range of outputs according to the laws of probability; this feature occurs because the information is drawn from frequency distributions. The larger the number of iterations, the better the outputs of the probabilistic modules will conform to these distributions.

BP maps are simulated for a single time step (1 year) on the basis of a large number (500 to 1000) of Monte Carlo simulations or iterations. BURN-P3 thus provides assessments of wildfire susceptibility based on static landscape conditions (i.e., forest succession is not modeled). For each simulated fire, the ignition location is modeled stochastically on the basis of historical spatial patterns of fire ignitions in the ignitions module (Fig. 3). In the burning conditions module, BURN-P3 draws its fire growth period from a distribution of spread event days. Variable fire weather conditions conducive to fire growth are associated with these spread event days. Finally, this information is relayed to the fire growth module, which simulates fire spread in a deterministic manner, using spatial data on forest fuels (i.e., vegetation) and topography. For each iteration, the perimeter of the simulated fire is stored if it is equal to or greater than the user-defined minimum escaped fire size (i.e., 200 ha). The modules are described in detail in the following sections.

For a complete run of BURN-P3, the number of escaped fires per iteration is subjected to stochastic variability according to the distribution of the number of escaped fires (Fig. 4). All simulated fires of a given iteration are recorded on a grid of the area burned; fires are not allowed to overlap within the same iteration. The same process is repeated for each iteration. The outputs for all iterations are added to a cumulative grid of area burned. BP in a given cell, i, is calculated as follows:

$$\mathrm{BP}_i = \frac{b_i}{N} \times 100 \qquad [1]$$

where b_i is the number of iterations that resulted in cell i being burned and N is the total number of iterations. BP, expressed as a percentage, represents the likelihood of burning different cells on a landscape in a single year (e.g., the upcoming fire season), given a specific set of landscape, fire, and weather inputs.

ignition module & burning conditions module: probabilistic
-> derived from historical data bases
-> i.e. specific set of inputs; yield a range of outputs; according to probability laws
> infor; drawn from frequency distribution (more iterations; more accurate)

fire growth module: deterministic
-> i.e. based on empirical equations
> specific inputs; always produce; same outputs

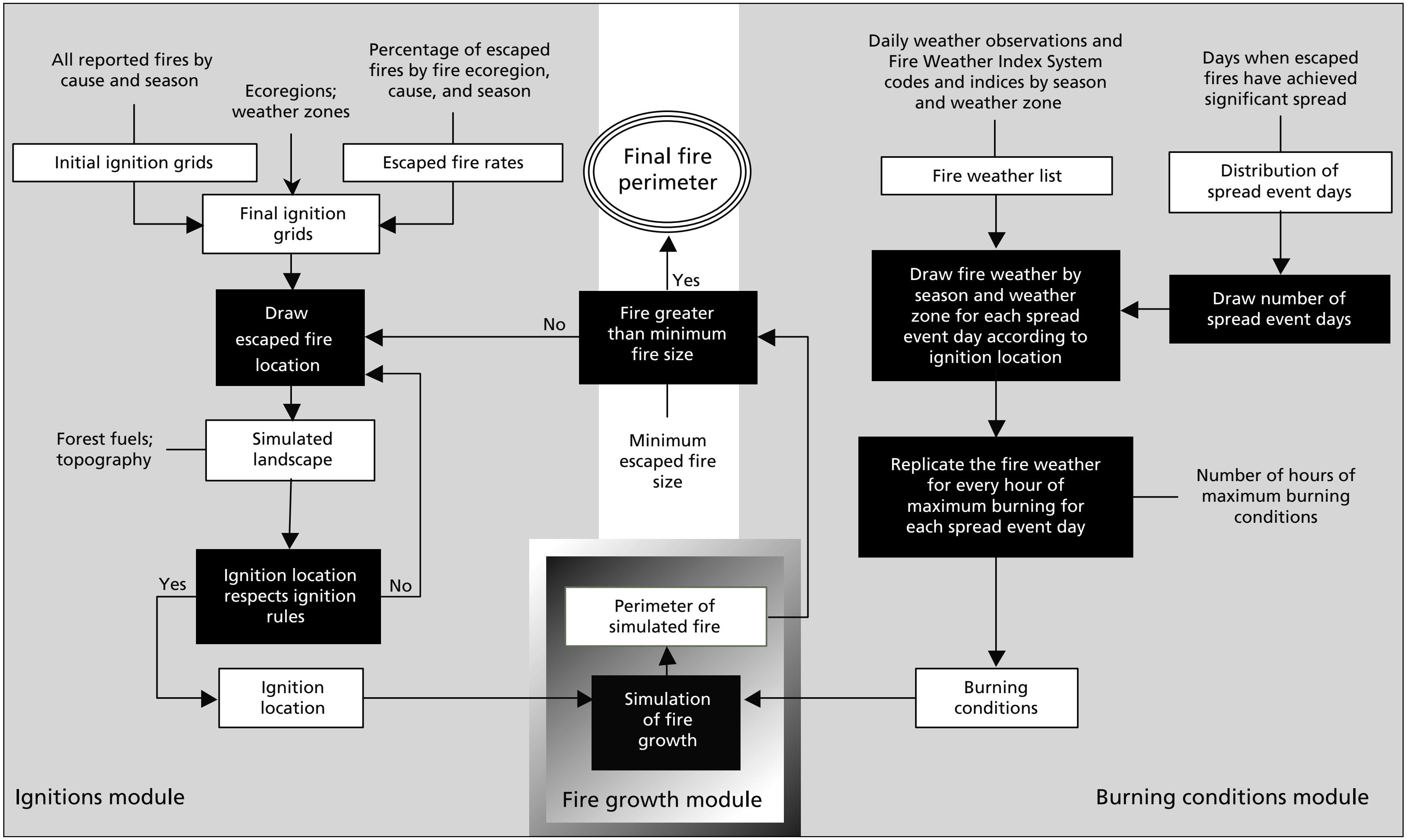

Figure 3. Simulation of individual fires in BURN-P3. The simulated landscape is the area under study. Any text appearing outside a box represents the source data, text in white boxes represents the BURN-P3 inputs, and text in black boxes represents the BURN-P3 processes. The events of the ignitions module and the burning conditions module together lead to the fire growth module. The product resulting from these events is the final fire perimeter.

BURN-P3 Modules

Ignitions Module

In BURN-P3, the ignitions module has two main functions. First, it determines the ignition location of every escaped fire on the study area (i.e., the simulated landscape) through spatially weighted probability grids (ignition grids) and user-specified ignition rules (Fig. 3). Second, it determines the number of escaped fires for each iteration according to a frequency distribution of escaped fires (i.e., the distribution of number of escaped fires) (Fig. 4).

The ignitions module (Figs. 3 and 4) has three main components: the ignition grids, the ignition rules, and the distribution of number of escaped fires; and together these comprise seven input variables.

Initial ignition grids: Coarse-resolution grids (100-km^2 cells) based on all reported fires (fire occurrence data), which represent the fine-scale spatial patterns of fire ignitions, by season and by cause. These grids consist of a count of all reported fires for every 100-km^2 cell by cause (human or lightning) and season (spring or summer), for a specified period (1981 to 2002), which were subsequently modified to better represent ignition patterns. In BURN-P3, coarse-resolution ignition grids are useful to spread out the likelihood of an ignition while conserving landscape-level spatial patterns. It is also important to add stochastic variability to the ignition locations to allow ignitions at points that are absent from the historical data. The cell size of the ignition grids can be determined through exploratory analysis of the distribution of fire locations at various cell sizes, as suggested by Cardille and Ventura (2001). The 100-km^2 resolution was deemed adequate to capture the spatial variation in fire ignitions in Saskatchewan.

Escaped fire rates: The rates (i.e., the likelihood) at which fires escape initial attack and become large, by cause, season, and ecoregion in the study area. Escaped fire rates are presented in tabular form and are calculated from the percentage of escaped fires (≥200 ha) for each combination of cause, season, and ecoregion. The escaped fire rates are used to adjust the initial ignition grids, which are based on all reported fires, to better reflect the

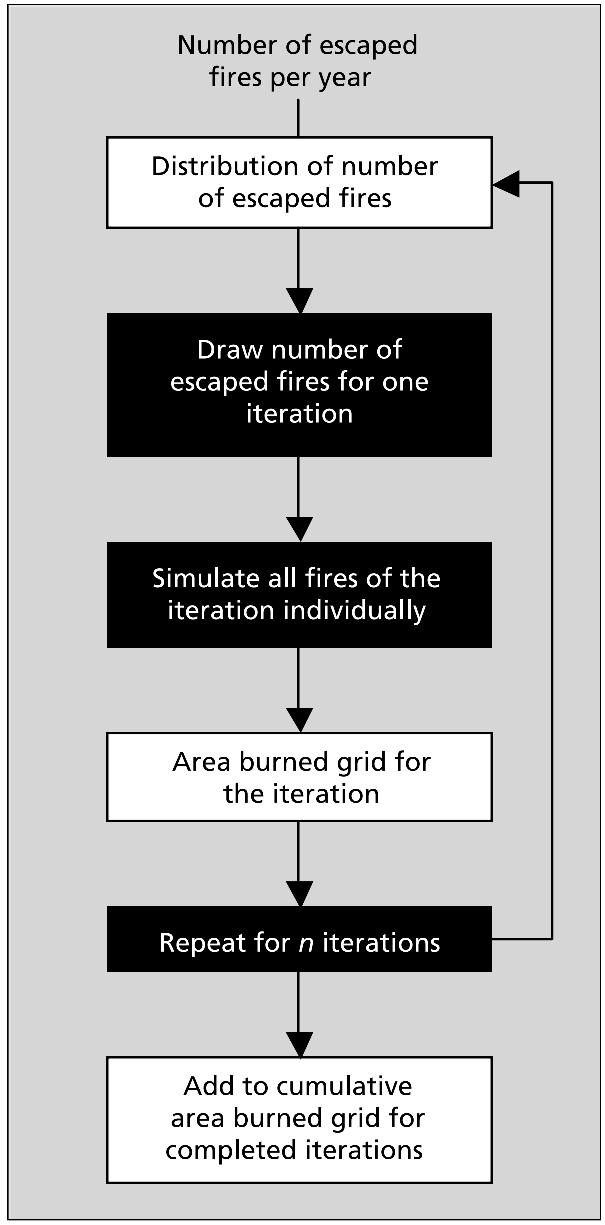

Figure 4. General design of BURN-P3. Any text appearing outside of a box represents source data, text in white boxes represents the BURN-P3 inputs, and text in black boxes represents the BURN-P3 processes. The cumulative area burned grid becomes a burn probability map once it has undergone the calculation in equation 1. A detailed description of the simulation of individual fires appears in Figure 3.

historical patterns of escaped fire ignitions. The initial ignition grids adjusted for escaped fire rates represent the final ignition grids (see below).

Final ignition grids: Spatially weighted probability of escaped fire ignitions, by cause and season. These grids are based both on fire occurrence (initial ignition grids) and escaped fire data (escaped fire rates). Whereas the fire occurrence data provide finer-scale patterns of ignitions, the escaped fire data provide the rates at which fires escape for various combinations of ecoregion, cause, and season. Once the ignition locations are drawn from the final ignition grids, they are located on the simulated landscape for assessment of whether ignition rules have been respected.

Simulated landscape: Representation of the study area, consisting of static grids of forest fuels (FBP System fuel types) and topography (elevation, slope, aspect). Fuel data are mandatory in BURN-P3, whereas topographic information is optional.

Ignition rules: Used to prevent ignitions in cells with specific attributes. These rules can be specific to a study area or may be based on a universal understanding of physical fire behavior that is independent of the study area. BURN-P3 ignition rules are combinations of fuel type, cause, season, and ecoregion for which ignitions are not permitted. These rules are often set through expert advice and are meant to make BURN-P3 ignitions more realistic.

Ignition location: Location of ignition of an escaped fire drawn from the final ignition grids and respecting all ignition rules. This information is transferred to the fire growth module.

Distribution of number of escaped fires: Frequency distribution of the number of escaped fires per year in the study area, based on historical data. BURN-P3 draws from this distribution to determine the number of escaped fires that will be simulated in each iteration.

Ignition grids

The ignition grids are composed of cells grouped into ecoregions. They are created by a stepwise approach, described below, whereby grids based on fire occurrence (the initial ignition grids) are adjusted according to escaped fire rates to produce the final ignition grids. In BURN-P3, the final ignition grids are relative values representing the likelihood that an escaped fire will ignite at a given location according to cause and season. For example, assuming that fuels and weather conditions are the same, a cell with a value of 3 has three times more chances of an ignition than a neighboring cell with a value of 1.

