Predicting the Daily Occurrence of People-Caused Forest Fires

B. Todd and P.H. Kourtz

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Prédiction quotidienne des feux de forêts causés par négligence.

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ABSTRACT

People are responsible for starting two out of every three forest fires in Canada. To efficiently suppress these fires while they are still small, a modern forest fire control organization must be able to predict their numbers and locations one day in advance. Contrary to popular belief, these fires do not occur at random times or in random locations. Instead, experience has shown that these fires are started under specific fuel and weather conditions and that the fires are predictable. During the past 20 years, various prediction methods have been developed and tested. The procedure presented here represents the current state of one of the paths taken in the search for a more accurate prediction system.

The goal is to predict the number and location of people-caused fires that will occur the next day in a large forest region. The procedure, encoded into a computer program, uses databases containing the region's historical fire occurrence patterns and tomorrow's predicted weather and fuel moisture index values. The program is written in Fortran and runs on a Digital VAX computer; the execution time is approximately 5 CPU seconds on a VAX 750. The program produces both tabular and map output.

The program was originally developed for use at the Société de Conservation de l'Outaouais' fire center in Maniwaki in southwestern Quebec. After several fire seasons of testing in this region, it was installed in other regions of the province. During the 1989 fire season, it was extensively tested and evaluated.

RÉSUMÉ

Au Canada, deux incendies de forêts sur trois sont causés par négligence. Pour que tels incendies puissent être éteints de façon efficace tandis qu'ils sont encore petits, il importe que l'on soit capable d'en prédire le nombre et le lieu un jour à l'avance. On croirait que ces feux peuvent survenir n'importe où et n'importe quand. Cependant, l'expérience a démontré que non seulement les feux étaient nés dans des conditions spécifiques quant à la combustion et la météorologie, mais aussi qu'il était possible de les prédire. Pendant les vingt dernières années, on a élaboré et soumis aux essais de diverses méthodes de prédiction. Le procédé dans ce rapport décrit l'étape actuelle sur une des voies de recherches que l'on suivait en vue d'un système de prédiction plus en plus précis.

Le but est de prédire d'un jour à l'avance le nombre et l'endroit des feux dans une région forestière étendue. La méthode fonctionne en tant qu'un programme d'ordinateur utilisant des bases de données. Dans ces dernières sont incorporés les détails sur les feux antérieurs, les prévisions météorologiques et l'indice de teneur en eau des combustibles. Le programme a été écrit en Fortran et il fonctionne à un ordinateur digital VAX. La durée d'exécution est environ de 5 seconds d'unité centrale au VAX 750. Les résultats peuvent être affichés en formes de tableaux ou sur cartes.

Ce programme a été réalisé d'abord au centre de prévention des incendies de Maniwaki, dans le cadre de la Société de la Conservation de l'Outaouais dans le sud-ouest du Québec, et soumis aux essais avant de l'appliquer aux autres régions de la province. Pendant la saison des incendies de 1989, on a reévalué cette méthode de façon exhaustive.

The Fire Prediction Problem

In Canada, people's activities and machinery are responsible for igniting about two out of every three forest fires that occur during an average fire season (Ramsey and Higgins 1986; Table 1). The proportion of people-caused fires varies from province to province, ranging from 46% to 82%. The percentage of the total area burned by these fires is even more variable, ranging from 13 to 83% across Canada and averaging 17%.

Table 1. People-caused fire occurrence and area burned, 1973-1982

Region	Percentage of Total Fire Occurrence	Percentage of Total Area Burned
Canada	61	11
All Provinces	62	17
Territories	37	1
British Columbia	57	28
Alberta	53	15
Saskatchewan	46	13
Manitoba	59	28
Ontario	63	19
Quebec	82	59
Newfoundland	58	15
New Brunswick	80	83
Nova Scotia	80	43
Prince Edward Island	70	71

Note: Statistics derived from Ramsey and Higgins (1986).

To efficiently suppress these fires while they are still small, a modern forest fire control organization must be able to predict their numbers and locations one day in advance. This is needed to plan adequate aerial detection patrols and to position suitable initial attack resources in anticipation of the occurrence of these fires. Contrary to popular belief, these fires do not occur at purely random times or in random locations. Instead, experience has shown that these fires are started under rather specific conditions and that their numbers are predictable at least in probability terms.

During the past 20 years, various prediction methods have been developed and tested. A subjective scheme that requires daily input by a knowledgeable person was developed and tested by Cunningham and Martell (1974). Primitive correlation methods that relate fuel moisture indexes to average fire occurrence have existed for the past 50 years and are attached in one form or another to both the Forestry Canada and USDA Forest Service fire index systems (Gisborne 1936, Beall 1939, Van Wagner 1970, 1987, Rothermel 1972, Stocks 1983). Another approach to the forecast problem uses more sophisticated correlation methods that account for historical and current patterns with respect to weather, fuel moisture, and geographic location (Kourtz 1977). This approach has been developed during the past 15 years and its current state is presented in this report.

Finally, the most recent approaches to fire prediction involve looking at the specific causes of people-caused fires. Here again, there are two approaches. Martell et al. (1987) use logistic regression to correlate occurrences to specific causes within a small forest region, whereas Kourtz (1989) uses expert system technology to consider various people-created risk situations and the likelihood of resulting fires.

Field tests involving these methods indicate that our knowledge of the prediction problem is slowly evolving. The following points summarize the knowledge that has been gained:

- The number of people-caused fires that will occur the next day is predictable in probability terms, with accuracy levels being adequate for most daily planning tasks.
- The Fine Fuel Moisture Code (FFMC), a component of the Canadian Fire Weather Index System, is a good indicator of the potential occurrence of people-caused fires (Van Wagner 1970). The FFMC reflects the fuel moisture conditions of the litter and fine fuels. As the fuel moisture in these fuels decreases, ignition becomes easier. This association is reflected by an increase in the occurrence of people-caused fires, especially under the influence of high winds.
- The number of fire starts in a specific geographic area is related to the number of people using that area and factors that affect the ease of ignition, such as fuel type, fuel moisture state, and wind speed.
- Historical fire occurrence data for a specific geographic area combined with the corresponding moisture content of fine fuels for the area can be used to predict the number of people-caused fires expected to occur on a specific day (Cunningham and Martell 1973).
- The occurrence of people-caused fires is adequately described by a Poisson process (Martell 1972). For example, the probability of a specific number of fires occurring on a given day within a geographic area can be calculated using the Poisson distribution, with its parameter being the number of fires expected on that day.
- A large region (i.e., 100 000 km^2) can be divided into much smaller units, such as cells, in a rectangular grid (each approximately 500 km^2 in size) and a prediction of fire occurrence in probability terms can be made for each of the smaller units. With this procedure, location accuracy still requires considerable improvement.
- The accuracy of the predicted number of occurrences improves as the fire frequency in a

specified geographic area increases. It is difficult to assess the value and accuracy of predictions for areas where fires rarely occur.

