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Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications

B. Mike Wotton

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Abstract Understanding and being able to predict forest fire occurrence, fire growth and fire intensity are important aspects of forest fire management. In Canada fire management agencies use the Canadian Forest Fire Danger Rating System (CFFDRS) to help predict these elements of forest fire activity. In this paper a review of the CFFDRS is presented with the main focus on understanding and interpreting Canadian Fire Weather Index (FWI) System outputs. The need to interpret the outputs of the FWI System with consideration to regional differences is emphasized and examples are shown of how the relationship between actual fuel moisture and the FWI System's moisture codes vary from region to region. Examples are then shown of the relationship between fuel moisture and fire occurrence for both human- and lightning-caused fire for regions with different forest composition. The relationship between rate of spread, fuel consumption and the relative fire behaviour indices of the FWI System for different forest types is also discussed. The outputs of the CFFDRS are used every day across Canada by fire managers in every district, regional and provincial fire management office. The purpose of this review is to provide modellers with an understanding of this system and how its outputs can be interpreted. It is hoped that this review will expose statistical modellers and other researchers to some of the models used currently in forest fire management and encourage further research and development of models useful for understanding and managing forest fire activity.

Keywords Fuel moisture · Fire occurrence · Fire behaviour · Area burned

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B. M. Wotton
Canadian Forest Service, Natural Resources Canada, Great Lakes Forestry Centre,
1219 Queen St East, Sault Ste Marie, Ontario, Canada P6A 2E5

B. M. Wotton (✉)
Faculty of Forestry, University of Toronto, 33 Willcocks St, Toronto, Ontario, Canada M5S 3B3
e-mail: mike.wotton@utoronto.ca

1 Introduction

During the fire season fire managers must make decisions each day on how many resources they will need and where those resources should be positioned. Fire crews and airtankers are assigned an alert status indicating how quickly they must be able to respond or may be sent to forward attack bases to be pre-positioned for quicker response in a particular area. Fire managers will make estimates of the number of fires they expect to occur in their regions each day; aircraft may then be assigned flight paths for detection of new fire starts. These decisions, and many more throughout the day and throughout the fire season, help determine the success of the fire management organization, limiting area burned and values (e.g., homes, merchantable timber) lost to fire. In Canada these decisions are based on the personal experience of fire managers and to a large part on outputs of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al. 1989).

Fire danger is a term used to describe the assessment of both the static and dynamic factors of the fire environment which determine the ease of ignition, rate of spread, difficulty of control and impact of a fire. It is important to distinguish fire danger from fire hazard and fire risk. Fire hazard represents the potential fire behaviour of a fuel complex, without consideration of the state of the fuel moisture: when the fuel structure, composition and arrangement remain the same, so to does the fire hazard. Fire risk represents the probability of a fire starting due to the potential number of ignition sources in the area. Fire Danger Rating is the process of evaluating and integrating the individual factors that define the elements of fire danger.

The structure of the CFFDRS is shown in Fig. 1. The system contains two major components which are used throughout Canada every day of the fire season: the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behaviour Prediction (FBP) System. The FWI System (Van Wagner 1987) provides a means of evaluating the severity of fire weather conditions in a common standardized forest type. It provides numerical ratings of fuel moisture in important fuel layers and several relative indices of fire behaviour. The FBP System (Forestry Canada Fire Danger Group 1992) relies on outputs from the FWI System and other information (such as