First, initial ignition grids are produced for each combination of fire cause and season (Fig. 5). For the Saskatchewan case study, it was determined that ignition patterns varied significantly between the spring (1 April to 31 May) and summer (1 June to 31 August) seasons, as well as between human-caused and lightning-caused fires (Parisien et al. 2004). The initial ignition grid value (I_{ij}) is based on a count of all reported fires ignited by cause c_i during season s_i in cell i of ecoregion j from 1981 to 2002. However, some modifications to the initial ignition grids are necessary to make the patterns of fire occurrence more representative of escaped fire ignitions. I_{ij} is therefore a modified representation of fire occurrence.

Modifications to the lightning-caused initial ignition grids in the case study consisted of replacing grid cell values of 0 (i.e., no historical fire occurrence) with a value of 1, representing a low relative probability of ignition. This modification was based on the fact that, even if no lightning fires had been reported in a certain area in the last 22 years, there might still be a potential for lightning ignitions in those areas. Modifications to the human-caused ignition grids were more complex because humans ignite more fires, yet are also very effective at extinguishing them while they are still small (e.g., <10 ha). In Saskatchewan, the vast majority of human-caused fire ignitions occurred within 5 km of a main road (Parisien et al. 2004). However, the effectiveness of fire suppression is also the highest in these areas because of early detection and proximity to initial attack bases; therefore, the fires are less likely to escape and burn large areas. Given the difficulty of taking into account the effectiveness of fire suppression, a particularly conservative approach (i.e., one that spread out the probability of ignition) was adopted for modeling human-caused ignitions. Grid cells where a historical fire had been reported were given a value of 2, whereas an occurrence value of 1 was given to cells that encompassed a road but where no fires had been reported in the past (Fig. 5).

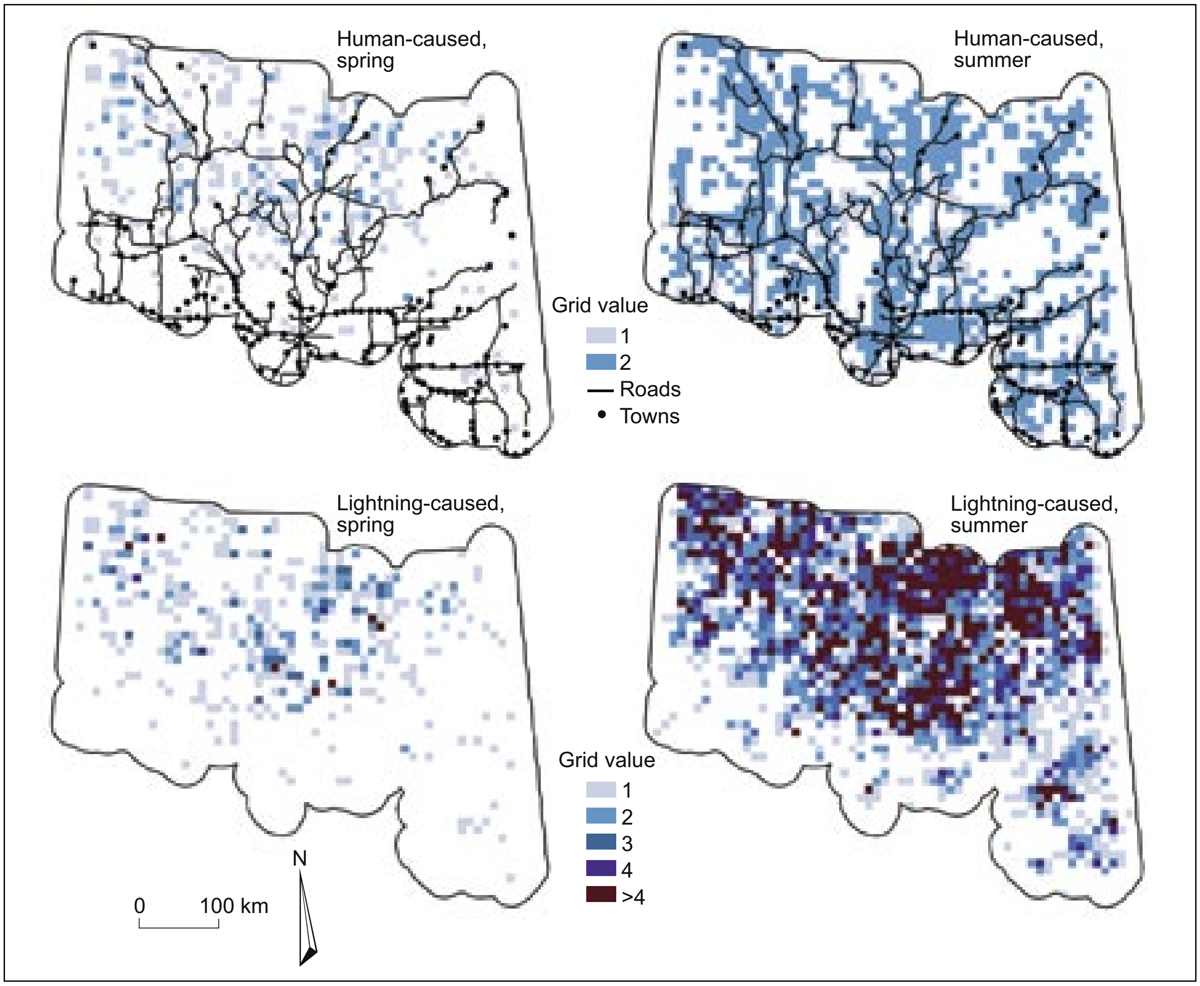

Figure 5. Fire ignition grids developed for the ignitions module. The value in each 10 x 10-km grid cell is a count of all reported fires that occurred in the area over the period 1981 to 2002, by cause and season. Modifications were applied to these grids to make them more representative of escaped fire ignitions (see text).

These modifications to the initial ignition grids are intended to improve the fine-scale spatial patterns of escaped fire ignition (e.g., around roads and towns). However, the rates at which fires escape and become large can vary much more markedly among large geographic areas (i.e., ecoregions) and among causes and seasons than is the case for fire occurrence rates. For example, in Saskatchewan, the ecoregion with the least number of large fires per unit area (the Boreal Transition ecoregion) experiences one of the highest levels of fire occurrence (Parisien et al. 2004). The value of each initial ignition grid must therefore be adjusted to reflect the potential for fires to escape and become large. This adjustment is accomplished via

escape(large) fire rate

the escaped fire rate (E_j), which is calculated for each ecoregion j and which represents the fraction, expressed as a percentage, of all reported escaped fires ≥200 ha in the study area that were ignited by cause c_i during season s_i in ecoregion j from 1981 to 2002:

$$E_j = \frac{e_j}{t} \times 100 \qquad [2]$$

where e_j is the number of escaped fires that occurred in ecoregion j and t is the total number of escaped fires that occurred in the study area from 1981 to 2002 for all ecoregions, seasons, and causes, as presented in Table 4.

Table 4. Escaped fire rates (%) for fires ≥200 ha in the study area[a]

	Lightning-caused		Human-caused	
Ecoregion	Spring	Summer	Spring	Summer
Boreal Transition	0.5	0.9	6.4	0.5
Mid-boreal Lowland	1.8	5.1	6.5	0.0
Mid-boreal Upland	13.4	23.0	14.8	3.2
Churchill River Uplalnd	6.0	15.2	0.0	2.8

[a]These inputs are based on the Canadian Forest Service Large Fire Database for 1981 to 2002.

To allow the escaped fire rates to be compared with fire occurrence rates, the values of each initial ignition grid are summed by ecoregion. The fire occurrence rate (F_j) represents the fraction of all fires reported in the study area that were ignited by cause c_i during season s_i in ecoregion j from 1981 to 2002:

$$F_j = \frac{f_j}{T} \qquad [3]$$

where f_j is the sum of all values of an initial ignition grid in ecoregion j and T is the total of values of initial ignition grids for all zones, seasons, and causes.

The final (i.e., adjusted) ignition grid value (AI_{ij}) for a cell i in zone j is represented by equation 4:

$$\mathrm{AI}_{ij} = I_{ij}\left(\frac{E_j}{F_j}\right) \qquad [4]$$

where I_{ij} is the initial ignition grid value for cell i in ecoregion j, E_j is the escaped fire rate for ecoregion j, and F_j is the fire occurrence rate for ecoregion j. For each simulated fire, the location of escaped fire ignition is drawn from the final ignition grid and compared with the landscape to assess if ignition rules have been respected.

Ignition Rules

The ignition location drawn from the final ignition grid provides the following information: geographic coordinates, cause, season, ecoregion, and weather zones (used only in the burning conditions module). However, the ignition location must be combined with the forest fuels landscape grid to determine the fuel type. Then BURN-P3 can evaluate if the ignition rules have been respected for each combination of fuel, cause, season, and ecoregion. If so, the ignition location is relayed to the fire growth module. If not, the ignition location is rejected and BURN-P3 samples another ignition location from the final ignition grid (Fig. 3).

The following ignition rules were used for the Saskatchewan case study:

- No lightning ignitions in hardwood fuels (D-1) — escaped fires seldom ignite in aspen (Anderson and Englefield 2001; Cumming 2001b).
- No lightning ignitions in Grass (O-1a, O-1b) fuel type — lightning fires typically do not ignite in grass (Cheney and Sullivan 1997).
- No human-caused ignitions in Grass (O-1b) fuel type in summer — standing grass does not usually sustain ignitions after green-up has occurred (FCFDG 1992; Lawson et al. 1994; Cheney and Sullivan 1997).
- No human-caused ignitions in Grass (O-1a) fuel type in the Boreal Transition ecoregion in either spring or summer — most of the land in this ecoregion is farmland (cropland and pasture) that is usually misclassified as the O-1 fuel type. However, in reality, escaped forest fires are rarely ignited by humans in farmland; such ignitions were therefore discarded to avoid an overestimate of escaped fires (based on observations from Saskatchewan Environment).

Distribution of Number of Escaped Fires

The distribution of number of escaped fires determines the number of escaped fires for each iteration. The number of fires is randomly drawn from a frequency distribution of the number of escaped fires per year (Fig. 6). This information was obtained from the CFS Large Fire Database for fires ≥200 ha (Stocks et al. 2003) that occurred between 1981 and 2002.

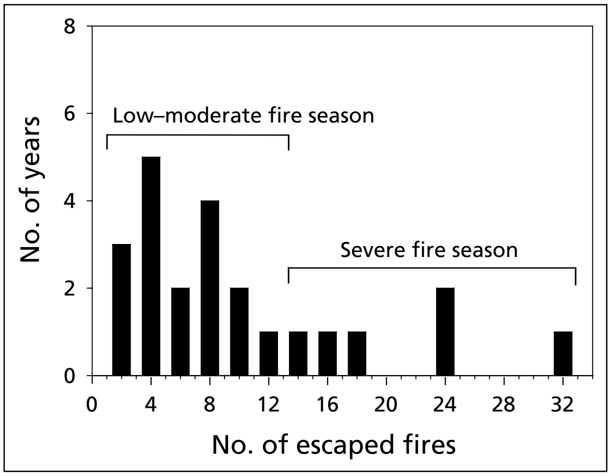

Figure 6. Frequency distribution of escaped fires (≥200 ha). This figure is based on data for the study area from the Canadian Large Fire Database for the period 1981 to 2002.

The frequency distribution of the number of escaped fires per year from 1981 to 2002 revealed two broad patterns in the occurrence of escaped fires (Fig. 6). Two classes of fire years were therefore created: low–moderate (0 to 12 fires per year) and severe (13 to 32 fires per year), representing 70% and 30% of fires, respectively. In BURN-P3, each class represented a uniform distribution, where values were randomly drawn 70% of the time from the low–moderate class and 30% of the time from the severe class for each iteration.

Burning Conditions Module

The burning conditions module provides two types of information: the fire weather conditions under which fire spread is simulated (the fire weather list) and the number of days of significant spread achieved by each fire (distribution of spread event days). While the ignitions module models processes occurring at the landscape scale, the burning conditions module models processes relating to individual fires.

The burning conditions module consists of two main components (the fire weather list and the distribution of spread event days) representing three input variables. The variables are listed here, and a more detailed description of the main components follows the list.

Fire weather list: A list of daily fire weather conditions that are conducive to significant fire spread (i.e., high and extreme conditions). The list is stratified by season and by geographic areas of distinct fire weather (weather zones).

Distribution of spread event days: A frequency distribution of spread event days that is used to determine the number of days for which fire spread is simulated in the fire growth module.

Burning conditions: The combination of fire weather conditions and number of spread event days for each simulated fire.