- The location and number of fires vary throughout the fire season, especially between spring and summer. This variation in the fire occurrence rate is related to fuel type conditions, the timing of green-up, and seasonal variations in people's use of the forest.
- The quality of historical records is poor, adding little to sophisticated statistical procedures. Fire cause, ignition time, weather conditions at the site, and fuel type and moisture conditions are often crude estimates. In some cases, about all that should be stated is that there probably was a fire.
- Patterns of people-caused fires can rapidly change over time. One must be cautious when relying on historical records as the only indicator of tomorrow's fires. Historical fire statistics should be adjusted to reflect changing forest patterns and uses over the last few years as well as within the present fire season (Kourtz 1981).
- The prediction process must be robust. It must work during all fire weather situations. Predicting expected fires during low to moderate fire weather situations is a fairly easy process. Predicting fires during high or extreme fire weather situations is a much more difficult process, but also a much more important one.
- People-caused fire occurrence predictions should include a short-term learning feature. Experience has shown that under "constant" weather conditions the average fire occurrence rate over the past few days will more accurately reflect tomorrow's expected number of fires than that predicted based on historical estimates (Kourtz 1981).
- A few experienced fire personnel can predict people-caused fires more reliably than through the use of historical fire statistical approaches. Local experts have better knowledge of the number of people currently using the forest, forecasted weather patterns and their effect on fuel moisture conditions, and other subjective assessments. Artificial intelligence expert systems could encode this human knowledge and expertise (Kourtz 1989).
- There is an intimate link between fire prediction reliability and detection activity. Fire prediction systems predict visually detectable fires. Because most areas are patrolled by aircraft, if the detection dispatcher doesn't believe that there are fires present, patrol efforts will be minimal and those fires occurring will not be reported until at least the following day. This makes the current day's forecast incorrect as well as that of the next day.
- Most fire control experts want consistently reliable fire occurrence predictions that can be incorporated into daily planning sessions. Managers do not expect exact numerical predictions, but rather some measure to identify the severity of a fire day. General classes of occurrence and some general indication of where fires are likely to occur within their region would suffice.

Quebec's Prediction Program

A new computer program, incorporating many of the considerations discussed above, has been developed to predict daily people-caused fire occurrence for large forest regions within the province of Quebec. The program was developed and initially tested in the Outaouais region of southwestern Quebec. The main features of the program are summarized here.

Goal of the Program

The program is to be used in the late afternoon to predict the number and location of people-caused fires that will be visually detectable the next day. Because the prediction depends upon fire weather and precipitation forecasts, a provision is made during the morning of the current prediction day to incorporate the 0800 weather station rainfall values and to revise the original prediction as required. This is necessary because weather forecasts are less than reliable, especially precipitation forecasts.

The Spatial Frame

The program is designed to predict people-caused fires over a forest region of about 100 000 km^2. The region is partitioned into cells that are each 0.25° in latitude and 0.25° in longitude and have an area of about 500 km^2. The Outaouais fire control agency operates 24 weather stations and for each of these stations there is a daily record of weather and fire weather indexes spanning the past 10 fire seasons. Each cell is assigned weather and fire weather index values from the most appropriate weather station, which, in many cases, is the nearest weather station. In addition, there is a 10-year record of fire occurrences for each cell. The program incorporates the historical fire occurrence and fire weather information for each cell and produces a corresponding fire prediction. The regional fire occurrence prediction is then derived from the individual cell predictions.

Temporal Variation

For most Canadian regions, there are distinct periods within a fire year that have unique fire occurrence rates. Rates vary over time because of differing intensities and types of activities carried out by forest users, differing types of ignitable fuels, and differing weather and fuel moisture conditions. Previous prediction programs partitioned the fire season into spring and summer periods. However, experience has shown that conditions during these two periods are significantly different. In fact, a transition period can be defined. The program identifies and uses three periods in the prediction process. Factors considered in defining these periods include:

1) initial and final dates of historical weather records, which restrict seasonal period definitions and statistical analyses;
2) the size of the geographic prediction cell and the corresponding number of fires and observation-days in each class;
3) the date and rate of regional green-up trends of the region's ground vegetation and deciduous species; and
4) patterns of fire occurrence during different times of the year in relation to cultural, recreational and industrial activities.

The current Quebec program uses the following time periods: spring, May 1 to May 24 (24 days); transition, May 25 to June 25 (32 days); and summer, June 26 to August 31 (67 days).

Table 2 presents a regional breakdown of the number of people-caused fires that occurred in Quebec in 1988 during each period as well as the two highest daily totals during each period. Distinct differences are apparent, especially when the number of fires that occurred during a period is related to the total number of days in the period. The summer period has a lower fire occurrence rate than either the spring or the transition periods in five of the six regions for which data are available for all three periods. In addition to having higher fire occurrence rates, the spring and transition periods also reveal variations from one region to another. Some regions have a higher number of spring fires, whereas others, such as the Outaouais region, have higher occurrence rates during the transition period. Also, the summer period has lower daily maximum occurrence rates compared with those experienced during the spring and transition periods. These daily maximum trends are consistent across all regions of the province. Fire distribution patterns within regions also vary over the seasonal periods. Figure 1 illustrates the number of fires by prediction cell and period for the Outaouais region of Quebec. Fluctuations and changes in the pattern of fire occurrence are evident among each of the periods.

Each of the seasonal periods has unique characteristics with respect to fire prediction. Predicting fires during the summer period is an easy process because the occurrence of people-caused fires is low and daily maximum levels are low. Consequently, fire prediction forecasts are fairly accurate. The spring period has variable regional fire occurrence levels and the highest maximum daily totals. This period requires a dynamic approach to fire prediction as the process must respond quickly to changing fuel moisture relationships. Fire predictions are less accurate during the spring. The transition period is intermediate in terms of the degree of difficulty in predicting fires and the expected accuracy of predictions relative to the other periods.