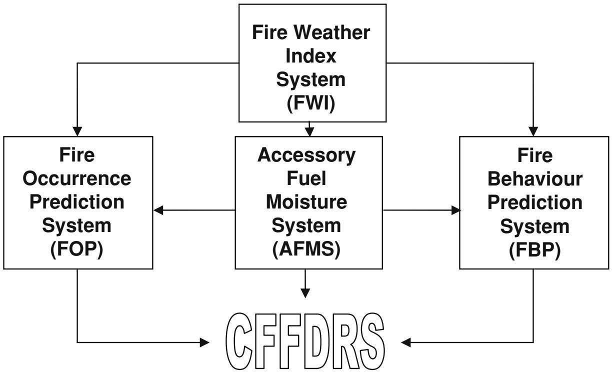

Fig. 1 The basic structure of the Canadian Forest Fire Danger Rating System

topography and time of year) and provides quantitative assessments of fire behaviour in a number of major fuel types across Canada. The Accessory Fuel Moisture System (AFMS) contains additional fuel moisture models to provide more temporal resolution to some fast response time fuels (e.g., Van Wagner 1977; Lawson et al. 1996) and a means of converting moisture code values to stand-specific moisture (e.g., Lawson et al. 1996b; Wotton and Beverly 2007). The Fire Occurrence Prediction (FOP) System does not represent a single developed system used in Canada; expected fire occurrence is typically estimated by local fire managers each day based on an evaluation of fuel moisture, lightning or potential human activity, and the fire manager's professional experience. There have been a number of regional fire occurrence prediction models developed in Canada (For human-caused fire occurrence: Martell et al. 1987, 1989; Todd and Kourtz 1992; Poulin-Costello 1993; Vega-Garcia et al. 1995; Wotton et al. 2003. For lightning-caused fire occurrence: Kourtz and Todd 1992; Anderson 2002; Wotton and Martell 2005); however no standardized national system exists. The FOP System is an important component of the CFFDRS however, despite the lack of a national system of standardized equations, as it represents the fire risk component of fire danger rating assessment.

The CFFDRS is used across Canada each day of the fire season and has been adopted by or adapted to a number of other countries (e.g., New Zealand, Indonesia, Portugal and the countries of southern Europe). In the US, fire management agencies use the National Fire Danger Rating System (NFDRS) (Deeming et al. 1977). The NFDRS and CFFDRS are used in a similar fashion and rely on the same definition of fire danger; however these two systems have developed from fundamentally different modelling philosophies. The NFDRS is based on detailed physical modelling and experimental burning in a controlled laboratory setting, while the Canadian system is based on basic physical models calibrated with field-based empirical observations of fuel moisture, fuel consumption and fire behaviour. Despite the difference in modelling approach there are similarities in the outputs of the systems. They both rely on weather information to estimate fuel moisture (though NFDRS does allow for use of actual fuel moisture estimates or fuel moisture surrogates (fuel moisture sticks) for fuels of specific size classes). While the intermediary steps are different, both systems summarize information into fire behaviour indices to indicate relative fire behaviour potential. It is, in general, these indices that fire managers use every day of the fire season to gauge and predict fire danger in their district.

The final statement of the preceding paragraph is an important point that bears emphasizing. While they are calculated using a universal system (that is, a common system to the country), outputs from the fire danger rating systems in the US and Canada must be interpreted regionally if they are to provide maximum possible information. A manager must understand what the numeric value of a particular index means in terms of fire potential given the specific forest type, climate and topography in their region. Typically, a fire management agency will evaluate historical fire activity and fire danger index values and determine threshold values to define a sequence of fire danger categories (e.g., Low, Moderate, High and Extreme). These categories will be used to determine resource requirements for the day. In Canada the thresholds which determine these category values can vary from province to province and even within province (in the case of British Columbia).

While the NFDRS is the main fire danger rating system used throughout the US, this paper will focus on fire activity in the forests of Canada and on the use and interpretation of the outputs of the CFFDRS. To lay the foundation for understanding how to interpret outputs of the FWI System (a system which has been in operational use in Canada for over 30 years) a very brief review of how it was developed is necessary. Outputs of the FWI System can be difficult to interpret without experience because raw output codes and indices have no real physical units. In contrast the FBP System outputs are recognizable and understandable quantities such as rate of spread, fuel consumption and fire intensity. The purpose of this paper is to provide a review of the CFFDRS (focusing on the elements of the FWI System) and a description of how output indices should be used and interpreted by researchers using the system for the development of statistical models of fire activity. This review will further show some examples of how the system outputs can be used in the development of models of regional fire activity.