Fire Weather List

Fire weather data consist of daily records of noon observations of temperature, relative humidity, wind speed, wind direction, and 24-h precipitation, as well as the associated fuel moisture codes and fire behavior indices of the Fire Weather Index (FWI) System (Van Wagner 1987). The FWI System is a subsystem of the CFFDRS that provides three fuel moisture codes — the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC) — and three fire behavior indexes – the Initial Spread Index (ISI), Buildup Index (BUI), and Fire Weather Index (FWI).

The fire weather data that are input into BURN-P3 represent a selection of daily fire weather records for conditions severe enough to be problematic for fire suppression (i.e., resulting in an escape). Studies and fire management observations have demonstrated that most fires ignite in moderate to severe fire weather conditions (Flannigan and Wotton 1991; Anderson and Englefield 2001; Wierzchowski et al. 2002), and achieve most of their propagation under extreme conditions (Stocks 1987, 1989; FCFDG 1992; Hirsch et al. 1998). These conditions typically vary seasonally and spatially, especially if the study area is large. In such cases, it is often necessary to split the study area into distinct weather zones to account for the spatial variation in fire weather. The case study area was therefore divided into seven weather zones (Fig. 7a) delimited on the basis of a combination of ecoregion and ecodistrict (subunits of ecoregions) boundaries. The frequency of wind direction by weather zone (Fig. 8) illustrates the spatial and seasonal variability in wind during high and extreme fire weather conditions from 1990 to 2002.

Fire weather records selected from weather stations in and around the study area (Fig. 7b) were

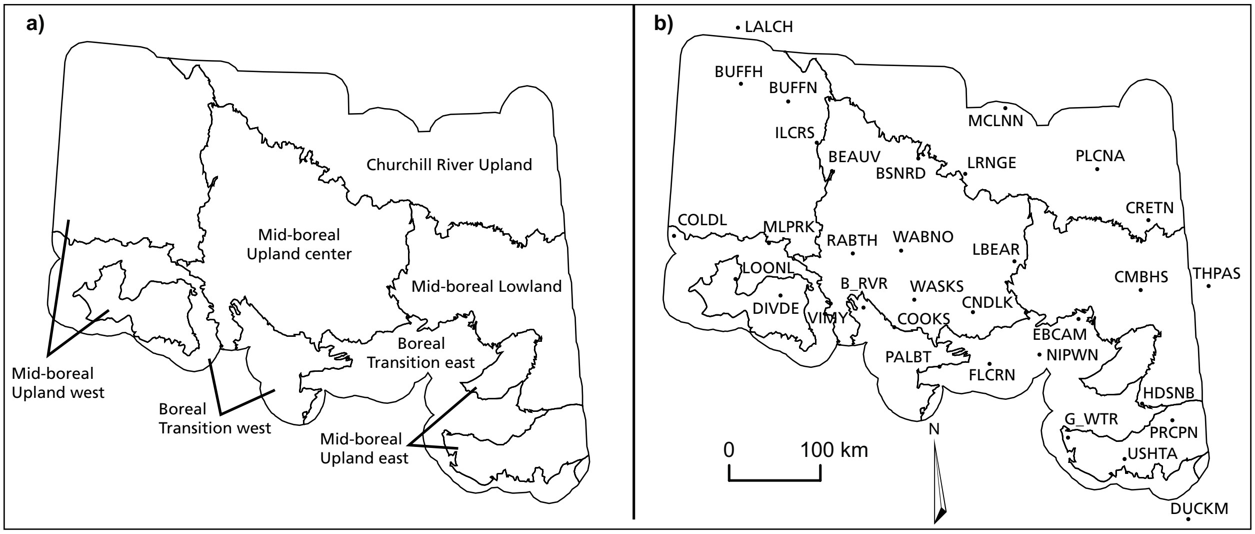

Figure 7. Weather zones of the study area (a) and weather stations used in the fire weather list (b).

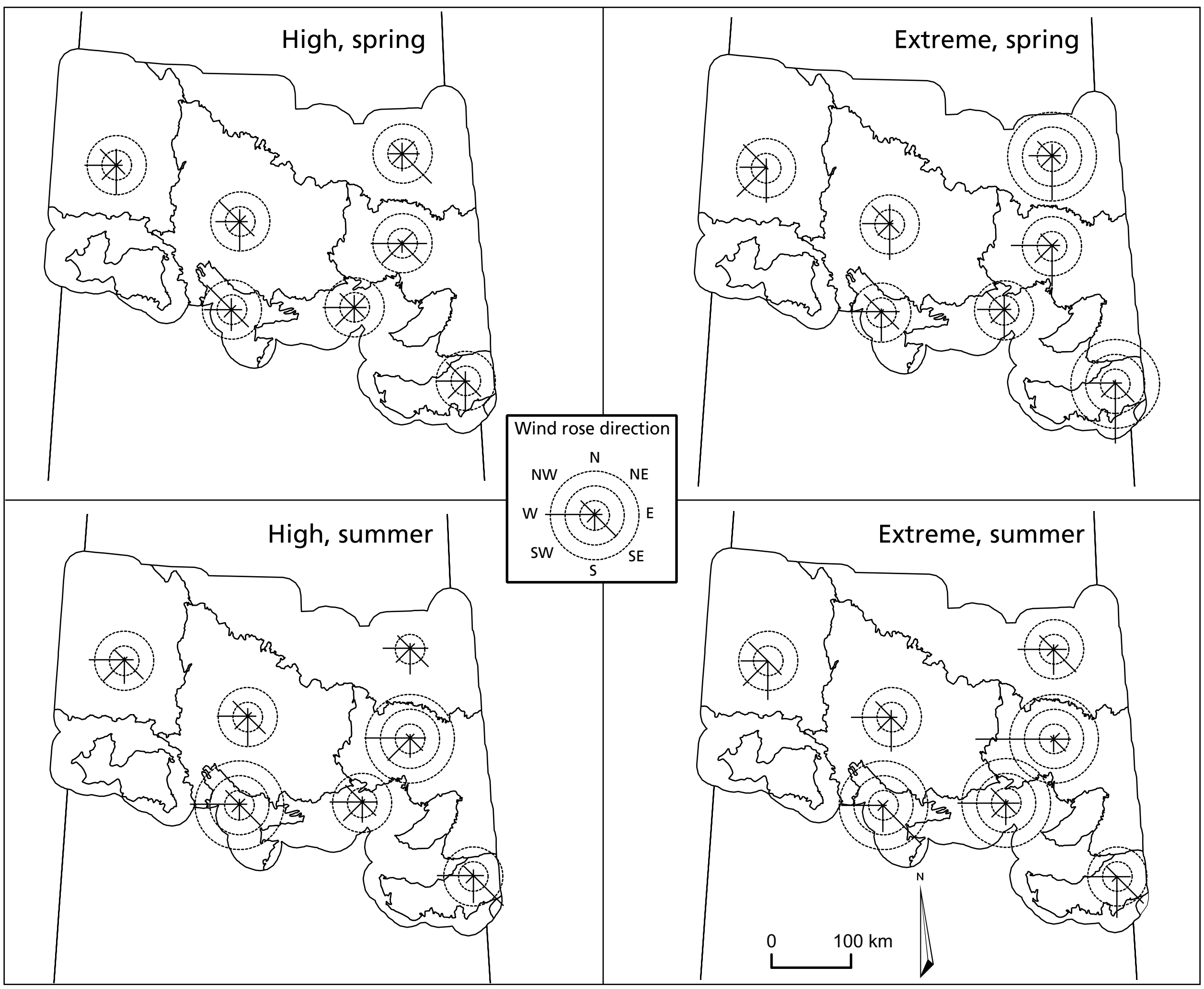

Figure 8. Frequency of daily wind direction for high (8.6 ≤ initial spread index < 12.6) and extreme (initial spread index ≥ 12.6) fire weather conditions for the period 1990 to 2002. This figure represents information in the fire weather list. The wind roses are located in the center of each weather zone. The length of each bar represents the frequency (percent of days), with the concentric rings representing 10% increments in frequency.

stratified by weather zone and season (spring and summer) (Appendix 1). Fire weather data spanned the period 1990 to 2002; weather data before 1990 were inconsistent and sporadic for the study area. To ensure that variability in fire weather was adequately sampled for each weather zone, all the available fire weather records were included (137 to 447 records for each combination of weather zone and season; Appendix 2). The same station was sometimes used for different weather zones to compensate for the small number of weather zones in certain regions.

For each spread event day of each simulated fire, one daily weather record was randomly selected for a given season and weather zone, as provided in the ignition location component of the ignitions module (Fig. 3). Because the fire growth module requires hourly weather data, BURN-P3 replicates the selected daily fire weather values for the number of hours that the fire will burn during the day (a user-specified value that remains constant for all fires). Although in reality, fire weather changes diurnally (Beck and Trevitt 1989), BURN-P3 simulates only the maximum fire weather conditions. Preliminary analyses comparing simulated fires with historical fires indicated that 4 h of burning under maximum conditions provided representative estimates of actual fires. Fires usually burn for more than 4 h a day, but fire weather conditions are usually less than maximum; therefore, this short burning time is compensated by the fact that fires burn more area under maximum fire weather conditions.

Fire weather records for the fire weather list were selected from the database of historical weather records on the basis of conditions that resulted in HFI for which fire suppression is difficult or impossible (≥4 000 kW/m) (Alexander et al. 1991; Stocks and Hartley 1995; Hirsch and Martell 1996; Hirsch et al. 1998). This HFI generally corresponds to conditions driving intermittent and continuous crown fires in coniferous fuel types. HFI is a measure of energy output of the fire per unit length of the fire front (kW/m) and represents one of the primary outputs of the FBP System (FCFDG 1992). Fire weather conditions that were high (4 000 kW/m ≤ HFI ≤ 10 000 kW/m) or extreme (HFI>10 000 kW/m), assuming a BUI of 50 (the average BUI of all fires in the FBP System database), were averaged for the C-2 (Boreal Spruce), C-3 (Mature Jack or Lodgepole Pine), and C-4 (immature Jack or Lodgepole Pine) fuel types. These fuel types were chosen because they are the main coniferous fuel types in the study area that are problematic for fire suppression. However, because HFI is not part of the fire weather databases, it had to be linked to a fire weather variable. The ISI was chosen because of its strong relation to the spread of large fires. Daily fire weather records could therefore be selected on the basis of their ISI values.

It was determined that days on which 8.6 ≤ ISI <12.6 corresponded to conditions of high HFI, whereas days with ISI ≥ 12.6 corresponded to conditions of extreme HFI. These two values represent the 90.3th and 96.7th percentile values of ISI for all days in the fire weather databases. The purpose of having both high and extreme fire weather categories was to ensure that a representative proportion of days from each category was included in the model to approximate the actual frequency of conditions under which escaped fires burn.

Distribution of Spread Event Days

The simulation of fires in BURN-P3 was modeled only for spread event days, because it is these days that are responsible for almost all of the area burned by a fire. Similar to the situation for distribution of number of escaped fires, BURN-P3 draws spread event days from a frequency distribution of spread event days. A spread event day was defined as a day when fire growth was ≥4% of the final fire size. The frequency distribution of spread event days derived from a database of daily estimates of area burned for 130 escaped fires (1993 to 2000) (Fig. 9) essentially conformed to a Poisson distribution (Zar 1999) with an intensity parameter (i.e., mean) of 3.76. As such, spread event days for the case study were incorporated into BURN-P3 by random draws from the Poisson distribution. However, any type of distribution may be used to model spread event days.

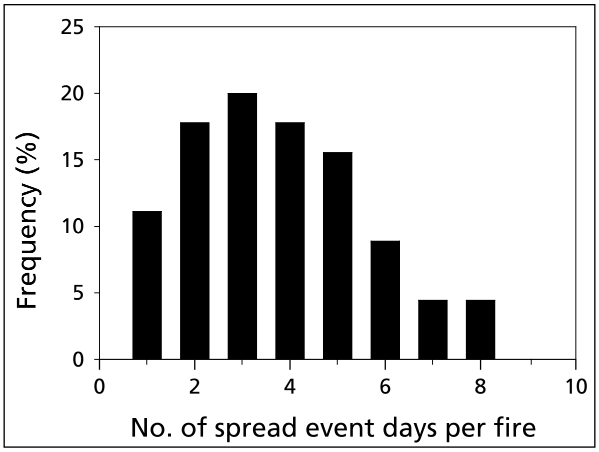

Figure 9. Frequency distribution of spread event days. This figure is based on data from the database of 130 escaped fires that occurred in central Saskatchewan from 1991 to 2000.