Ignition Class Definition

The FFMC for a particular day for a particular geographic cell is a good indicator of people-caused fire occurrence rates. The FFMC is a numerical rating that directly reflects the fuel moisture conditions of the litter and fine fuels and indicates the overall ease of ignition of forest fuels. Higher FFMC values indicate lower fuel moisture conditions and are closely associated with higher fire occurrence rates. Although the FFMC/fire occurrence relationship provides "ballpark" results, experience indicates that it does not adequately cover many important situations. The accuracy of fire predictions can be improved by including other factors related to the ignition process. Earlier research has identified two important elements that affect the ignition process: the ease of ignition and the rate of spread immediately after ignition (Muraro 1977). The ease of ignition is best described by the FFMC and the Duff Moisture Code (DMC), whereas the rate of spread is best described by the DMC and the Initial Spread Index (ISI). The DMC is a numerical rating of the moisture content in upper duff layers, whereas the ISI is a numerical index that combines the FFMC and wind to reflect fire spreading rates. All three indexes (FFMC, DMC, and ISI) are components of the Canadian Fire Weather Index System.

The three fire weather indexes have been combined to form a new category called the Ignition Index. This index combines fuel moisture conditions in two different fuel layers with wind speed, and attempts to identify situations that are conducive to fire ignition. Many factors govern the ease of fire ignition. High FFMC and DMC values under high winds present ideal conditions for easy ignition and high occurrence rates can be expected when large numbers of people are using the forest. Low to moderate FFMC values combined with high DMC values and high winds also represent good conditions for easy ignition. This situation, which could be caused by light rainfall affecting only the fine fuels, would have resulted in low ignition probabilities in earlier fire prediction programs. Use of the ignition class in the current program relates the ease of fire ignition in different fuel complexes to the capability of fires to spread and become detectable.

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Figure 1. People-caused fire occurrence patterns for the Outaouais region, 1981-1983.

Table 2. People-caused fire occurrence in Quebec, 1988

Region	Spring (May 1 - 24)		Transition (May 25 - June 25)		Summer (June 26 - August 31)	
	Total Number of People-caused Fires					
La Gaspésie	41		NA		NA	
Sud du Québec	59		35		9	
Québec-Mauricie	78		83		19	
Côte nord	21		14		28	
Saguenay/Lac St-Jean	57		24		12	
Outaouais	33		108		25	
Nord-ouest	76		54		40	
	The Two Highest Daily Number of People-caused Fires					
La Gaspésie	15	6	NA		NA	
Sud du Québec	16	11	7	4	3	2
Québec-Mauricie	16	16	8	8	6	2
Côte nord	5	4	3	2	2	1
Saguenay/Lac St-Jean	15	8	4	3	3	2
Outaouais	8	5	28	11	3	2
Nord-ouest	18	16	7	5	5	3

Because weather forecasts and, therefore, corresponding indexes are often inaccurate, broad class limits for the FFMC, DMC, and wind are used to determine the Ignition Index. Other considerations in defining these limits include seasonal variations in the indexes, historical fire occurrence patterns, and the need for significant numbers of observation days and fires within the classes for each geographic cell.

Table 3 lists the FFMC, DMC, and wind speed classes for each seasonal period used for the Outaouais region of Quebec. The FFMC index is divided into six classes, the DMC index into five classes, and the wind speed into four classes. Note that FFMC class limits are highest during the spring period and decline through the transition and summer periods, reflecting significantly higher FFMC values during the pre-green-up period because of lower relative humidities. Wind speed reveals the reverse trend. Wind speed class levels are lower in the spring because of the types of fires that occur during this period. Spring fires occur mainly in grass or dead fine fuels, which require very little wind to create adequate spreading rates for continuous combustion. On the other hand, firebrands that occur during the transition and summer periods require higher wind speeds to achieve adequate fire ignition due to the type and nature of the fuels that are susceptible to ignition during these periods. The DMC category is an oddity in that class levels do not show a definite trend or pattern during different seasons. The spring period has lower index values than the summer period, but the transition period has the highest values of the three seasonal periods. The fire occurrence predition program uses seven ignition classes that are determined by a cell's FFMC, DMC, and wind speed classes (Appendix 1). Thus, for a specific day and cell, given the FFMC, DMC, and wind speed, the ignition class can be determined.

Table 4 lists fire occurrence levels by ignition class and seasonal period for the Outaouais region of Quebec. The number of fires that occurred in the cells, the number of cell-day observations, and the corresponding means are presented for each ignition class. As the ignition class level increases, the number of fires per cell increases, whereas the number of observation day's decreases. In general, more fires occur in fewer days at higher ignition class levels.

Table 3. FFMC, DMC, and wind speed classes used for ignition class definition

Period	FFMC	DMC	Wind Speed (km/h)
Spring	0 - 65 66 - 79 80 - 84 85 - 88 89 - 91 92+	0 - 7 8 - 15 16 - 25 26 - 38 39+	0 - 6 7 - 12 13 - 18 19+
Transition	0 - 60 61 - 80 81 - 83 84 - 86 87 - 89 90+	0 - 14 15 - 28 29 - 45 46 - 58 59+	0 - 10 11 - 20 21 - 30 31+
Summer	0 - 55 56 - 71 72 - 80 81 - 84 85 - 87 88+	0 - 11 12 - 23 24 - 35 36 - 48 49+	0 - 10 11 - 20 21 - 35 36+

Table 4. People-caused fire occurrence levels by for the Outaouais region, 1981-1983

Period	Ignition Level	No. of Fires	No. of Observation Days	Mean
Spring	1	14	6216	0.0023
	2	6	2018	0.0030
	3	36	2355	0.0153
	4	50	4345	0.0115
	5	66	2744	0.0241
	6	49	737	0.0665
	7	8	209	0.0383
Transition	1	7	11191	0.0006
	2	6	3130	0.0019
	3	13	2998	0.0043
	4	11	2980	0.0037
	5	32	2861	0.0112
	6	22	1557	0.0141
	7	3	115	0.0261
Summer	1	12	13506	0.0009
	2	11	6947	0.0016
	3	29	8600	0.0034
	4	41	7189	0.0057
	5	79	9776	0.0081
	6	76	5133	0.0148
	7	21	841	0.0250

