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FORECASTING DIURNAL VARIATION IN FIRE INTENSITY FOR USE IN WILDLAND FIRE MANAGEMENT APPLICATIONS

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1. INTRODUCTION

The notion that wildland fire activity varies throughout the day as dictated by diurnal variations in fire weather conditions (Schroeder and Buck 1970), dead fuel moisture (Rothermel et al. 1986) and fuel temperature (Countryman 1966) is a relatively well-entrenched fact in wildland fire management circles as evident by its treatment in operational manuals and textbooks (Gaylor 1974; Moberly et al. 1979; Campbell 1995; Goodson and Adams 1998). These same principles have been translated into more integrated measures of wildlland fire potential in the form of fire danger indices (Fahnestock 1951; Brown 1964; Noste 1971; Alexander 1982b). Nonetheless, except for Beck and Trevitt's (1989) work, illustrating how quantitative measures of fire behavior vary diurnally has quite surprisingly not been a common practice.

De Groot and Alexander (1986) first introduced the concept of displaying equilibrium head fire intensities with the use of the Canadian Forest Fire Danger Rating System (CFFDRS). This paper provides an overview of the manner in which fire intensity is forecast diurnally, within the context of the CFFDRS. This process has been implemented in daily operations by the British Columbia Forest Service for safe and productive wildland firefighting.

2. BACKGROUND

2.1 *Byram's Fire Intensity*

The most basic characteristics of a free-burning wildland fire are that it spreads, it consumes fuel, and it emits heat energy (principally radiation and convection) and light in the form of a visible flaming combustion reaction. Byram's (1959) formula for calculating fire intensity, which he defined as the rate of heat energy release per unit time per unit length of fire front (regardless of its depth or width), incorporates these fundamental features:

$$\boldsymbol{I} = \boldsymbol{Hwr} \qquad [1]$$

where $\boldsymbol{I}$ = fire intensity (kW/m), $\boldsymbol{H}$ = net low heat of combustion (kJ/kg), $\boldsymbol{w}$ = quantity of fuel consumed in the active flame front (kg/m^2), and $\boldsymbol{r}$ = linear rate of fire spread (m/sec). Alexander (1982a) provides detail on how to calculate and interpret fire intensities.

Fire intensity thus defined can vary more than 1000-fold (i.e. 10-100 000 kW/m or more) and can be calculated for the head, back or flanks of the fire (Catchpole et al. 1992) or any portion of the fire perimeter. For practical purposes, $\boldsymbol{H}$ is generally considered a constant (~ 18 000 kJ/kg), and most of the potential variation in $\boldsymbol{I}$ is due largely to $\boldsymbol{r}$ rather than $\boldsymbol{w}$.

Byram's (1959) fire intensity is directly related to flame size. While several empirical relationships exist linking fire intensity to flame length and height (Alexander 1998), the following rough rule of thumb is regarded as adequate for field use (after Newman 1974):

$$\boldsymbol{I} = \mathbf{300}\, \boldsymbol{L}^{\mathbf{2}} \qquad [2]$$

where $\boldsymbol{L}$ = flame length (m), which represents the distance between the tip of the flames and the midpoint of the flame front depth. The vertical height of a flame front in turn determines the degree of radiant heat received at a given distance from the fire perimeter (Leicester 1985; Butler and Cohen 1998). Fire intensity is one of the major determinants associated with the difficulty of controlling or containing a free-burning wildland fire (Alexander 2000). Fire intensity dictates, for example, the likelihood of the initiation of a crown fire (Alexander 1998), the distance spot fires will be transported (Morris 1987), and whether or not existing or prepared barriers to fire spread will be breached (Wilson 1988b; Fogarty 1996).

Fire intensity is also a factor that influences whether or not a house will survive the passage of a wildfire (Wilson 1988a). Intensity also determines certain fire impacts and effects such as the height of lethal crown

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scorch (Alexander 1998), which in turn affects post-fire tree mortality (Reinhardt and Ryan 1988).