Fire Growth Module

The fire growth module requires outputs from the other two modules, such as fire ignition information (season, coordinates for the point of origin, stage of green-up), hourly fire weather data, and number of spread event days. It also uses spatial data: the FBP System fuel grid, which is mandatory, and topography grids (elevation, aspect, and slope), which are optional. For this case study, topography was omitted to reduce computing time and because the study area is flat to gently rolling. Fire weather provided by the burning conditions module is processed in the fire growth module in hourly time steps for a user-specified number of hours per day. The user must experiment with the length of the daily burning period to ensure that resulting fire sizes and shapes are realistic.

The fire growth module uses a deterministic fire growth model, Wildfire (Todd, J.B. 1999. User documentation for the Wildland Fire Growth Model and the Wildfire display program. Fire Res. Network, Can. For. Serv., North. For. Cent., Edmonton, AB. Unpubl. rep.), which was used previously by Hirsch et al. (2004) for landscape fire modeling. Wildfire is a computerized eight-point elliptical fire growth model that uses geographic information system data, FBP System calculations, and diurnally adjusted weather calculations (Beck and Trevitt 1989) to estimate hourly fire perimeters, although this last function is turned off in BURN-P3. For BURN-P3, Wildfire outputs final fire perimeter and size, as well as the area burned, by fuel type, for each fire.

Before Wildfire is used in BURN-P3, various internal settings must be adjusted. Some FBP System fuel types, especially the ones affected by green-up, have adjustable parameters. Here, throughout the study area, these adjustable fuel types were defined as leafless during the spring season and green or leafed out during the summer season. The percent curing (i.e., percent dead) of the Grass (O-1a, O-1b) fuel type was set at 65% for spring and 55% for summer, whereas the fuel load for this fuel type was set at the standard 0.3 kg/m^2. It was necessary to set curing at rather low levels to partly offset inadequacies in the fuel data, namely the misclassification of large agricultural areas as the O-1 fuel type. The Mixedwood (M-1, M-2) fuel type was set at 50% conifer on the basis of the average vegetation cover for this fuel type. For other applications of BURN-P3, these adjustments should be done heuristically by the user, in accordance with expert advice.

Scenarios

The purpose of producing BP map scenarios is to evaluate the response or sensitivity of the BP to certain variables or conditions. Three versions of the BURN-P3 BP map were produced to evaluate the change in BP under different conditions (Table 5): a recent BP map of the study area with full vegetation (i.e., not incorporating the nonfuel areas of recent burns), to evaluate the spatial pattern in BP when the area is fully vegetated; a recent BP map of the study area in which the large recent burns from 1993 to 2002 appear, to evaluate the spatial effects of large burns on BP; and a historical BP map from 1993, to assess if recent burns (from 1993 to 2002) have occurred in regions of proportionally higher BP. The fuels coverage of the historical BP scenario was the same as for the fully vegetated area scenario. The second scenario represents variation in the fuels grids relative to the first scenario, and the third scenario represents variation in the ignition grids relative to the first scenario. Another scenario, presented below in the section entitled "BP mapping with uniform ignition grids," was also created. The values for this BP map were sampled by fuel type from the FBP fuels grid to examine whether fuel type was the main factor controlling BP. The results were used in the discussion of the BP map of the fully vegetated area scenario.

Table 5. Characteristics of the three BURN-P3 scenarios produced for the case study in Saskatchewan

Scenario	Map year	Large fires[a] and ignitions[b]	Fuels grid
BP[c] map of fully vegetated area	2003	1981–2002	Does not include recently burned areas
BP map including recent burns	2003	1981–2002	Fires from 1993 to 2003 reclassified as nonfuel
Historical BP map	1993	1981–1992	Does not include recently burned areas

[a]These data were incorporated directly into the distribution of number of escaped fires.
[b]These data were used to make the ignition grids by season and cause in the ignitions module.
[c]BP = burn probability.

Validation and Calibration

This section describes some aspects of the performance of BURN-P3. First, an analysis was performed to evaluate whether recent fires have occurred in regions of higher BP proportionally more often than in areas where no fires occurred in the historical BP scenario. Second, the model was analyzed to verify whether the BURN-P3 inputs yielded representative distributions of fire size. Third, stability — the relative change in different BP maps with the same inputs — was assessed as a function of the number of iterations. Fourth, the sensitivity of the model to changes in historical spatial patterns of ignitions was evaluated by producing a BP map with uniform ignition grids. Finally, the effect of changing the distribution of spread event days on the resulting BURN-P3 fire size distributions was examined.

Recent Fires in Relation to BP and Historical Fire Occurrence

The historical BP scenario was produced to assess the predictive capability of BURN-P3. This analysis involved evaluating the relationship between large fires observed between 1993 and 2002 and the BP determined from a 1993 BP map produced with ignition grids based on historical fires from 1981 to 1993. Despite the limited large fire data set, if BURN-P3 is effective in predicting wildfire susceptibility, areas of high BP should be found where recent large fires have occurred more often than would be expected by chance alone. A contingency table was used for this comparison, whereby the BP values of each cell of the historical BP scenario were categorized into seven classes (0%, >0% to 0.6%, >0.6% to 1.2%, >1.2% to 1.8%, >1.8% to 2.4%, >2.4% to 3.0%, >3.0%). The contingency table was used to compare the proportions of BP classes and to demonstrate whether fires occurred more often than expected in cells with high BP. The BPs were tallied for cells where fires occurred between 1993 and 2002 (“fire presence”), as well as cells where no fires occurred (“fire absence”). The results were summarized in a 2 × 7 table for each ecoregion. A goodness-of-fit test (chi-square) was used to compare the observed and expected frequencies for the BP in each class.

Fire Size Distribution

Frequency distributions of the size of simulated fires for the BP map of the fully vegetated area and the BP map incorporating recent burns were compared with the historical distribution of fire size for the study area from 1945 to 2002. The purpose of this comparison was to evaluate how well BURN-P3 replicates the fire sizes on which its inputs are based.

Optimal Number of Iterations

BURN-P3 is a computationally intensive model, largely because of the deterministic fire growth modeling. For this study, it took approximately 120 h to produce one 500-iteration BP map for the study area on a 1.0-GHz, 256-MB personal computer. Therefore, it was necessary to find an acceptable number of iterations representing a reasonable compromise between the stability of the modeled outputs and computation time.

To determine the optimal number of iterations, an initial BP map was produced with 50 iterations, and the simulation was then repeated to produce 19 additional versions, each with a progressively larger number of iterations. The total number of iterations in each successive simulation was increased by 50, such that the 18th, 19th, and 20th maps were produced with 900, 950, and 1 000 iterations, respectively. The average change in BP between two successive simulations was calculated from equations 5 to 7.

To determine the change in BP between two successive maps, the values in each cell had to be standardized (s):

$$\mathrm{sBP}_{ik} = \frac{\mathrm{BP}_{ik}}{\left(\frac{\sum_{i=1}^{n} \mathrm{BP}_{ik}}{n}\right)} \qquad [5]$$

where BP_{ik} is the BP for cell i produced with k iteration intervals, and n is the total number of cells.

The change in standardized BP ($\Delta\mathrm{sBP}_{ik}$) that results when the simulation is run for an additional 50 iterations is determined from equation 6:

$$\Delta\mathrm{sBP}_{ik} = \frac{\left|\mathrm{sBP}_{ik} - \mathrm{sBP}_{i,k-1}\right|}{\mathrm{sBP}_{ik}} \qquad [6]$$

where sBP_{ik} is the standardized BP for cell i produced with k iteration intervals and $\mathrm{sBP}_{i,k-1}$ is the standardized BP for cell i produced with k–1 iteration intervals.

The average change in BP over all cells in a map produced with k iteration intervals that results from adding 50 iterations to the simulation is determined from equation 7:

$$\overline{\Delta\mathrm{BP}_k} = \frac{\sum_{i=1}^{n} \Delta\mathrm{sBP}_{ik}}{n} \qquad [7]$$

where n is the total number of cells.

By plotting the $\overline{\Delta\mathrm{BP}_k}$ according to the number of iterations, the optimal number of iterations can be selected according to a minimum desired level of relative change, which is usually determined beforehand.

BP Mapping with Uniform Ignition Grids

Inputs to the ignitions module were changed to examine the degree to which spatial patterns of ignitions influence the BP. Two actions were carried out to homogenize the probability of ignition: all cells in the ignition grids were given the same relative weight (e.g., 1), and the escaped fire rates were ignored. Ignitions were not completely randomized, since the fuels-based ignition rules were retained to provide a basis for comparing this BP map with the BP map of the fully vegetated area scenario.

Effect of Changing Distribution of Spread Event Days on Fire Size Distribution

The distribution of spread event days was modified to evaluate its effects on the size distribution of simulated fires. Although other factors affect fire size distribution, the spread event days distribution is the most important because it determines the duration of fires. It is also the easiest input to modify to obtain a more historically accurate fire size distribution in BURN-P3.

Two BP maps were produced with two different modifications to the Poisson distribution used to select spread event days. The first modification consisted of forcing a uniform distribution of four spread events on each simulated fire. Second, spread event days were modeled as an exponential function with mean equal to the mean number of spread event days (3.76 per fire) observed in the spread event days database:

$$f(x) = e^{-\lambda x} \qquad [8]$$

where x represents the number of spread events per fire and $\lambda = 1/\bar{x}$, where $\bar{x}$ is the mean number of spread event days. These two distributions were used strictly for exploratory purposes.

Scenarios

BP Map of Fully Vegetated Study Area

The BP maps produced by BURN-P3 represent the likelihood of each cell burning in a single year, expressed as a percentage (Fig. 10). Despite a wide range of BP values (0% to 5.4%), the highest values are still relatively low, such that burning is unlikely in any given cell; the map as a whole represents a collection of these low probabilities. The BP for each cell could represent an absolute measure of wildfire susceptibility. However, because there is still much to learn about the approach and the role of the different inputs, the BPs are probably best interpreted in a relative context, whereby a cell with a BP of 3% is more likely to burn than a cell with a BP of 1%.

After 500 iterations, the BP map for the fully vegetated area scenario contained highly contrasting regions of high and low BP (Fig. 10). BP was spatially variable across the region, which suggested that average values of fire recurrence over an entire region (e.g., ecoregion, township, forest management area) may be a poor indication of the likelihood of burning at a specific location within an area. That areas of high BP are highly localized, despite the fact that ignitions are modeled in a spread-out, conservative manner, is partly a consequence of fire size. For example, given the size of fires in the boreal mixedwood of western Canada, which were the basis for the model, spatial dependency between neighboring cells might be expected. In other words, the outcome for each cell is not only dependent on its own conditions affecting fire ignition and spread but is also strongly dependent on the conditions affecting its neighbors. The influence of these surrounding cells will vary because of spatial variations in ignitions, fuels, and fire weather, but also in terms of landscape features, such as lakes and recent burns.

A visual comparison between the ignition grids (Fig. 5) and the BP map shows that BP is influenced, but not primarily driven, by ignitions (see "BP mapping with uniform ignition grids," below). Similarly, the amplitude in the values of average BP among fuel types was not as important as had been anticipated, as shown by analysis of a BP map produced with the same fuel grids as the BP map of the fully vegetated area scenario but with uniform ignition grids (Fig. 11). The difference in average BP between the most flammable fuel type, Boreal Spruce (C-2), and the least flammable, Leafless Aspen (D-1), was less than 1% for the BP map with uniform ignition grids, which suggests that many factors influencing BP operate at multiple spatial scales or that factors driving BP undergo complex interactions. The results suggest that in a fire regime where large fires are responsible for most of the area burned, features at a considerable distance can affect BP at a given location. Indeed, the spatial distribution of BP appears to be chiefly a function of the amount and configuration of flammable fuels and features at the landscape scale, but this interpretation remains to be fully assessed.

The greatest concentration of high BP areas occurred in the central part of the study area, which is characterized by large tracts of the Boreal Spruce fuel type, consistent with the results of Rupp et al. (2002) in Alaska. However, even in continuous C-2 fuel type, the BP of some high BP areas is 10 times higher than that of adjacent areas. The presence of nearby D-1 fuel type seems to be responsible for the lower BPs in conifer-dominated areas. Conversely, some regions where D-1 fuels are present have a high BP, which indicates that, in the study area, there might be a threshold in terms of the quantity and configuration of potential fuel reduction treatments to become effective in reducing BP.