Fire Occurrence History

The fire occurrence prediction program must consider historical fire occurrence patterns, recent fire occurrence patterns, and current fuel moisture conditions for each prediction cell. Martell (1972) showed that the Poisson distribution adequately describes forest fire occurrence given the mean number of fires expected for the current weather and fuel moisture conditions. Poisson probabilities are calculated the formula

$$f(x) = \frac{\lambda^x e^{-\lambda}}{(x)!} \quad \text{for } x = 0,1,2,\ldots \quad [1]$$

where x is the number of fires expected to occur in the cell and 1 is the mean number of fires for the fuel moisture and weather conditions in the cell. The mean and variance must be about equal to use the Poisson distribution. This is not always the case in historical fire occurrence data; in fact, with fire occurrence the variance can often significantly exceed the mean. One can assume that the Poisson distribution holds for a specific cell, but the parameter 1 (mean number of fires), for a specific ignition class, is itself a random variable with a gamma distribution. The gamma distribution is described by the equation

$$f(\lambda) = \frac{\alpha^{v} \lambda^{v-1} e^{-\alpha\lambda}}{\Gamma(v)} \quad [2]$$

where λ is the mean of the distribution (and also the Poisson parameter) and v and α are the two parameters that define a gamma distribution. These two parameters can be defined from the mean and variance of the data set (Mangel and Clark 1986). The variable v is a measure of the degree to which the variance exceeds the mean and is defined by the formula

$$v = \frac{mean^2}{variance - mean} \quad [3]$$

The variable α is defined by

$$\alpha = \frac{v}{mean} \quad [4]$$

Mangel and Clark (1986) point out that the integrated Poisson and gamma distributions can be restructured to take the form of a negative binomial distribution. It is interesting to note that Bruce (1963) identified this distribution as being suitable for fire prediction.

Incorporating New Trends in Fire Occurrence

Historical means and variances for each cell and for each ignition class could be used with Poisson, gamma, or negative binomial distributions to predict the probability of n fires occurring. However, such a scheme is heavily biased by past history. New fire occurrence patterns have likely developed. One way to combine historical and recent occurrence trends for a specific ignition class and cell is with a Bayesian revision of the gamma parameter (Mangel and Clark 1986, Cunningham and Martell 1974). The Bayesian approach provides a consistent method for identifying and incorporating new patterns in fire occurrence into the prediction process. Bayes' formula is

$$LR\,(H{:}E) = \frac{P\,(E{:}H)}{P\,(E{:}H')} \quad [5]$$

where the likelihood ratio LR is defined as the probability of the event or evidence of E given a particular hypothesis H divided by the probability of the evidence given the falsity of the evidence H' (Forsyth 1984). Therefore, if the probability distribution is already known and new evidence occurs, the likelihood of the new distribution can be computed based on the new evidence.

The Bayesian approach to incorporating the information that t new observations have contributed n new fires, given a Poisson occurrence process with a gamma distribution of 1,is expressed by the following equation (Mangel and Clark 1986):

$$f(\lambda \mid n,t)) = \frac{e^{-(\alpha+t)\lambda}\lambda^{n+v-1}\alpha^{n+v}}{\Gamma(n+v)} \quad [6]$$

where n is the number of fires occurring during the period and t is the number of observation days during the period. The two parameters of the gamma distribution, v and α, are easy to calculate, and the Bayesian mathematics can be integrated and simplified so that the distribution is easy to update and maintain. As observation days accumulate for a given cell and FFMC/DMC class, revisions to the previous gamma parameters can be made according to the following Bayesian updating process:

$$New\ v = Old\ v + n \quad [7]$$

and

$$New\ \alpha = Old\ \alpha + t \quad [8]$$

The mean of the revised gamma distribution, which is the Poisson parameter or the expected number of fires, is described by the formula

$$Gamma\text{-}mean = \frac{v}{\alpha} \quad [9]$$

In any system, "learning," or the inclusion of new information to modify old information, is a subjective process. With the gamma/Bayesian process, the response to new information is controlled by the duration of the updating record as well as the extent of the deviation from the historical pattern. The process quickly "forgets" historical patterns if the revision period is long. Fire prediction experience over the past 20 years has shown that both a medium-term and a short-term revision of the historical occurrence pattern are required. Here, the medium-term revision is designed to include those changes that have occurred in the historical fire pattern during the past 4 or 5 years. The short-term revision is aimed at changes taking place during the current season.

The medium-term revision is accomplished by applying the Bayesian process, starting with the historical-based gamma parameters, and modifying them using observations from the past 4 or 5 years. The resulting mean (equation [8]) is used as the fire prediction for the cell and ignition class unless this value is modified by the short-term adjustment.

For the short-term revision, a separate set of gamma parameters is carried for each cell and ignition class but, unlike the medium-term set, they are initialized to zero at the beginning of the current fire season. For each day, from the beginning of the season to the current day, the appropriate parameter sets are updated. The adjustment for short-term trends is made simply by averaging the medium- and short-term parameters.

In summary, there are five steps in preparing a regional fire prediction system according to this scheme. The five steps are performed for each cell for each of the three periods that make up the fire season. These steps include the following:

Step 1: Identification of the FFMC, DMC, and wind speed classes that define the appropriate ignition classes for the region of interest. Table 3 lists the class levels for the three seasonal periods as they apply to the province of Quebec.

Step 2: Calculation of the mean and variance of the historical fire occurrence on a cell basis for each ignition class. The problem here is the number of observations to include in the calculation knowing that these parameters serve as the basis for the medium-term updating process. Experiments showed that for Quebec, the years 1981 to 1983 were sufficient to identify the basic relationship between past fire history and fuel ignition patterns.

Step 3: Calculation of the parameters for the gamma distribution. These are functions of the mean and variance of step 2 (equations [2] and [3]).

Step 4: Calculation of the medium-term Bayesian updating process. This is a daily process that revises the appropriate gamma distribution parameters for each ignition class and observation day according to the Bayesian updating scheme. This gives the final gamma distribution parameters that reflect the fire occurrence pattern for each cell, at least at the beginning of the current fire season. The years 1984 to 1988 were used for the medium-term Bayesian updating process.

Step 5: Calculation of the short-term Bayesian updating process. This involves a separate estimate of the gamma parameters for each cell and ignition class. It is revised each new day of the current prediction season and is intended to give the most recent fire occurrence patterns extra weight. The calculations are identical to those used in step 4, but the starting values and the length of the updating process are different. Here, observations from the past two years are used with zero values for the starting observation days and fire occurrences. The short time frame combined with zero values for the starting parameters allow the distributions to be more volatile and to respond quicker to new information. The resulting gamma parameters respond quickly to new trends in fire occurrence. This short-term estimate is averaged with the edium-term estimate to guarantee that recent fire trends will not be too biased by past fire history.