2 The Fire Weather Index System

The current fire danger system in Canada has its roots in research that began near Chalk River, Ontario at the Petawawa Forest Experiment Station in the 1920s. This research comprised a program of meteorological observation coupled with field sampling of moisture from various fuel types and fuel layers. Along with this in situ fuel moisture sampling, small scale test fires were used to measure flammability of forest fuels in their undisturbed state on the forest floor. This program of moisture content measurement and ignition testing began in pine and hardwood types and then through the 1940s to early 1960s expanded to include major forest types spanning from Newfoundland west to British Columbia and north to the Northwest Territories. From these fuel moisture and ignition observations, fire hazard and fire danger tables were developed for various regions in Canada. In the late 1960s, with the recognition that there were strong similarities in all of these danger rating tables and that there was a need for common indices in terms of sharing fire fighting resources, a universal system was proposed and developed (Muraro 1968; Van Wagner 1974). This universal system was to contain models to capture the important features common to the major forest types within Canada (e.g., moisture in fine surface fuels, moisture in the organic layer). Outputs from this universal model were to be interpreted regionally across the country.

The FWI System was built to integrate weather information into fuel moisture and fire danger indices without regard to differences in forest type. The standard forest type chosen for the FWI System was mature Jack Pine (*Pinus banksiana* Lamb.) and Lodge Pole Pine (*Pinus contorta*). In terms of their stand structure and fire behaviour characteristics, these two species are similar and are a very common forest type found across Canada. Although there are numerous published descriptions of the FWI System and its components (e.g., Stocks et al. 1989), the mathematical structure of the system, as it is used today, was described by Van Wagner (1987).

The basic structure of the FWI System is shown in Fig. 2. It relies on once a day measurements (taken at 1,300 LDT) of air temperature and relative humidity (measured at 1.4 m above the ground in a radiation shielded screen), 10 m open wind speed,

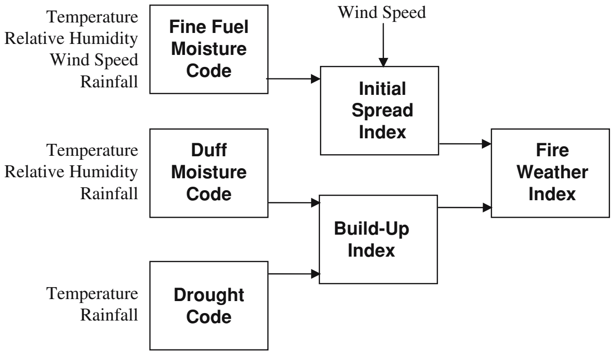

Fig. 2 The structure of the Canadian Forest Fire Weather Index System

and 24 h accumulated precipitation. The system contains three moisture codes tracking moisture in different levels of the forest floor. Moisture code values for the current day are calculated from the day's observed weather and the previous day's fuel moisture code values. At the heart of each of the moisture code calculations is a simple moisture exchange model. In the absence of rain, moisture change in each fuel layer follows an exponential curve towards an equilibrium moisture value. The response time of moisture exchange and the equilibrium moisture content value can depend on the fire weather conditions measured for the day. When rain has occurred, the existing moisture is added to the moisture in the fuel layer and then moisture exchange with the atmosphere begins. These moisture codes will be described in more detail later in the paper. The remaining three fire behaviour codes are created from the moisture codes (Fig. 2) and are relative ratings of fire behaviour potential capturing fire spread rate, fuel consumption and fireline intensity. A fourth fire behaviour index, called the Daily Severity Rating (DSR), is also an output of the FWI System. It is simply a transformation of the Fire Weather Index (FWI) and is generally used for averaging daily fire danger into monthly or seasonal values. One of the major strengths of the FWI System lies in these three moisture codes which track moisture in three layers of the forest floor critical to fire ignition, fire spread and fire suppression.