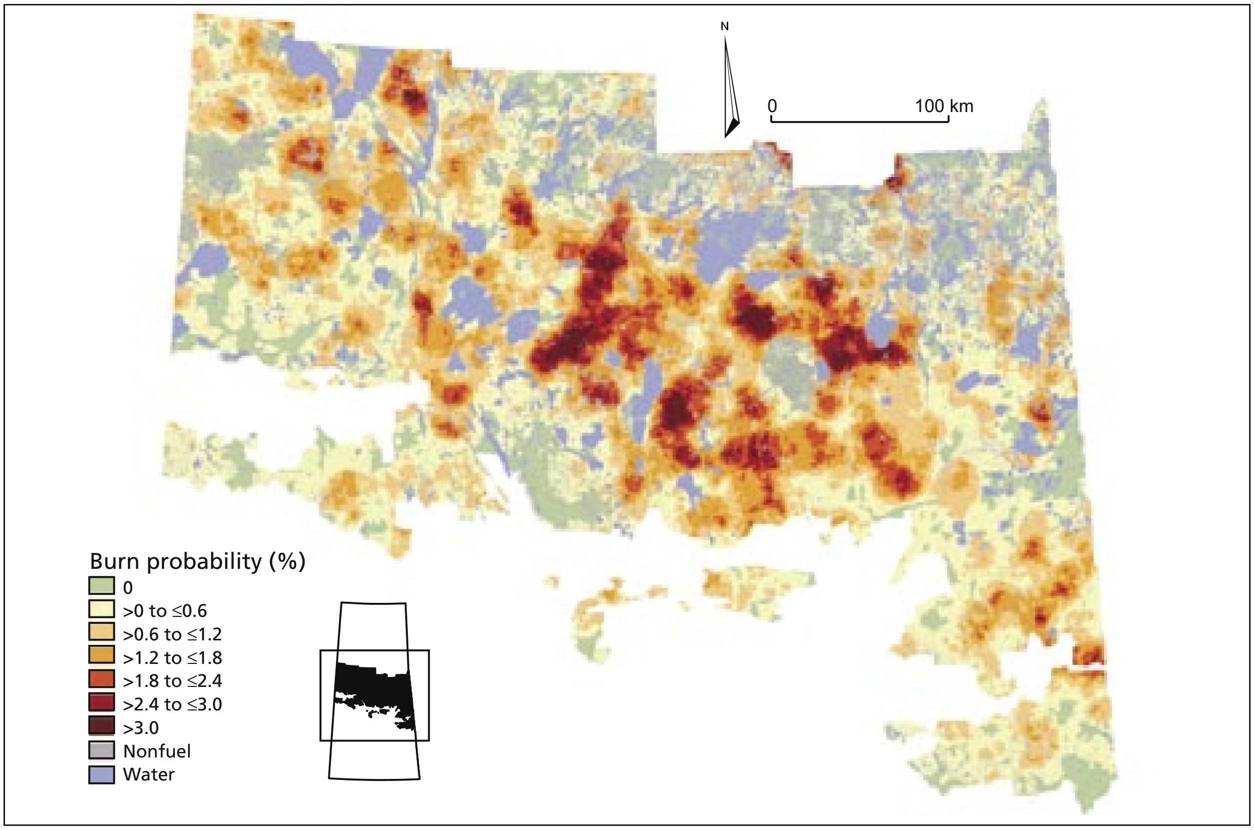

Figure 10. A 500-iteration burn probability map of the fully vegetated area scenario, as applied to the study area in central Saskatchewan, for 2003.

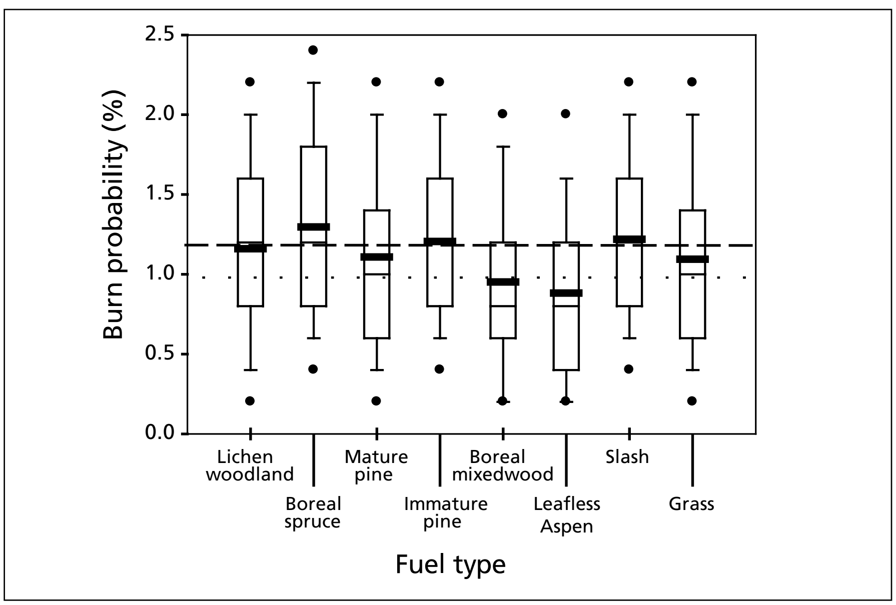

Figure 11. Central tendency and dispersion of the burn probability values for each fuel type for a BP map using uniform ignition grids (with ignition rules applied). In each case, the box represents the 25th and 75th percentiles, the thin horizontal line within the box is the median, the whiskers represent the 10th and 90th percentiles, the bold horizontal line represents the mean, and the points represent the 5th and 95th percentiles.

BP Map Incorporating Recent Burns

The BP map incorporating recent burns included as nonfuels represent the areas on the landscape that had been burned by recent large fires (Fig. 12). This is the best available representation of current vegetation conditions in Saskatchewan, as reported by Amiro et al. (2001). However, the recent burns do not include unburned areas within the fire perimeters, which can represent a significant fraction of their area (5% to 20%) (Eberhart and Woodard 1987; Bergeron et al. 2002; Andison 2003). Recent burns may also have a certain degree of flammability, due to variation in burn severities (Kafka et al. 2001) or because of regrowth of fine fuels, such as grass a few years after a fire, which can sometimes support a spring fire. In general, fire spread is reduced or halted in areas of recent burns because horizontal and vertical fuel continuity has been eliminated or reduced (Schimmel and Grandström 1997).

Relative to the previous scenario (see Fig. 10), the addition of recent burns produced similar BP in some areas, increases in BP in other areas, and decreases in BP in yet others. There was less area available for burning, but the number of simulated fires was the same as in the previous scenario, which explains why some areas of high BP were more concentrated. In spite of this, an overall reduction in average BP across the landscape (from 1.20% to 1.07%) was observed, with many areas of reduction located along the edges of the recent burns. This peripheral decrease in BP can be attributed to a disruption of the trajectories of the simulated fires, as well as a reduced probability of ignition in the area surrounding a burn because of increased regional cover of nonfuel. Parisien et al. (2003) reported a reduction in BP >30% in a 1-km band outside in the periphery of recent burns of greater than 10 000 ha. This observation exemplifies the potential influence of prescribed burning in reducing landscape-level BP, because the reduction in wildfire susceptibility not only occurs within the burns, but can also extend well beyond their perimeters.

Fires were on average smaller in this scenario (see "Fire size distribution," below) than in the fully vegetated area scenario. This observation is consistent with results from the Swedish boreal forest (Niklasson and Grandström 2000; Hellberg et al. 2004), where fires that burned in areas with a high cover of nonflammable fuels (e.g., recent burns, wetlands) were likely to be smaller, on average. In the boreal mixedwood of Saskatchewan, such a spatiotemporal feedback mechanism could entail changes in the number of escaped fires, as well as their final size. If so, a period of high fire activity could be followed by a subsequent decrease in area burned. Conversely, it is possible that in some regions fire suppression by modern methods extinguished small to medium-size fires, which might have led to greater horizontal fuel continuity on the landscape over time, making it more susceptible to very large fires, as proposed by Bergeron et al. (2004) for an area of western Quebec.

Historical BP Map

To estimate the predictive capabilities of BURN-P3, the historical BP scenario was used to evaluate BP for 1993 (Fig. 13). This coarse assessment provided a first approximation of the model's capabilities. Furthermore, the fires observed in 1993–2002 to which BP was compared represented only one of an infinite number of possible outcomes. The historical BP scenario is similar to the BP map for the fully vegetated area scenario because the same fuels were used and the period for modeling ignitions overlapped between the two scenarios (1981 to 1992 and 1981 to 2002).

Visual assessment showed that most of the large fires of the last decade occurred within or near areas of high BP. However, the occurrence of fires in low BP areas (Fig. 13) does not imply poor prediction. Some areas burned more than expected, but low BP areas are also expected to burn from time to time. For example, during years of severe drought, such as 1995 and 1998, fuels that typically have low flammability, like bogs and muskegs, can become highly flammable.

Here, the BP is best interpreted by ecoregion. The Churchill River Upland, for example, had lower BP than the other ecoregions, but these results seem questionable. In this ecoregion, the numerous small lakes constantly disrupt fire paths, which results in smaller fires, and hence lower BP. In BURN-P3, this problem is somewhat amplified because Wildfire does not model breaching of nonfuels through fire spotting, which is a common phenomenon in high-intensity boreal fires. Even though lakes can effectively reduce fire size (Amiro et al. 2001; Kasischke et al. 2002; Rollins et al. 2002), in Saskatchewan large fires of the Boreal Shield ecozone have historically been as large as the ones in the Boreal Plain ecozone (Parisien et al. 2004). However, it was not possible to exclude the possibility that, before fire suppression, the largest fires of the Boreal Plain ecozone were indeed larger than those in the Boreal Shield, as evidenced by some fire history studies (e.g., Murphy and Tymstra 1986).

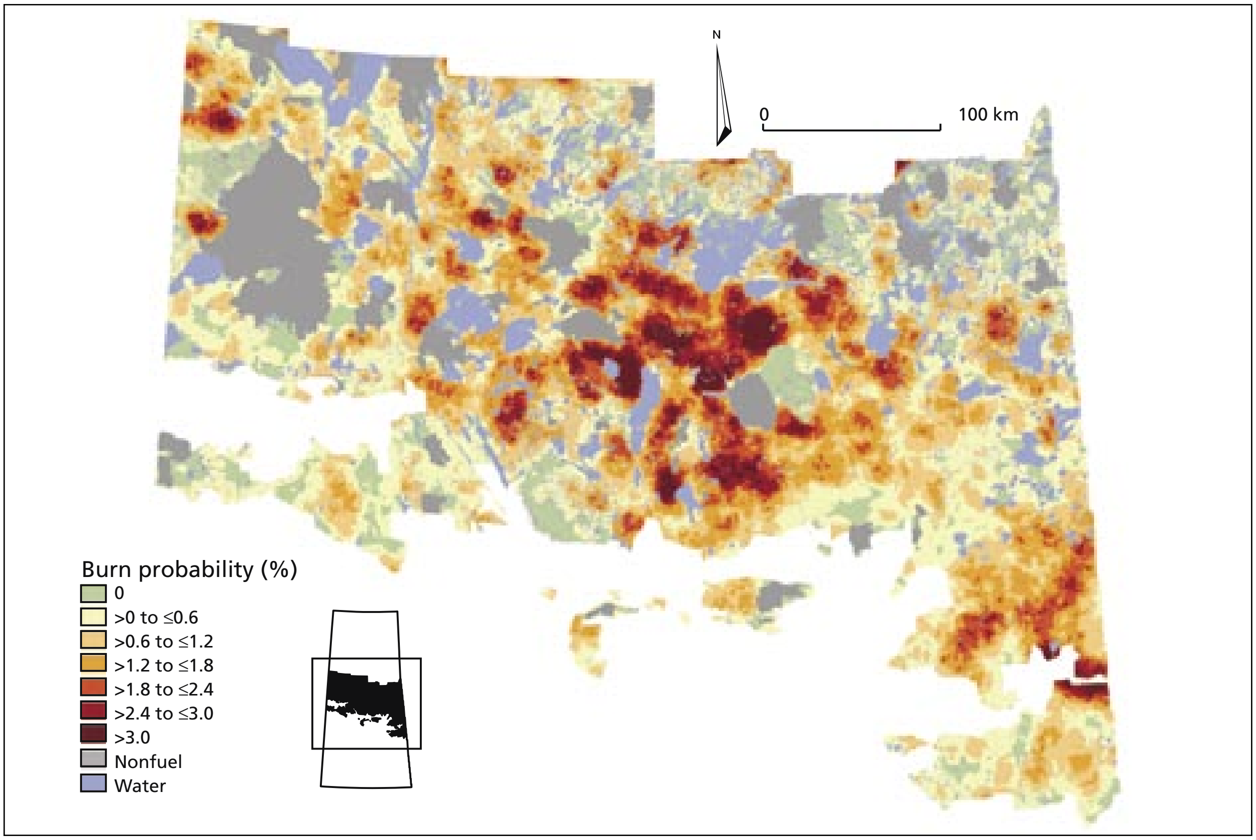

Figure 12. A 500-iteration burn probability map incorporating recent burns, as applied to the study area in central Saskatchewan, for 2003.