A Look at Some Historical Data

Appendix 2 contains data for three individual cells in the Outaouais region of Quebec. These data were produced following steps 2, 3, and 4 for each ignition index class and they show the changes in cell predictions after the gamma/Bayesian updating process. The data from cell 2408 for the spring period show the impact of the Bayesian process. The cell experienced a decreasing number of fires over the last eight years and the distribution of fires by ignition index class has changed. Over the 3-year period 1981-1983, there were 18 fires, none of which occurred in ignition index classes 1 and 2. Over the 5-year period

1984-1988, there were 12 fires, five of which occurred in ignition index classes 1 and 2. The Bayesian process, as reflected by the 1984-1988 Bayesian means, provides a better representation of this new trend in fire occurrence rates and the distribution of fires by Ignition Index class than the 1981-1988 fire means. The gamma/Bayesian process produced higher mean values in ignition classes 1 and 2 and lower means in the other ignition classes and reflects the change in the people-caused fire occurrence pattern.

Data from cell 2109 for the summer period show a similar fire occurrence pattern. There were 14 fires during the 1981-1983 period and five fires during the 1984-1988 period. The gamma/Bayesian-based means again represent more realistic approximations of the most recent fire patterns than the 8-year fire averages.

Data from cell 1609 for the transition period show the effect or impact of the gamma/Bayesian process on increasing fire occurrence trends. Over the period 1981-1983, there was only one fire; whereas over the period 1984-1988, there were seven fires, five of which occurred in class 6. The Bayesian process, as reflected by the 1984-1988 gamma/Bayesian means, provides a better representation of present fire occurrence trends than the 1981-1988 fire means.

A Fire Prediction Forecast

Once the season and FFMC, DMC, and wind speed classes have been defined and the revised gamma parameters have been determined for each cell, a daily fire prediction forecast can be made. The process consists of four steps.

Step 1: *Determination of a cell's ignition classes.* For the cell of interest, today's Fire Weather Indexes for a station are combined with the next day's fire weather forecast for the area containing the cell to calculate tomorrow's Fire Weather Indexes. The FFMC, DMC, and wind speed values in this forecast are then used to determine the Ignition Index. A minor smoothing algorithm, based on the index values of the cell of interest and the surrounding four cells, is applied to the forecast values. This smoothing process is used to handle the abrupt changes occurring in cells between adjacent weather stations when large variations in precipitation occur.

Step 2: *Predicting fire occurrence for a cell.* Given the season and the ignition class, the corresponding medium- and short-term Bayesian estimators are determined. However, these two means may reflect different fire occurrence trends. Cells that have experienced very recent increases in the number of fires because of changes in fire occurrence patterns over the last two years will have higher short-term means than medium-term means, whereas cells that have experienced typical fire occurrence levels will have similar values for both medium- and short-term means. Therefore, these two Bayesian means are averaged to guarantee that the mean reflects the most recent fire occurrence pattern. This average is the forecast of people-caused fires for the cell.

Step 3: *Assigning a fire occurrence probability statement to the cell.* The Poisson distribution is used to calculate the probabilities of one or more fires occurring in the cell given the predicted mean l (equation [1]). Probabilities are more meaningful to the user than the actual number of predicted fires. Most often, the predicted number of fires for a cell is considerably less than one.

Step 4: *Predicting fire occurrence for the region.* Fire control agencies want to know how many fires are expected the next day and where they will occur. The answer as to where fires can be expected to occur is provided by the cell predictions and corresponding occurrence probabilities, which provide estimates of fire problem areas. These values are classified into general occurrence/severity classes and are displayed for the user in the form of colored maps of the region. The maps clearly show the specific areas of concern in the region.

The expected number of fires for the region is generated from the individual cell predictions. Because the sum of Poisson-distributed random variables is also Poisson, with the mean equal to the sum of the individual cell values, the regional probabilities of any number of fires can be calculated. From this regional summation, the Poisson process can be used to generate a confidence statement of expected fire occurrence. For example, if six fires are predicted, there is a 90% chance that from 2 to 10 fires may occur. However, there are two problems associated with this process: the regional summation can give an incomplete picture of the total expected fire situation and the associated confidence statement has little practical use because the range is too large. Each cell's distributions are unique. Cells that have experienced similar fire occurrence patterns over the years will have very stable distributions with small variances. Cells that are experiencing a changing fire occurrence pattern will have unstable distributions with large variances and will be quite volatile in their response to new information. To handle these two problems, a process has been developed, based solely on experience, that gives regional fire managers a more realistic prediction of possible fire occurrence. This process consists of a table that uses the average regional Ignition Index and the average regional relative humidity in conjunction with the total number of regional predicted fires, as reflected by the regional probability summations (Appendix 3a). The regional averages for the Ignition Index and relative humidity are based on only those cells predicted to have some chance of a fire. The output of the table is a "narrower window" or range of expected fire occurrence. This window provides a more practical estimate of the level of expected fire occurrence than the Poisson confidence statement. For the benefit of those managers who prefer a non-numeric description, this range is further divided into one of four classes: low, moderate, high, and extreme. This classification process is unique to each region. Appendix 3b presents the rules that were used to define the fire window and fire category classes for a specific range of regional expected fire occurrence of 3.26 to 3.75.

Table 5 provides a sample output of the prediction program. The prediction was for June 11, 1988 and covered the Outaouais region of Quebec. For the region, the model predicted an average of 4.52 fires, a Poisson range of 2 to 11 fires, an adjusted window of 4 to 8 fires, a HIGH fire situation level, and a 75% chance of having 3+ fires. There were 51 cells that had some chance of a fire; in these cells, the average Ignition Index was 6 and the average relative humidity was 40. There were actually four people-caused fires on this day. In this case, the actual fire occurrence was fairly close to the model's prediction of the expected regional fire average but, more importantly, it fell within the range of the adjusted fire window.