In practice, fire intensities are sometimes expressed as a class or rank delineated on the basis of relatively distinctive differences in effectiveness of various fire suppression resources. In Canada, the following fire intensity class ranges 1 through 6 are most commonly used (Alexander and Cole 1995; Cole and Alexander 1995): < 10, 10-500, 500-2000, 2000-4000, 4000-10 000, and > 10 000 kW/m (the first two and last two classes may be combined at the discretion of the user).

2.2 *The Canadian Forest Fire Danger Rating System*

The Canadian Forest Fire Danger Rating System (CFFDRS) as developed by the Canadian Forest Service is the accepted method or tool for predicting or forecasting fire behavior in Canadian forests (Stocks et al. 1989; Alexander et al. 1996; Van Nest and Alexander 1999; Alexander and Cole 2001). The CFFDRS is comprised of two major subsystems or modules (Figure 1): the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service, 1984; Van Wagner 1987); and, the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Taylor et al. 1997).

The outputs of the FWI System consist of six relative numerical ratings for various aspects of fire danger for a reference fuel type (i.e. mature pine stand) on level terrain based on a continuous record of four weather observations (Turner and Lawson 1978) taken daily at 1300 hours daylight time, namely dry-bulb temperature, relative humidity, 10-m open wind speed and 24-hr accumulated rainfall. Because calculation of the FWI System components depends solely on weather readings and the time of year (i.e. month), they can just as easily be calculated from forecast weather as observed weather.

The FBP System allows users to obtain a quantitative estimate of spread rate, fuel consumption, and fire intensity for potential fires that are either still accelerating or have in fact reached an equilibrium or steady-state with their environment. The system also allows for a general description of the type of fire (i.e. surface, intermittent crowning, continuous crowning). A simple elliptical fire growth model is used to estimate the size (i.e. area and perimeter) and shape as well as the flank and back fire characteristics of fires that originate from a single ignition source. At present, 16 benchmark fuel types are recognised in the FBP System (Table 1). The FBP System takes into account the mechanical effects of slope steepness on fire spread and intensity.

Two components of the FWI System, specifically the Initial Spread Index (ISI) and Buildup Index (BUI), are major inputs to the FBP System. The ISI and BUI are relative numerical ratings that incorporate the combined effects of short- and long-term weather conditions on potential rate of fire spread and fuel available for combustion, respectively.

Table 1. List of FBP System fuel types*

Group/Identifier	Descriptive name
Coniferous	
C-1	Spruce-lichen woodland
C-2	Boreal spruce
C-3	Mature jack or lodgepole pine
C-4	Immature jack or lodgepole pine
C-5	Red and white pine
C-6	Conifer plantation
C-7	Ponderosa pine/Douglas-fir
Deciduous	
D-1	Leafless aspen
Mixedwood	
M-1	Boreal mixedwood-leafless
M-2	Boreal mixedwood-green
M-3	Dead balsam fir mixedwood-leafless
M-4	Dead balsam fir mixedwood-green
Slash	
S-1	Jack or lodgepole pine slash
S-2	White spruce-balsam slash
S-3	Coastal cedar/hemlock/Douglas-fir slash
Open	
O-1a	Standing grass
O-1b	Matted grass

*See De Groot (1993) or Taylor et al. (1997) for photographic examples.