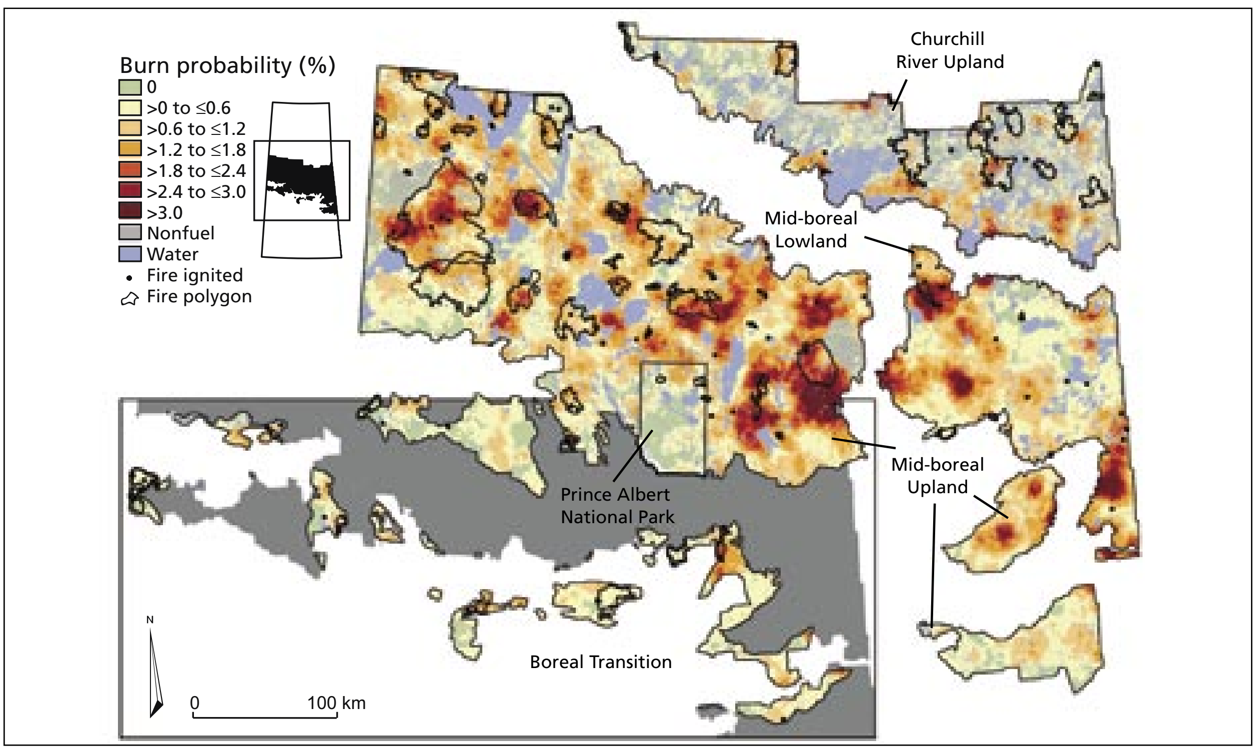

Figure 13. A 500-iteration burn probability (BP) map of the historical BP scenario, as applied to the study area in central Saskatchewan, for 1993. Each ecoregion is shown separately. The Saskatchewan Environment polygons of fires ≥1 000 ha and the point locations from the Canadian Large Fire Database for fires ≥200 ha (1993 to 2002) are overlaid on the BP map.

Validation and Calibration

Recent Fires in Relation to BP and Historical Fire Occurrence

In all ecoregions, there were significant differences in the area (i.e., number of cells) of simulated BP classes where fires had burned recently (1993 to 2002) (“fire presence”) and those that remained unburned (“fire absence”) (chi-square, df = 6, $p < 0.001$ for each ecoregion). However, the contrast was minimal in the Boreal Transition ecoregion (Fig. 14). Excluding this latter ecoregion, cells where fires had burned were proportionally more often associated with high BP classes than “fire absence” cells. This was particularly obvious for the Mid-boreal Lowland and Mid-boreal Upland ecoregions, where the area with a BP greater than 2% was much higher in the “fire presence” cells than in the “fire absence” cells. The former of these two regions had an unexpectedly high proportion of cells in the >0 to 0.6% (i.e., low) BP class for the “fire presence” category. This is mostly due to the previously stated inaccuracies in the fuel data, as a large proportion of the C-2 fuel is actually wetland. The statistical test was not entirely appropriate, because there is some degree of dependence among the cells (i.e., spatial autocorrelation). An attempt was made to reduce the sample size (i.e., number of cells) in the goodness-of-fit analysis according to spatial autocorrelation (i.e., spatial dependency), which extends to about 25 km in an isotropic variogram (Cressie 1993), but this resulted in a data set that was too small for chi-square analysis.

The approach used here for evaluating BURN-P3’s predictive capabilities represents a preliminary step and should be interpreted with caution. For example, 10 years of data is not nearly enough to reveal a realistic trend in areas burned; a longer period (e.g., 50 years) would be required to accurately assess the method. Furthermore, the BP map to which large fires are compared should be updated every few years to provide adequate spatial representation of wildfire susceptibility, because as the landscape changes, so does BP. In spite of this, BURN-P3 appeared to predict the area burned by large fires fairly well.

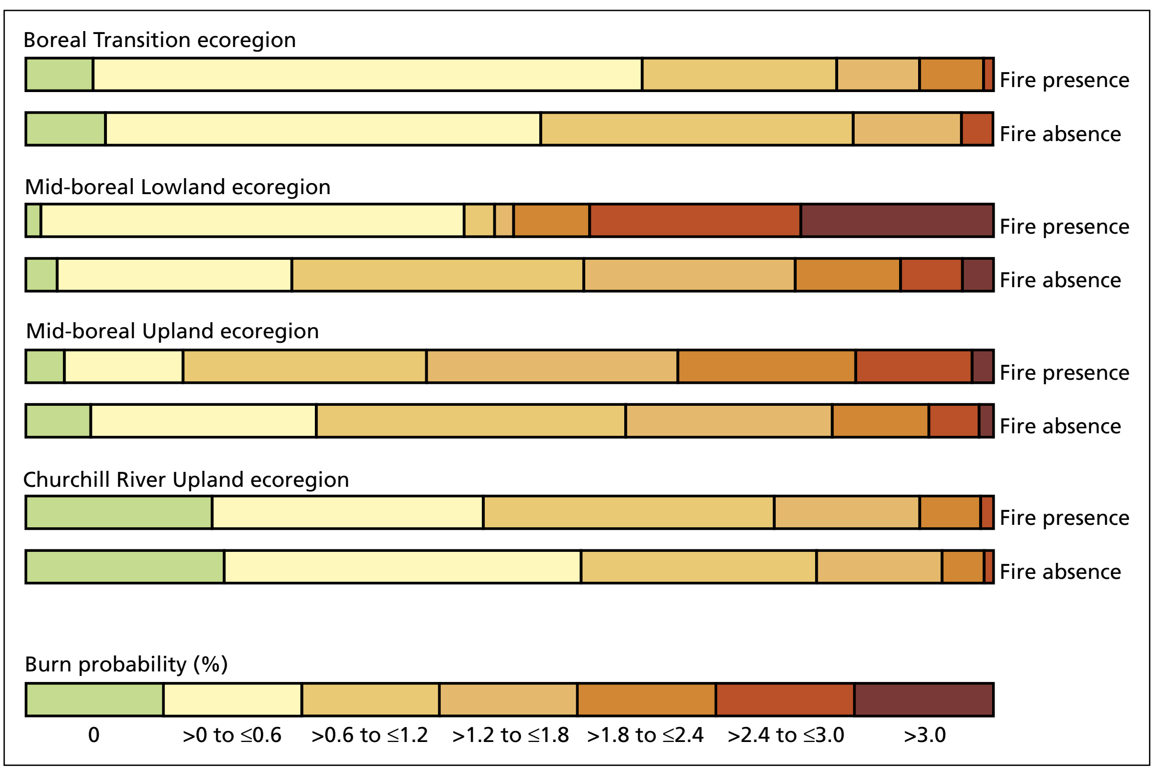

Figure 14. Proportions of cells across the landscape in each burn probability (BP) class of the historical BP scenario for areas where a fire burned between 1993 and 2002 (fire presence) and areas where no fires burned during that period (fire absence).

Fire Size Distribution

The fire size distribution produced by BURN-P3 approximated an exponential function, similar to the historical distribution for all three scenarios, which suggests that the simulated fire sizes were realistic (Fig. 15). However, the shape of the distribution of simulated fires differed slightly from the historical database. BURN-P3 produced an insufficient proportion of fires < 5 000 ha, but accurately simulated the proportion of very large fires (> 50 000 ha), which have historically accounted for over 70% of the total area burned in Saskatchewan (Parisien et al. 2004).

The mean fire size was significantly greater than that of historical fires for some ecoregions (Table 6), particularly in the Boreal Transition and Mid-boreal Upland ecoregions, where the size of simulated fires was on average heavily overestimated, largely because of the poor quality of fuel data. It is also possible that, for some ecoregions, the number of spread event days was too high. For example, the duration of escaped fires in the Boreal Transition ecoregion is typically shorter than in the other ecoregions of the study area. By contrast, the size of simulated fires in the Mid-boreal Upland and Churchill River Upland ecoregions, where the fuel data are a more accurate representation of the current landscape, was similar to that of historical fires. These two regions therefore represent the most accurate estimates of BP, although BURN-P3 did not do as well in terms of predicting recent fires in relation to BP in the Churchill River Upland ecoregion.

The BP map incorporating recent burns produced gaps in fuel continuity because of recent burns that resulted in an overall reduction of mean fire size (by about 1 000 ha) relative to the BP map of the fully vegetated area. This feature was observed for all ecoregions except the Boreal Transition ecoregion (Table 6). However, this ecoregion and the Mid-boreal Lowland ecoregion were not as fragmented by incorporation of recent burns as the other two ecoregions.

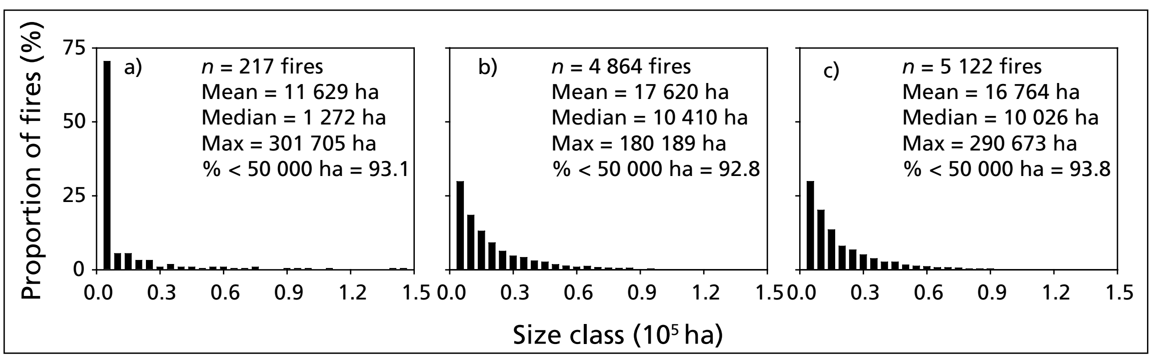

Figure 15. Frequency distribution (5 000-ha classes) of escaped fires (≥200 ha) from the Canadian Large Fire Database (1981 to 2002) (a), the burn probability (BP) map of the fully vegetated area scenario (b), and the BP map incorporating recent burns (c).

Table 6. Mean escaped fire size (ha) for historical fires (1981 to 2002) and simulated fires from the burn probability (BP) map of the fully vegetated area and the BP map incorporating recent burns

Ecoregion	Historical	BP map of fully vegetated area	BP map incorporating recent burns
Boreal Transition	6 664	28 367	28 730
Mid-boreal Lowland	1 630	21 678	20 625
Mid-boreal Upland	15 796	18 201	17 099
Churchill River Upland	11 629	10 617	10 281

Optimal Number of Iterations

Increasing the number of iterations by increments of 50 resulted in a sharp decrease in the relative change in average BP up to about 400 iterations, after which the degree of change started leveling off (Fig. 16). At 500 iterations, the relative change in average BP was approximately 10%. A 10% relative change in BP was considered acceptable because model inputs are highly variable and because of limitations in computation time. To obtain a relative change in average BP of 5% for the study area, 900 to 1000 iterations would be required. Visual changes in the locations of high BP areas were not evident as model iterations were increased beyond 500, which suggests that a BP map based on 500 iterations provides an adequate visual representation of BP.