Table 5. Sample output of the prediction Model

People-caused Fire Prediction for June 11, 1988
Fire Weather Index values and past historical fire statistics indicate that today's expected fire average will be 4.52
The overall range of expected fire occurrence is 2 to 11 fires
There are 51 cells that have expected fire occurrence levels : The average fire ignition class level is 6 The average relative humidity level is 40
The adjusted window of fire occurrence is 4 to 8 fires The regional fire situation is classified as HIGH
The probability estimate of 1 or more fires is 98% 3 or more fires is 75%

Evaluating the Predictions

Scoring rules were used to evaluate the performance of several previous fire occurrence prediction programs. Each day, such a rule compared the previous day's prediction with the actual occurrence and assigned a numeric reward or penalty. This value was accumulated during the fire season. The size of the reward or penalty was a function of both the difficulty of the prediction situation and the nearness of the prediction to the actual occurrence. In low occurrence situations, only a small reward was assigned for predicting close to the actual occurrence. The reward was much larger for a close prediction in situations where many fires occurred. Likewise, if there was a large discrepancy between predicted and actual fires in difficult situations, the penalty was much larger. The scoring rule used was

$$SCORE = (m - 200)^2 - (k \times (p - a)) \quad [10]$$

where p is the predicted number of fires, a is the actual number of fires, and k and m are defined by the equations

$$m = 18.8 + 4.35a - 0.0001772a + 200^3 \quad [11]$$

and

$$k = \frac{m}{\left(\frac{(15 + 1.25a)}{2}\right)^2} \quad [12]$$

Just before each day's computer prediction was made, the most experienced decision-maker made a personal prediction of occurrence. Using the same scoring rule, this prediction was rated and the result accumulated similar to the program's prediction score. At the end of the season, the two accumulated scores showed how well the program could make predictions relative to the people experienced in predicting fire occurrence. In general, scores were quite close, indicating that the computer program was about as good at predicting fire occurrence as individuals who rely on personal experience to make such predictions.

Simple statistics have also been used to evaluate the accuracy of the predictions. The number of times that the predictions were within a specified number of fires of the actual occurrence was determined. Because fire prediction is a fairly easy task during wet periods, the analysis only considered the success of the program on days that had fire activity. This method showed that past programs predicted within two fires 70-80% of the time and within one fire about 60% of the time.

Appendix 4 presents evaluation data for a 15-day spring period for four regions in Quebec. The spring period is a particularly difficult time to predict fires as these results indicate. The predicted "windows" contained the actual number of fire occurrences on 67% of the forecast days. A close look at these data illustrates some of the difficulties associated with fire prediction. Clearly, exact numerical predictions are not possible. It is more realistic to use fairly broad non-numerical classes to describe the expected occurrences. Terms such as "low", "moderate", "high," and "extreme" convey the occurrence situation to the fire control manager adequately for most planning tasks.

SUMMARY

The computer program described here uses historical fire occurrence patterns correlated with weather and forest fuel moisture to provide forecasts of fire occurrence for the following day in a large forested region. A large region is partitioned into cells and separate predictions are made for each cell. Historical patterns of occurrences within each cell are assumed to follow a Poisson process, with the Poisson parameter having a gamma distribution. Revisions to the two gamma parameters are made by means of a Bayesian updating process that incorporates new fire occurrence deviations from the historical patterns.

The cellular fire predictions are accumulated for the regional prediction forecast. The regional forecast is modified using a subjective rule set to define a narrower range of expected fire occurrence and is then classified into one of four general fire situation categories. The end result is an operationally useful daily forecast of expected people-caused fire occurrence on a cell and regional basis.

Previous discussions have outlined the limitations of the historical correlation approach to fire prediction. There are always several important fire days within a fire season when such prediction systems fail. Although logical explanations can always be made for these failures, fire experts who utilize local knowledge of individual fire risks seem to be able to provide more consistent predictions, especially during more difficult periods. The next generation of people-caused fire occurrence prediction systems will relate estimates of the daily use of the forest and will look at specific causes. These systems will encode the expertise of the most experienced people and will incorporate historical fire statistics, expert perceptions of forest-use patterns, daily risk factors associated with each cause, levels of detection efficiency, precipitation patterns, and weather forecasts (Kourtz 1989). The program described here is intended to provide an interim solution until better programs are developed.

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Appendix 1. Ignition class definitions

Ignition Class 1 - defined by 5 possible cases		
FFMC Class 1	DMC Class 1	Wind Class 1 or 2
	DMC Class 2	Wind Class 1 or 2
FFMC Class 2	DMC Class 1	Wind Class 1
Ignition Class 2 - defined by 8 possible cases		
FFMC Class 1	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 3 or 4
	DMC Class 3	Wind Class 1
FFMC Class 2	DMC Class 1	Wind Class 2
	DMC Class 2	Wind Class 1
FFMC Class 3	DMC Class 1	Wind Class 1
Ignition Class 3 - defined by 22 possible cases		
FFMC Class 1	DMC Class 3	Wind Class 2 or 3 or 4
	DMC Class 4	Wind Class 1 or 2 or 3
	DMC Class 5	Wind Class 1 or 2
FFMC Class 2	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 2 or 3
	DMC Class 3	Wind Class 1 or 2
	DMC Class 4	Wind Class 1 or 2
	DMC Class 5	Wind Class 1
FFMC Class 3	DMC Class 1	Wind Class 2
	DMC Class 2	Wind Class 1
	DMC Class 3	Wind Class 1
FFMC Class 4	DMC Class 1	Wind Class 1 or 2
Ignition Class 4 - defined by 22 possible cases		
FFMC Class 1	DMC Class 4	Wind Class 4
	DMC Class 5	Wind Class 3
FFMC Class 2	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 3
	DMC Class 5	Wind Class 2
FFMC Class 3	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 2 or 3
	DMC Class 3	Wind Class 2
	DMC Class 4	Wind Class 1 or 2
	DMC Class 5	Wind Class 1
FFMC Class 4	DMC Class 1	Wind Class 3
	DMC Class 2	Wind Class 1 or 2
	DMC Class 3	Wind Class 1
FFMC Class 5	DMC Class 1	Wind Class 1 or 2
FFMC Class 6	DMC Class 1	Wind Class 1
Ignition Class 5 - defined by 22 possible cases		
FFMC Class 1	DMC Class 5	Wind Class 4
FFMC Class 2	DMC Class 4	Wind Class 4
	DMC Class 5	Wind Class 3
FFMC Class 3	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 3
	DMC Class 5	Wind Class 2 or 3
FFMC Class 4	DMC Class 1	Wind Class 4
	DMC Class 2	Wind Class 3

Appendix 1. (Cont'd)