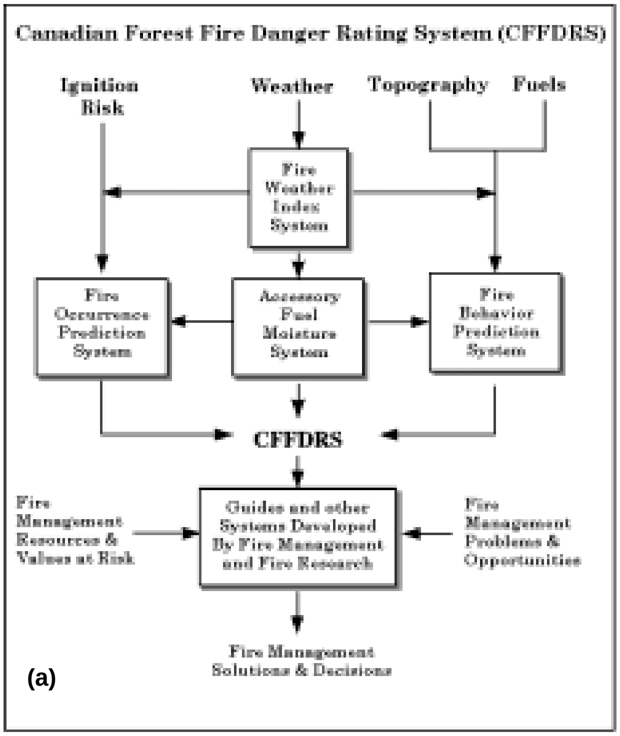
3. OPERATIONAL DEVELOPMENT AND USE

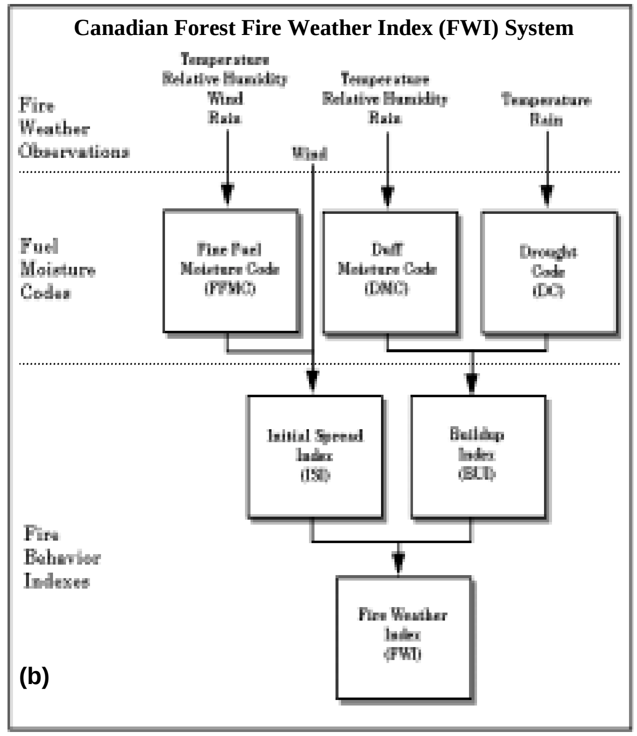
On the evening of Wednesday, July 20, 1994, the Garnet Fire started in the Ellis Creek canyon, just outside of the municipal boundary of Penticton, British Columbia (Pattison 1995). The fire continued to spread towards the southeast between July 20th and 24th despite the containment efforts of the British Columbia Ministry of Forests. Winds changed direction on July 25th and the fire spread rapidly resulting in the evacuation of over 3000 people and the loss of 18 homes in the Upper Carmi subdivision. An independent review (Price Waterhouse 1995) of the management of this incident revealed that changes in the fire weather forecast were not applied effectively to initiate the evacuation of the Upper Carmi soon enough. Neither were the potential implications of change in the wind communicated to residents to ensure they were apprised of the revised status of the fire.