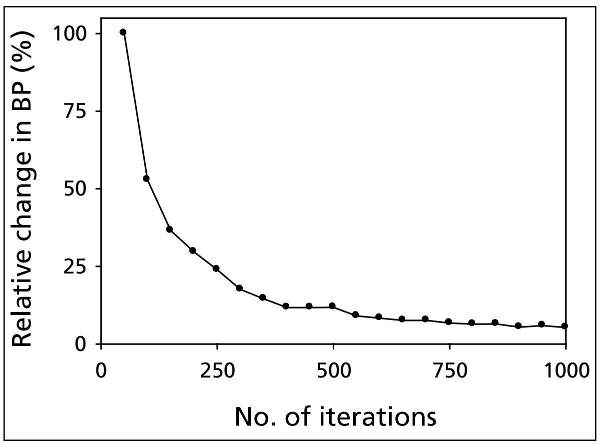

Figure 16. Relative change in burn probability (BP) as a function of number of iterations (50-iteration classes) for the BP map of the fully vegetated area.

BP Mapping with Uniform Ignition Grids

A BP map produced with uniform ignition grids and use of the ignition rules (Fig. 17) differed considerably from the BP map of the fully vegetated area (Fig. 10). The map produced with uniform ignition grids had a more even distribution of BP than the map of the fully vegetated area, but the former still had some regions of very high BP, especially for areas with large tracts of unfragmented flammable fuels. These results suggest that if a spatial relationship between the ignition locations of escaped fires and the historical patterns of fire occurrence (i.e., all reported fires) is assumed, as was shown for both lightning-caused and human-caused fires in the study area (Parisien et al. 2004), it would be unwise to disregard spatial patterns of fire occurrence in BP mapping.

A reduction in the number of modeled ignitions for an area clearly results in a decrease in BP. This is evident in the historical BP scenario (Fig. 13) for Prince Albert National Park, an area that had considerably lower fire occurrence rates than the neighboring areas outside the park. However, the presence of high BP in Figure 10 emphasizes the importance of fuel continuity in the emergence of spatial patterns of BP. This result implies that when fires are very large, as in Saskatchewan, imprecision in modeling ignition locations can be partly compensated by the configuration of forest fuels and landscape features. In other words, over long periods of time, high BP areas represent consistent paths facilitating fire spread, regardless of where the fires actually start.

Effect of Changing Distribution of Spread Event Days on Fire Size Distribution

The distribution of fire size affects spatial patterns simulated at the landscape scale (Lertzman et al. 1998). The magnitude and variability of fire size are the most important factors in the calibration of BURN-P3, so attempts must be made to obtain a historically representative fire size distribution from the modeled inputs. Given that this distribution cannot be defined beforehand, as is the case in many statistical and fully probabilistic models (Mladenoff and Baker 1999), the effectiveness of BURN-P3 is reflected in the resulting fire size distribution and the BP map. In most parts of the boreal forest, the distribution of fire size follows an exponential function (Van Wagner 1988; Cumming 2001a), although the shape (i.e., scale parameter) of this distribution is highly variable among boreal regions.

The fire size distribution produced by BURN-P3 was modified by changing the distribution of spread event days. The BP map created with a uniform distribution of four spread event days contained highly unrepresentative fire sizes, as evidenced by the bell-shaped fire size distribution (Fig. 18a). On the other hand, the BP map produced with an exponential distribution of spread event days produced the most historically representative fire size distribution (Fig. 18b). A distribution of spread event days that produces the most accurate fire size distribution is recommended for future applications of the model, even though it is not directly inferred from the source data, because it could represent another unaccounted-for mechanism.

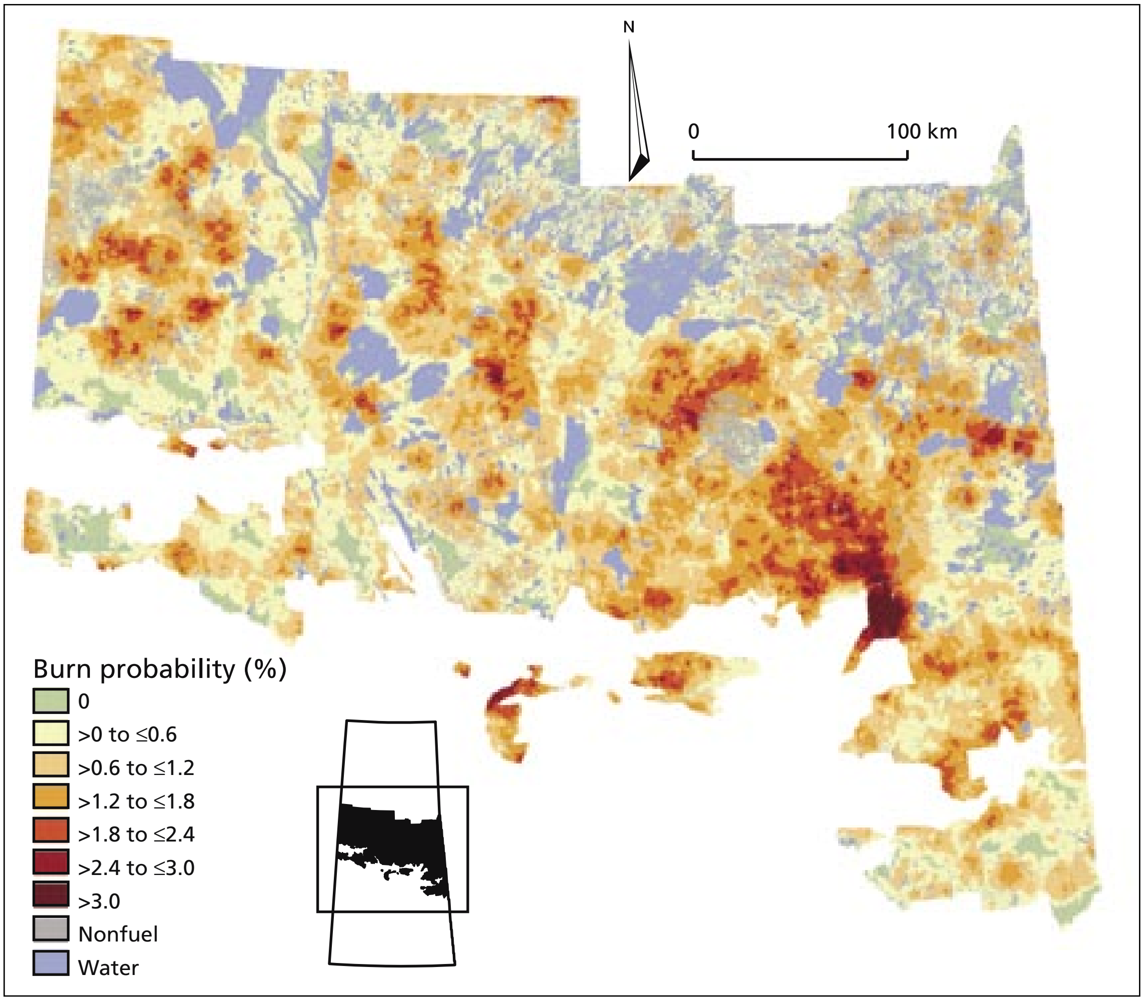

Figure 17. A 500-iteration burn probability map produced with uniform ignition grids and retention of ignition rules.

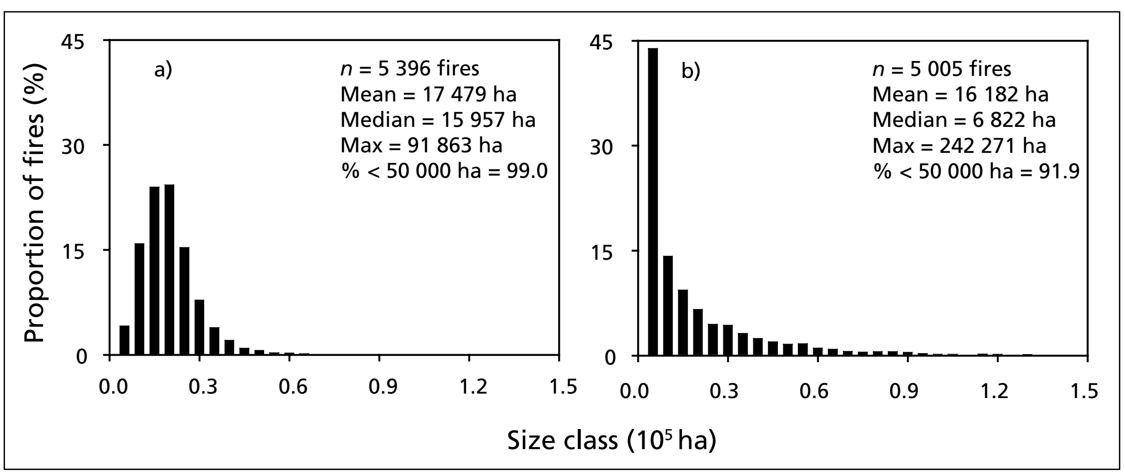

Figure 18. Frequency distribution of sizes of escaped fires (≥200 ha) produced by model simulations using an equal number of spread event days per fire (a) and a number of spread event days drawn from an exponential distribution (b).

Advantages of and Potential Improvements to BURN-P3

BURN-P3 represents a hybrid approach to landscape fire modeling that combines smaller-scale deterministic modeling of individual fires and larger-scale probabilistic components of the fire regime. BURN-P3 provides a quantitative evaluation of wildfire susceptibility for fine-resolution units (i.e., cells) of the landscape as a function of the physical factors that affect the ignition and spread of large fires. In other words, changes in the fuels, weather, or topography of an area would change the BP. Modeling the physical aspects of fire spread allows BURN-P3 to simulate fire behavior characteristics (e.g., rate of spread, HFI, crown fraction burned) that can be used in modeling fire effects and disturbance response (e.g., succession).

It is recognized that "no strategy for large-scale fire modeling is superior for all situations" (McKenzie 1998) and that the approach described here caters to the specific objective of creating a tool for strategic planning by fire management agencies. A statistical or fully probabilistic approach (e.g., Baker et al. 1991; Li and Apps 1995; Gardner et al. 1997; Perry and Enright 2002) is sufficient for exploring general large-scale relationships or to produce "what-if" scenarios, but "Process-based models may be preferable when the extent and quality of empirical data are adequate" (McKenzie 1998). Although statistical or fully probabilistic models can be used to calculate BPs for an area, they do not have the capacity to simulate the fine-scale physical processes that drive fire spread. Conversely, entirely mechanistic or physical models (Vasconcelos and Guertin 1992; Keane et al. 1996; Finney 1998) are usually very data-heavy and do not operate on a spatial scale as large as the study area for this analysis, because many aspects of the fire regime are difficult or impossible to model deterministically, such as the weather events leading to ignition.

To reflect the actual fire regime, the input fire information must encompass adequate temporal and spatial variability and accuracy to produce realistic landscape fire patterns (Baker 1989; Lertzman et al. 1998). In BURN-P3, fire information such as ignition patterns and burning conditions are empirical and represent the actual fire regime of the study area. The probabilistic modules of BURN-P3 are based on a detailed fire regime analysis (Parisien et al. 2004) supplemented by advice from operational fire management staff.

An imminent improvement to BURN-P3 is the planned replacement of Wildfire by the Canadian Wildland Fire Growth Model, Prometheus, which is based on the same modeling method as the FARSITE fire growth model (Finney 1998) used in the US. Prometheus uses wave propagation (Richards 1995) to simulate fire spread and is expected to produce more realistic burn simulations. A feature to simulate the breaching of nonfuels (i.e., fire spotting) will be added to Prometheus in the near future. This feature is important to model fire spread in heavily fragmented or heterogeneous landscapes (Hargrove et al. 2000), such as the Churchill River Upland. Regular additions and upgrades to BURN-P3 are expected, and a graphic user interface (GUI) for BURN-P3, using the Prometheus fire growth model, is currently being developed; the GUI will maximize user flexibility by allowing the user to develop every input to the modules.