	Ignition class 5 (cont'd)	
	DMC Class 3	Wind Class 2
	DMC Class 4	Wind Class 1 or 2
	DMC Class 5	Wind Class 1
FFMC Class 5	DMC Class 1	Wind Class 3
	DMC Class 2	Wind Class 1 or 2
	DMC Class 3	Wind Class 1
	DMC Class 4	Wind Class 1
FFMC Class 6	DMC Class 1	Wind Class 2
	DMC Class 2	Wind Class 1
Ignition Class 6 - defined by 22 possible cases		
FFMC Class 2	DMC Class 5	Wind Class 4
FFMC Class 3	DMC Class 4 or 5	Wind Class 4
FFMC Class 4	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 3
	DMC Class 5	Wind Class 2
FFMC Class 5	DMC Class 1	Wind Class 4
	DMC Class 2	Wind Class 3
	DMC Class 3	Wind Class 2 or 3
	DMC Class 4	Wind Class 2
	DMC Class 5	Wind Class 1 or 2
FFMC Class 6	DMC Class 1	Wind Class 3 or 4
	DMC Class 2	Wind Class 2 or 3
	DMC Class 3	Wind Class 1 or 2
	DMC Class 4	Wind Class 1
Ignition Class 7 - defined by 19 possible cases		
FFMC Class 4	DMC Class 4	Wind Class 4
	DMC Class 5	Wind Class 3 or 4
FFMC Class 5	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 4
	DMC Class 4	Wind Class 3 or 4
	DMC Class 5	Wind Class 3 or 4
FFMC Class 6	DMC Class 2	Wind Class 4
	DMC Class 3	Wind Class 3 or 4
	DMC Class 4	Wind Class 2 or 3 or 4
	DMC Class 5	Wind Class 1 or 2 or 3 or 4

Appendix 2. Statistical comparison of three cells in the Outaouais region of Quebec

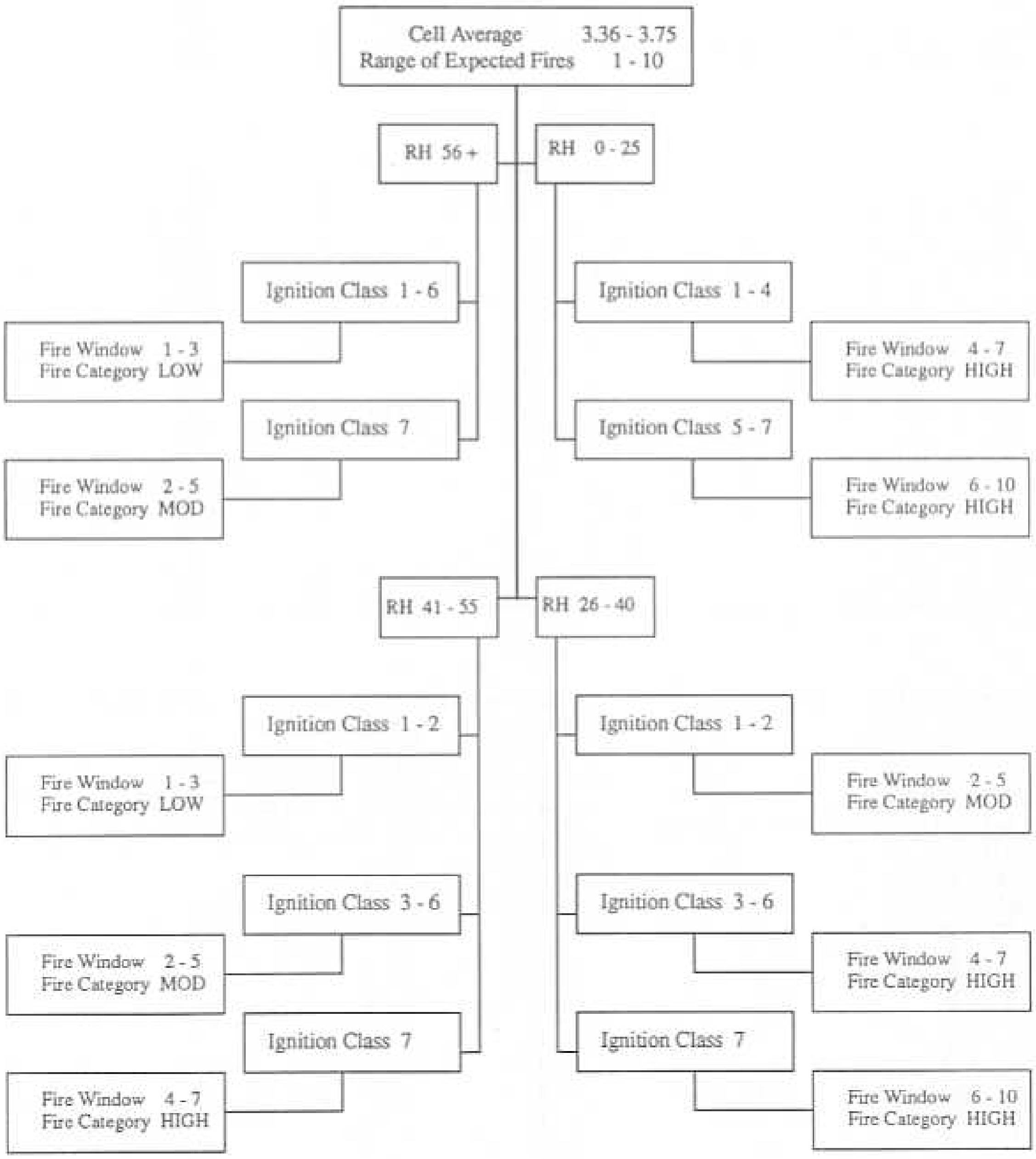
Ignition Level	1981-1983 No. of Fires	1981-1983 No. of Days	Mean	1984-1988 No. of Fires	1984-1988 No. of Days	Bayesian Mean	1981-1988 Overall Mean
			Cell 2408, spring period				
1	0	28	0.0000	1	35	0.0286	0.0159
2	0	7	0.0000	4	30	1.1333	0.1081
3	6	13	0.4615	2	24	0.0867	0.2162
4	4	18	0.2222	0	13	0.0060	0.1290
5	5	17	0.2941	3	19	0.1598	0.2222
6	2	10	0.2000	1	12	0.0941	0.1364
7	1	3	0.3333	1	11	0.0909	0.1429
			Cell 2109, summer period				
1	1	62	0.0161	0	100	0.0001	0.0062
2	0	40	0.0000	0	40	0.0000	0.0000
3	0	38	0.0000	0	57	0.0000	0.0000
4	3	29	0.1034	2	54	0.0377	0.0602
5	3	49	0.0612	2	2	0.0280	0.0413
6	7	36	0.1944	0	70	0.0005	0.0660
7	0	14	0.0000	1	9	0.1111	0.0435
			Cell 1609, transition period				
1	0	43	0.0000	0	47	0.0000	0.0000
2	0	21	0.0000	0	26	0.0000	0.0000
3	0	18	0.0000	0	21	0.0000	0.0000
4	0	19	0.0000	1	14	0.0714	0.0303
5	1	13	0.0769	0	35	0.0001	0.0208
6	0	11	0.0000	5	33	0.1515	0.1136
7	0	3	0.0000	1	16	0.0625	0.0526