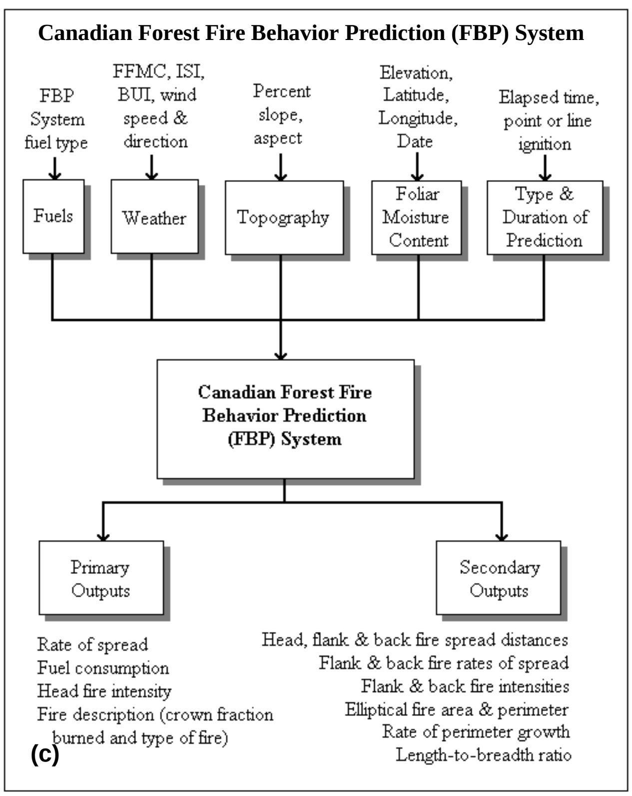
As the Garnet Fire was being fought, the tragic loss of firefighters during the South Canyon Fire in Colorado (USDA, USDI and USDC 1994) and the potential implications of problems in the communication of anticipated changes in fire weather and behavior reached British Columbia. Management sought change to prevent similar events from occurring in British Columbia.

In 1995, the British Columbia Ministry of Forests introduced a Fire Weather and Behavior Advisory and Warning System to ensure the safety of firefighters and to address weaknesses highlighted in the review of the Garnet Fire. British Columbia's Fire Weather and Behavior Advisory and Warning System (BCMFPP 2001) has evolved a great deal since its inception, and represents the first of its kind that has been implemented in Canada.

It is important to note that although the federal Meteorological Service of Canada issue public weather advisories, fire weather forecasting is beyond their







Canadian Forest Fire Weather Index (FWI) System Codes and Indexes

FFMC – A numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel.

DMC – A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-size woody material.

DC – A numerical rating of average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, and amount of smoldering in deep duff layers and large logs.

ISI – A numerical rating of the expected rate of fire spread. It combines the effects of wind and **FFMC** on rate of spread without the influence of variable quantities of fuel.

BUI – A numerical rating of the total amount of fuel available for combustion that combines **DMC** and **DC**. The **BUI** was constructed so that when the **DMC** is near zero the **DC** would not affect daily fire danger (except for smouldering potential) no matter what the level of the **DC** (i.e. when the **DMC** is near zero, so is the **BUI**, no matter what the **DC** value).

FWI – A numerical rating of fire intensity that combines **ISI** and **BUI**. It is suitable as a general index of fire danger in Canada.

(d)

Figure 1. Simplified structure diagrams for (a) the Canadian Forest Fire Danger Rating System illustrating the linkages to fire management actions, (b) the Canadian Forest Fire Weather Index (FWI) System, (c) the Canadian Forest Fire Behavior Prediction (FBP) System, and (d) the definitions of the six standard components of the FWI System (adapted from Canadian Forestry Service 1984; Alexander et al. 1996; Forestry Canada Fire Danger Group 1992).

current mandate. Hence, the responsibility for the issuance of fire weather advisories and warnings rests largely with provincial and territorial fire management agencies, who interpret weather information as part of a comprehensive assessment of the fire environment, fire management objectives and suppression capabilities.

The principles that guide BC's Fire Weather and Behavior Advisory and Warning System state that fire management must anticipate wind events and extreme fire behavior, and apply this information to determine and implement appropriate suppression strategies and tactics. To ensure the safety of all line staff, this information must be communicated effectively to workers who may be at risk due to hazard associated with strong winds or extreme fire behavior.

3.1 *Wind Advisory*

A Wind Advisory is issued when wind conditions are forecast to present hazards (e.g. wind throw, hazardous flying conditions for aircraft) or conditions that exceed safe limits for the transportation of workers. A Wind Advisory may be issued for: severe turbulence; strong winds; downbursts; or hail.