Implications for Resource Management

Initially, BURN-P3 was tailored to fit the needs of a specific fire agency, Saskatchewan Environment, which plans to use the resulting BP maps for integrating fire risk into a values-at-risk model, as well as for strategic planning of fire management activities. Mapping BP can help fire managers, as well as land managers, to focus their efforts and set priorities. BP maps can be used in conjunction with other tactical and strategic tools to optimize the use of scarce fire-suppression resources. More specifically, BP maps can be used by fire managers to find the optimal locations for permanent lookout towers, create anchor points (i.e., areas where the construction of control lines start or end) for firefighter safety, locate areas of potentially limited suppression effectiveness (e.g., because of inaccessibility or scarcity of water sources), assess the risk in backfire or burnout operations (e.g., indirect attack), identify high-priority areas for wildland–urban interface mitigation activities, and identify zones that require landscape-level fuels management.

Combining fire risk with values-at-risk assessments, such as the Wildfire Threat Rating System (WTRS) (Hawkes et al. 1996; Sneeuwjagt 1998), has been used for strategic land management planning in the past, but these approaches derive fire risk qualitatively, whereas BURN-P3 provides a quantitative evaluation of the likelihood of burning. Although the WTRS is useful, especially when considerable expert advice is available, it remains a largely subjective approach. The integration of a BP map from BURN-P3 into the WTRS would provide a quantitative assessment of fire risk that could either replace or complement the traditional approach. It would be interesting to compare different fire risk assessment techniques, similar to the work of Farris et al. (1999), who compared BP maps derived from models of increasing complexity for a small area of the US Northwest.

In past decades, several tools or program applications have been developed to assist in daily fire management operations in Canada. The subsystems of the CFFDRS, the FWI System and FBP System, evaluate general fire danger conditions; fire occurrence prediction models such as PEOPLE (Todd and Kourtz 1991), SPARKY (Kourtz and Todd 1991), and LC-FOP (Lightning-caused fire occurrence prediction model; Anderson 2002) predict the number and locations of detectable fire ignitions at various spatial and temporal scales, and Wildfire Ignition Potential Prediction (Lawson et al. 1994) estimates the ease of fire ignitions on the basis of the FWI System outputs. The Spatial Fire Management System (Englefield et al. 2000) is used by a number of Canadian fire management agencies to automate the creation of daily maps that display outputs from these applications. BURN-P3 complements these tactical (i.e., daily) planning tools by providing information relevant to longer-term (i.e., strategic) planning.

The usefulness and uniqueness of BURN-P3 in strategic planning relates to its explicit modeling of the area burned, which is necessary for capturing the spatial dependency (i.e., spatial autocorrelation) of cells, since the BP of a given cell is, to various degrees, dependent on neighboring cells. Other efforts that recognize this advantage are also being developed. An approach to BP mapping has been designed that simulates fire ignitions using the FWI System and FBP System and fire spread using Wildfire (Cui, W.; Johnson, J.; Martell, D.L.; Hirsch, K.G.; McAlpine, R.; Todd, J.B.; Wotton, B.M. Predicting spatially explicit burn probabilities across forest landscapes. Submitted to For. Sci. In review). BurnPro, a method of mapping BP in which potential fire spread is calculated from an optimal search algorithm instead of deterministic fire growth modeling, has also recently been developed (Miller 2003).

Estimates of BP also provide opportunities to integrate fire and forest management activities. Forest companies must be able to evaluate the likelihood that timber will be present at the projected time of harvest. BURN-P3 outputs could be incorporated into timber supply modeling (Reed and Errico 1986; Boychuk and Martell 1996), especially in regions of high fire recurrence, such as the study area, to estimate fire losses by stand type, stand age, or other factors.

CONCLUSIONS

BURN-P3 is a new fire management tool that provides a quantitative assessment of wildfire susceptibility for large fire-prone areas. Because BURN-P3 uses deterministic fire growth modeling to simulate individual fires, the BP can be evaluated according to the physical factors that drive fire spread: forest fuels, fire weather, and topography. BURN-P3 requires a large amount of inputs and is computationally intensive, but the resulting BP map is useful for as long as the landscape does not change significantly through land use, large burns, or insect outbreaks. Although this approach has been developed for strategic fire management planning, it could be useful to any land managers who require a high-resolution assessment of wildfire susceptibility. BURN-P3 can also be used in wildfire research, because it has the potential to explore an array of fire concerns, such as the potential effectiveness of landscape-level fuel management strategies. Furthermore, this approach can provide insight into the factors that control wildfire susceptibility at multiple spatial scales. In the near future, this tool will become widely available as a stand-alone windows-based application designed for maximum user flexibility in terms of inputs. Hopefully, this will promote further enhancements and updates to BURN-P3.

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APPENDIXES

Appendix 1. Values of Daily Weather Observations and Fire Weather Index System Codes and Indices

Region[a]	No.of days	Temperature (°C)	RH (%)	ws (km/h)	pcp (mm)	Fire weather components[b] FFMC	DMC	DC	BUI	ISI	FWI
High conditions											
Spring											
Boreal Transition east	158	17.4±5.0	35.5±12.0	17.6±6.2	0.0±0.2	89.8±2.1	41.1±19.4	262.0±83.2	57.6±23.6	10.2±1.2	23.7±5.4
Boreal Transition west	274	17.4±4.9	31.2±9.7	14.9±5.2	0.0±0.2	90.7±1.9	49.8±26.6	286.4±92.1	67.5±30.1	10.2±1.1	25.4±6.1
Mid-boreal Lowland	115	17.9±5.5	34.9±11.0	17.7±6.3	0.0±0.2	89.8±2.3	35.4±17.4	238.6±102.2	49.4±21.2	10.3±1.2	22.0±5.1
Mid-boreal Upland east	82	17.5±4.7	35.6±12.6	17.4±6.6	0.0±0.0	89.8±2.2	36.7±15.5	252.6±78.8	52.3±19.5	10.1±1.1	22.5±4.8
Mid-boreal Upland centre	211	18.3±5.2	32.4±9.0	15.1±4.6	0.0±0.1	90.7±1.7	44.6±21.0	278.1±90.1	61.9±24.4	10.2±1.1	24.6±5.1
Mid-boreal Upland west	213	17.6±5.3	32.3±11.0	15.1±5.7	0.0±0.2	90.6±2.1	46.8±23.8	279.9±96.5	64.4±27.9	10.1±1.1	24.7±5.7
Churchill River Upland	93	16.6±5.4	35.6±11.1	18.0±6.7	0.0±0.1	89.6±2.3	35.7±14.1	206.2±83.7	48.4±17.8	10.2±1.2	21.7±4.7
Summer											
Boreal Transition east	311	23.4±3.7	42.6±9.4	19.2±5.8	0.1±0.3	89.3±1.9	41.8±22.3	345.8±129.4	62.3±29.0	10.3±1.1	24.6±6.2
Boreal Transition west	309	23.1±3.5	40.9±8.9	17.5±5.7	0.0±0.1	89.7±1.8	47.8±23.9	378.5±114.1	70.4±30.1	10.1±1.1	25.8±5.7
Mid-boreal Lowland	279	23.6±3.7	42.5±9.4	18.6±5.4	0.1±0.2	89.4±1.9	35.7±18.0	307.2±117.6	53.1±23.1	10.1±1.1	22.5±5.2
Mid-boreal Upland east	139	23.1±4.0	44.2±10.0	19.7±5.6	0.1±0.3	89.1±1.8	35.8±16.4	337.8±130.9	55.3±23.8	10.2±1.1	23.1±5.4
Mid-boreal Upland centre	330	24.0±3.6	36.6±7.8	14.9±4.5	0.0±0.2	90.6±1.5	45.9±26.4	330.7±129.0	65.9±32.3	10.1±1.1	24.8±6.5
Mid-boreal Upland west	292	23.4±3.5	38.4±8.7	15.9±5.4	0.0±0.2	90.3±1.8	49.3±25.8	382.5±127.9	72.0±32.3	10.0±1.1	25.9±6.3
Churchill River Upland	292	23.4±4.0	38.9±9.5	16.6±5.9	0.1±0.4	90.2±2.1	41.7±22.7	336.3±118.4	61.6±28.8	10.2±1.1	24.3±6.1
Extreme conditions											
Spring											
Boreal Transition east	128	17.9±5.1	31.9±9.4	28.1±7.2	0.0±0.1	90.8±2.0	44.4±20.0	289.0±102.9	62.0±24.0	21.2±10.8	39.3±13.4
Boreal Transition west	157	19.1±5.2	30.4±8.3	24.2±7.7	0.0±0.1	91.2±1.9	46.1±21.9	296.4±89.9	64.0±25.0	18.0±7.9	35.9±9.7
Mid-boreal Lowland	45	22.6±4.4	38.7±9.6	27.8±6.9	0.0±0.2	90.0±1.9	36.2±15.0	311.6±117.8	53.7±19.6	18.3±7.9	33.8±10.7
Mid-boreal Upland east	47	19.3±4.3	29.3±9.6	26.9±9.3	0.0±0.1	91.4±2.4	34.9±16.6	221.9±81.5	48.8±20.2	22.6±12.1	36.7±15.7
Mid-boreal Upland centre	85	21.9±4.9	28.0±9.0	18.8±5.5	0.0±0.1	92.5±1.8	44.7±22.2	281.4±72.3	61.3±24.8	15.8±3.0	32.9±7.6
Mid-boreal Upland west	52	21.9±5.0	29.6±8.4	21.3±7.6	0.1±0.2	91.5±2.1	44.4±18.0	273.5±82.2	61.4±22.0	15.9±3.5	32.7±5.8
Churchill River Upland	60	18.6±5.3	30.7±9.1	25.7±7.6	0.0±0.1	91.1±1.9	40.5±16.2	222.7±97.4	53.7±20.4	19.5±9.4	34.9±11.4
Summer											
Boreal Transition east	147	23.4±3.8	38.8±8.8	27.5±7.0	0.0±0.2	90.1±1.9	44.6±23.1	350.6±129.7	65.3±29.4	18.1±5.9	36.4±11.0
Boreal Transition west	113	22.7±4.1	38.1±9.1	26.4±7.0	0.1±0.3	90.1±2.0	45.3±25.5	360.9±122.8	66.6±31.5	16.8±4.7	35.0±10.1
Mid-boreal Lowland	106	23.9±3.8	40.9±8.0	27.9±6.5	0.0±0.2	89.9±1.6	35.1±13.9	331.1±100.6	53.5±18.2	17.6±6.0	33.0±8.8
Mid-boreal Upland east	53	24.8±4.0	43.2±9.0	27.0±5.6	0.0±0.0	89.8±1.6	36.5±15.1	354.5±128.7	56.6±21.7	16.7±3.6	33.0±8.3
Mid-boreal Upland centre	79	25.5±4.6	32.1±8.6	17.9±4.4	0.0±0.1	92.0±1.6	51.5±25.2	386.4±120.8	75.4±30.2	14.1±1.5	33.6±6.4
Mid-boreal Upland west	57	23.9±3.5	35.8±9.4	21.4±5.8	0.0±0.0	90.9±1.9	45.0±19.2	431.3±150.6	70.0±27.3	14.3±1.6	32.6±5.9
Churchill River Upland	128	23.5±4.2	36.5±8.3	24.4±6.6	0.1±0.3	90.6±1.8	46.7±22.9	356.6±122.0	68.4±29.6	16.4±4.7	35.0±9.7

[a]High conditions, $8.6 \leq ISI < 12.6$; extreme conditions, $ISI \geq 12.6$; spring = May; summer = June to August.

[b]ISI = Initial Spread Index, RH = relative humidity, ws = wind speed, pcp = precipitation, FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, BUI = Buildup Index, FWI = Fire Weather Index. Data are computed from daily fire weather records of the fire weather list and are presented as mean ± standard deviation.

Appendix 2. Number of Daily Fire Weather Records and Weather Stations from Which They Were Obtained

Weather zone	No. of days Spring	No. of days Summer	Weather stations
Churchill River Upland	148	420	LRNGE, PLCNA, MCLNN, CRETN, BSNRD*
Mid-boreal Lowland	187	401	CMBHS, THPAS, HDSNB, EBCAM*, LBEAR*
Mid-boreal Upland west	293	248	BUFFH, BUFFN, ILCRS, LOONL, DIVDE, BEAUV*, MLPRK*, COLDL*, LALCH*
Mid-boreal Upland centre	276	269	RABTH, VIMY, WABNO, WASKS, CNDLK, LBEAR, BEAUV
Mid-boreal Upland east	137	199	G_WTR, USHTA, PRCPN, HDSNB
Boreal Transition west	461	370	COLDL, B_RVR, COOKS, PALBT, MLPRK, DIVDE*, LOONL*, VIMY*
Boreal Transition east	266	447	PALBT, NIPWN, FLCRN, G_WTR*, HDSNB*, DUCKM*

*Stations located outside the study area.