Appendix 3. Classification of expected regional fire occurrence based on the averages of expected fires, relative humidity, and ignition classes

Regional Fire Averages	Poisson Fire Range	Adjusted Fire Windows – Average Relative Humidity 56+	41 - 55	26 - 40	0 - 25
0.00 - 0.10	0 - 1	0 - 1	0 - 1	0 - 1	0 - 1
0.11 - 0.44	0 - 2	0 - 1	0 - 1	0 - 1	0 - 2
0.45 - 0.74	0 - 3	0 - 1	0 - 1	0 - 2	1 - 3
0.75 - 1.08	0 - 4	0 - 1	0 - 2	0 - 3	1 - 4
1.09 - 1.42	0 - 5	0 - 1	0 - 2	1 - 3	2 - 5
1.43 - 1.76	0 - 6	0 - 2	0 - 3	1 - 4	2 - 6
1.77 - 2.25	0 - 7	0 - 2	0 - 3	1 - 4	3 - 7
2.26 - 2.75	0 - 8	0 - 2	1 - 3	2 - 5	3 - 8
2.76 - 3.25	1 - 9	1 - 3	2 - 5	3 - 7	4 - 9
3.26 - 3.75	1 - 10	1 - 3	2 - 5	4 - 7	6 - 10
3.76 - 4.75	2 - 11	2 - 4	3 - 5	4 - 8	7 - 11
4.76 - 5.75	2 - 12	2 - 5	4 - 7	5 - 9	8 - 12
5.76 - 6.75	3 - 14	3 - 5	4 - 8	6 - 10	9 - 14
6.76+	4 - 16	4 - 6	5 - 9	8 - 11	10 - 16

Appendix 3 - Cont'd

(b) Sample of Rule Oriented Classification Method



Appendix 4. Comparison of model results in four regions of Quebec for the spring period of 1988

Date		Regional Cell Averages for			Expected Fires			Actual No. of Fires
		Relative Humidity	Ignition	Prediction	Range	Window	Category	
				Québec - Mauricie Region				
May	1	75	1	0.41	0 - 2	0 - 1	Low	0
	2	59	1	0.53	0 - 3	0 - 1	Low	0
	3	27	4	2.92	1 - 9	3 - 7	Moderate	1
	4	22	4	3.71	2 -10	4 - 7	High	6
	5	24	5	5.53	2 -12	8 -12	Extreme	9
	6	24	5	5.68	2 -12	8 -12	Extreme	16
	7	28	5	5.26	2 -12	6 - 9	High	10
	8	20	5	5.38	2 -12	8 -12	Extreme	16
	9	31	5	4.62	2 -11	4 - 8	High	3
	10	43	5	6.14	3 -14	4 - 8	Moderate	2
	11	62	4	2.43	0 - 8	0 - 2	Low	0
	12	29	4	2.79	1 - 9	3 - 7	Moderate	4
	13	53	4	3.34	2 -10	2 - 5	Moderate	1
	14	38	1	0.79	0 - 4	0 - 2	Low	4
	15	36	3	1.90	0 - 7	1 - 4	Moderate	1
				Saguenay/Lac-St Jean Region				
May	1	72	1	0.50	0 - 2	0 - 1	Low	0
	2	50	1	0.50	0 - 3	0 - 1	Low	0
	3	14	5	2.98	1 - 9	4 - 9	High	1
	4	13	5	3.94	2 -11	7 -11	Extreme	6
	5	19	5	3.74	2 -10	6 -10	High	6
	6	34	5	4.24	2 -11	4 - 8	High	3
	7	27	5	3.83	2 -11	4 - 8	High	8
	8	16	6	7.41	4 -16	10 -16	Extreme	15
	9	34	6	3.55	2 -10	4 - 7	High	5
	10	38	6	3.62	2 -10	4 - 7	High	8
	11	57	4	1.60	0 - 6	0 - 2	Low	0
	12	29	4	2.16	0 - 7	1 - 4	Moderate	2
	13	54	5	2.74	0 - 8	1 - 3	Low	1
	14	35	2	0.66	0 - 3	0 - 2	Low	2
	15	41	4	1.25	0 - 5	0 - 1	Low	0
				Outaouais Region				
May	1	62	2	1.37	0 - 5	0 - 1	Low	0
	2	56	3	1.51	0 - 6	0 - 2	Low	0
	3	31	3	2.14	0 - 7	1 - 4	Moderate	4
	4	26	4	2.39	0 - 8	2 - 4	Moderate	2
	5	28	4	2.20	0 - 7	1 - 4	Moderate	3
	6	30	4	2.60	0 - 8	2 - 5	Moderate	5
	7	31	4	2.43	0 - 8	2 - 5	Moderate	8
	8	28	5	2.96	1 - 9	3 - 7	Moderate	2
	9	43	5	3.76	2 -11	3 - 5	Moderate	2
	10	57	5	2.46	0 - 8	0 - 2	Low	0
	11	53	3	1.36	0 - 5	0 - 1	Low	1
	12	48	3	2.35	0 - 8	1 - 3	Low	0
	13	77	1	0.97	0 - 4	0 - 1	Low	0
	14	38	1	0.71	0 - 3	0 - 2	Low	1
	15	54	2	1.35	0 - 5	0 - 1	Low	2

Appendix 4. (con'd)

Date		Regional Cell Averages for Relative Humidity	Ignition	Prediction	Expected Fires Range	Window	Category	Actual No. of Fires
				Sud d'Québec Region				
May	3	NA	NA	NA				
	4							
	5	23	5	3.46	2-10	6-10	High	4
	6	32	5	4.25	2-11	4-8	High	11
	7	28	6	3.99	2-11	4-8	High	4
	8	39	5	3.88	2-11	4-8	High	8
	9	27	6	4.51	2-11	4-8	High	6
	10	46	6	4.20	2-11	3-5	Moderate	2
	11	66	4	1.95	0-7	0-2	Low	0
	12	38	4	2.50	0-8	2-5	Moderate	0
	13	29	6	5.04	2-12	6-9	High	16
	14	56	2	0.88	0-4	0-1	Low	1
	15	41	4	1.31	0-5	0-1	Low	1