3.2 *Fire Behavior Advisory*

A Fire Behavior Advisory is issued when intensities in excess of Intensity Class 4 are forecast for a particular fuel type. Fire behavior characteristics in excess of 4000 kW/m will likely challenge direct suppression efforts.

3.3 *Extreme Fire Behavior Warning*

An Extreme Fire Behavior Warning indicates that fire behavior is expected to exceed Intensity Class 4 for a particular fuel type. Moreover, conditions are expected to change or escalate rapidly in association with one of the following: the passage of a cold front; a significant change in wind direction (> 90 degrees); severe localized thunderstorms and downdrafts; or the development of a low-level jet.

3.4 *Operational Procedures*

It is the responsibility of operational and key administrative staff including dispatchers to be aware of potential threats to field personnel and air operations. It is the Fire Control Officer's responsibility to ensure that adequate Advisories and Warnings are issued. When personnel are dispatched to an area for which an Advisory or Warning has been issued, the dispatch information must include the Advisory or Warning. Incident Commanders or project leaders must confirm their understanding of the situation and provide the dispatch centre with feedback on actual weather conditions and fire behavior characteristics.

Every advisory and warning must include:

- type of advisory or warning issued;
- date and time of issuance;
- applicable geographic area (simple geographic description of the specific area affected);
- expected arrival time and duration of disturbance;
- description of conditions expected; and
- details on who should receive copies of the advisory or warning and how it is to be distributed.

A Wind Advisory must include the type and intensity of disturbance (e.g. outflow winds gusting to 50 km/h). Wind Advisories may be issued in the absence of aggressive fire behaviour.

A Fire Behavior Advisory must include the relevant FBP System fuel type(s). Issuing offices must adopt a format that highlights the period during which forecast conditions are expected to exceed Intensity Class 4.

In addition to the requirements of a Fire Behavior Advisory, an Extreme Fire Behavior Warning must include:

- intensity of disturbance (e.g. 70 km/h winds from the southwest); and
- expected effect on fire behavior (e.g. change in spread direction or fire intensity).

An Extreme Fire Behavior Warning must be issued independently of any other advisory, since these conditions pose the greatest threat to worker entrapment.

3.5 *Operational Practices*

Diurnal intensity curves are produced daily in support of BC's Fire Weather and Behavior Advisory and Warning System for both potential and actual ongoing fires. Weather inputs forecast for solar noon are used to calculate forecasted daily FWI codes and indexes for approximately 40 weather stations for each of six regional fire centres in British Columbia. A representative fuel type is chosen for each weather station. Diurnal FFMC values are generated using equations developed by Lawson et al. (1996), and the forecasted afternoon wind speed is applied every hour; a relative humidity estimate required between 0600 and 1159 LST is inferred from the forecasted noon LST value. When this process was first introduced, these data were entered manually into the FBP System software developed by REMSOFT Inc. of Fredericton, New Brunswick (http://www.remsoft.com/index.html), which is a windows-based CFFDRS application that is available commercially. Graphs projecting fire intensity throughout the day were then drawn by hand (Figure 2) and faxed to fire crew bases. Although illustrated here in black and white, the diurnal fire intensity class chart can also be color coded.

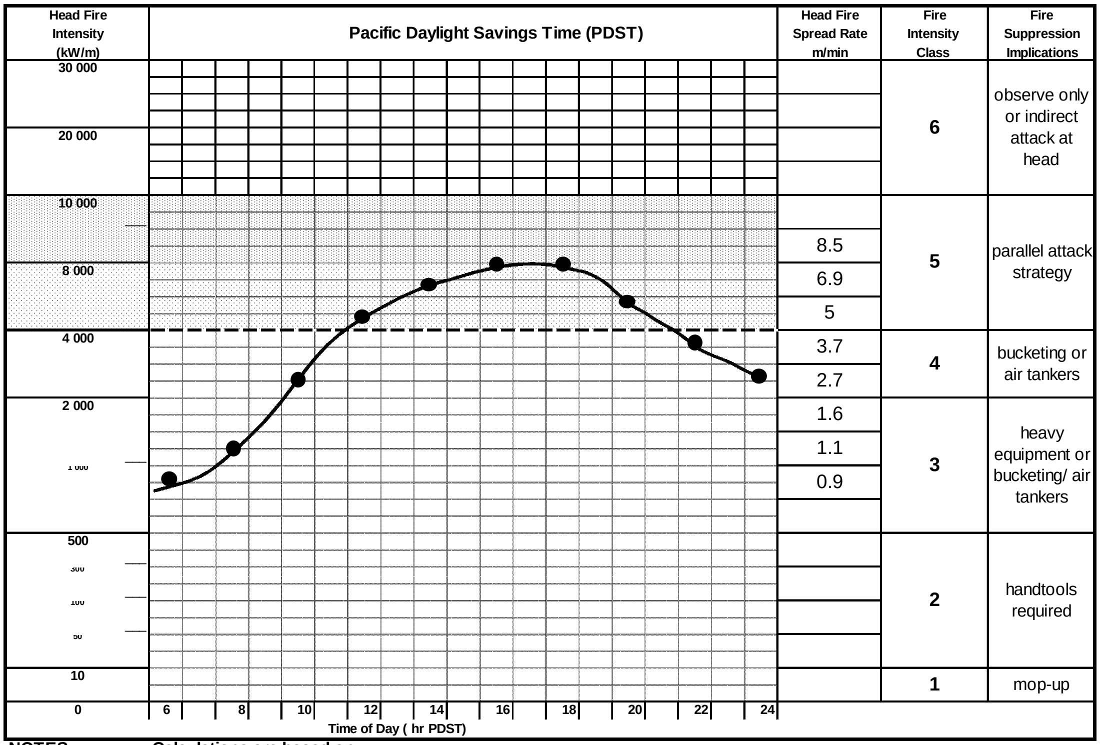
In May 2000, the reporting and graphics capabilities of WeatherPro3 software developed by REMSOFT Inc. were introduced to automate and simplify the process of generating diurnal fire intensity curves (Finn 2001). With this development, a line that depicts the critical surface fire intensity required to initiate a crown fire has also been added to the curves (Figure 3). Weather information is forecast for the next three days, hence diurnal intensities can be generated for up to three days in advance, and forecast information and the graphs are updated daily. Graphs of diurnal fire behavior

FIRE BEHAVIOR PREDICTION for ***94-07-25*** **(Date)**

ZONE/FIRE:
Garnet Fire

FUEL TYPE:
C-7 Ponderosa pine/Douglas-fir

prepared by: ***Fire Behavior Specialist***



NOTES: **Calculations are based on;**
=> ***forecasted*** **indices from** ***Penticton R/S*** **Wx**
=>1300hr winds of ***15*** **km/h, and RH of** ***22*** **%**
=> 1700hr FFMC of ***95*** **, and BUI of** ***152***
=> assumption of level (no slope) ground

** ***FBP must be recalculated on site to account for any changes in fuel type, wind, and slope***

ADVISORIES: * ***potential for intensities greater than 4000 kW/m exists*** *
* ***from 11:00 to 21:00 hours*** *
* *

EXTREME * ***winds are expected to change direction from the northwest to*** *
FIRE * ***the southwest after 13:00 hrs*** *
BEHAVIOR * *
WARNING * *

Figure 2. Sample diurnal intensity diagram generated in support of the British Columbia Ministry of Forests Fire Weather and Behavior Advisory and Warning System.

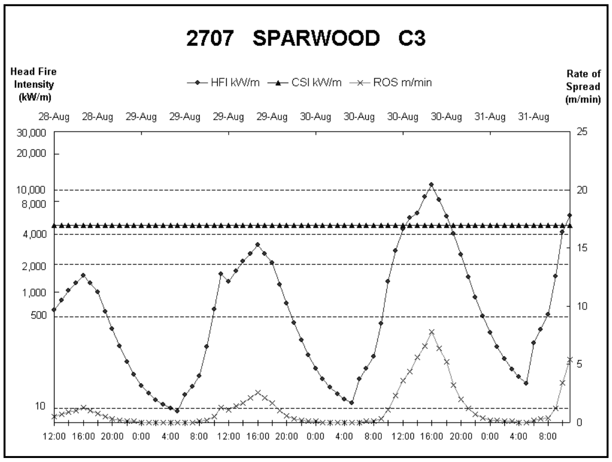


Figure 3. Diurnal intensities (HFI), rates of spread (ROS) and the critical surface fire intensity required to initiate a crown fire (CSI) are generated for up to three days in advance using FBP97 by Remsoft Inc.

characteristic are now produced and posted on BC's intranet automatically, and these are emailed readily.

3.6 *Training*

Wildland fire behavior specialists in Canada are now also trained to review the value and use of displaying fire behavior characteristics on a diurnal basis (ETC and CIFFC 2001). Students are asked to examine the implications of expected diurnal variation in head, back and flank fire rates of spread and intensities, on the potential for loss of life and property through the use of the 1985 Butte Fire (Rothermel and Mutch 1986; Alexander 1991) and 1994 Garnet Fire (Pattison 1995; Figure 2) case studies.

4. POTENTIAL IMPROVEMENTS

The present system developed in British Columbia for forecasting diurnal variation in fire intensity is viewed as only a moment in time. Several potential areas could be improved upon in order to increase the relative accuracy of the forecasted values. For example, rather than simply applying the 1300 hr forecast wind speed, fire operations personnel should have the option to also apply a climatologically-based wind speed trend (Beck and Trevitt 1989). Fire weather forecasters should be required to provide more time-specific wind speed information than they would normally undertake for general forecast purposes; this would be especially important for ongoing wildfires.

While the simplisticity of using the Lawson et al. (1996) equations to estimate the FFMC for a given hour principally as a function of time of day is advantageous, the drawback with this method occurs when the actual diurnal changes in temperature and relative humidity for a given day depart dramatically from the assumed diurnal trend. This could be overcome by utilizing the empirical modeling approach developed by Beck and Trevitt (1989) for predicting diurnal variation in temperature, relative humidity and wind speed given daily forecasted maximum and minimum values, (which are routinely provided by fire weather forecasters), latitude and calendar date, coupled with the hourly version of the FFMC model (Van Wagner 1977; Alexander et al. 1984), at least during rainless periods when it is needed the most.

At present, the diurnal forecasted values in fire intensity are for a single representative point on the landscape but there's no reason that the same information could not also be displayed spatially with the use of geographic information system technology (Lee et al. 2001).

5. CONCLUDING COMMENTS

In contrast to other fire weather advisories, alerts and warnings, the BC Fire Weather and Behavior Advisory and Warning System is unique in that it takes into account considerations of the fuel component of the fire environment explicitly (i.e., fuel load and moisture content) through application of the CFFDRS. While the concept of forecasting diurnal fire intensities has been applied in support of wildland firefighter safety, the same principles could easily be extended to other applications such as in assessing the length of the "burning period" for daily preparedness planning purposes (Beck 2001).

Perhaps part of the hesitancy by wildland fire management organizations to forecast fire intensities and other physical fire characteristics on a diurnal basis can be traced to the inherent complexity and uncertainty associated with predicting fire behavior. The point is acknowledge but hopefully through continued fire behavior training, including a review of the limitations and assumptions involved in tools and products like the CFFDRS and fire weather forecasts, this situation can be remedied. Such training is equally important to ensure that users don't apply the kind of outputs illustrated in Figures 2 and 3 blindly, without a comprehensive assessment of the forecast, the fire environment, fire management objectives and suppression capabilities.

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