Outputs of the CFFDRS, most commonly the FWI System, have been used in numerous research studies to develop models of: fire occurrence (e.g., Martell et al. 1987, 1989; Kourtz and Todd 1992); crown scorch height and tree mortality (e.g., Van Wagner 1973); depth of burn on the forest floor (e.g., Stocks 1987, 1989); and, area burned for regions across Canada (Harrington et al. 1983; Flannigan and Harrington 1988; Flannigan et al. 2005). The system also forms a cornerstone for studies of the impacts of climate change on fires and forests of Canada (Flannigan and Van Wagner 1991; Stocks et al. 1998; Flannigan et al. 1998, 2000, 2005; Wotton et al. 2003) and is now being used in estimating carbon loss from fire for the annual carbon budget of the Canadian forest (e.g., Amiro et al. 2001).

2.1 Fine Fuel Moisture Code

When fire begins to spread in a forested stand as a surface fire, it is strongly influenced by the moisture in the small readily consumed fuels on the surface of the forest floor.

In the Canadian FWI System the moisture content in fine surface fuels is described by the Fine Fuel Moisture Code (FFMC). In the FWI System this is considered a 1.2 cm thick layer of pine litter with a fuel weight of 0.25 kg/m^2. The value of the FFMC increases with increasing dryness varying from 0 at saturation (250% moisture content) to a maximum possible value of 101, when the litter layer is completely dry. This inverted scale was created for psychological effect, so that high numbers of the code represent high fire danger. All the codes and indices of the FWI System are similarly arranged. Central in the FFMC is a simple exponential model of moisture exchange. At the start of its calculation each day, the previous days' FFMC is converted back to moisture content (mc) via the equation,

$$\text{mc} = 147.2 \cdot \frac{101 - \text{FFMC}}{59.5 + \text{FFMC}} \tag{1}$$

Any rainfall above the threshold of 0.5 mm that has fallen in the previous 24 h is added to the moisture of the layer (though this absorption of rain depends on the original moisture content of the layer itself), and then the layer's moisture exchange with the atmosphere is calculated for the day. The temperature and relative humidity conditions in the atmosphere determine an equilibrium moisture content to which the layer attempts to move following a simple exponential drying (or wetting) curve. This exponential model for drying is based on a physical understanding of how cellulose materials lose or gain moisture in reaction with atmospheric conditions. The rate at which the fuel layer moves toward equilibrium in this exponential model is called the response time and is dependant on temperature, relative humidity and wind speed. For conditions of 25°C, relative humidity of 30% and wind speed of 10 km/h the response time of the FFMC in the FWI System is approximately 0.5 days.

It is important to remember that the moisture codes (and fire behaviour indices) of the FWI System are built to represent the standardized jack pine or lodge pole pine fuel type. Figure 3a shows the association between daily FFMC value and pine litter moisture samples from several pine stands from Manitoba and Saskatchewan and the standard FFMC/moisture content relationship from Eq. 1. Each point on this graph represents the average moisture content of all sample days (collected through the spring and summer sampling periods) at each integer value of the FFMC: only values with more than 25 samples at an integer FFMC class were used in this graph. The moisture data in Fig. 3a–c are from Canadian Forest Service (CFS) field experiment sites involved in the original CFS small scale test fire program (Paul 1969; Simard 1970; Beverly and Wotton 2007). While the FFMC was designed to track moisture in an idealized pine stand, it is also associated with moisture in other stand types. In Fig. 3b the relationship between surface litter (leaf) moisture and FFMC is shown for a group of aspen stands in Manitoba and Saskatchewan. It is clear the FFMC is still strongly associated with moisture in aspen leaf litter over a wide range of leaf moisture; however the exact relationship between moisture content and FFMC has changed. Thus, a user of the system would have to understand that for a large region with a FFMC of 80 for example, the actual moisture in the surface fuels of a pine stand in that region would be lower (drier) than in the surface fuels of an aspen stand in that same region. The relationship between litter moisture and FFMC for spruce

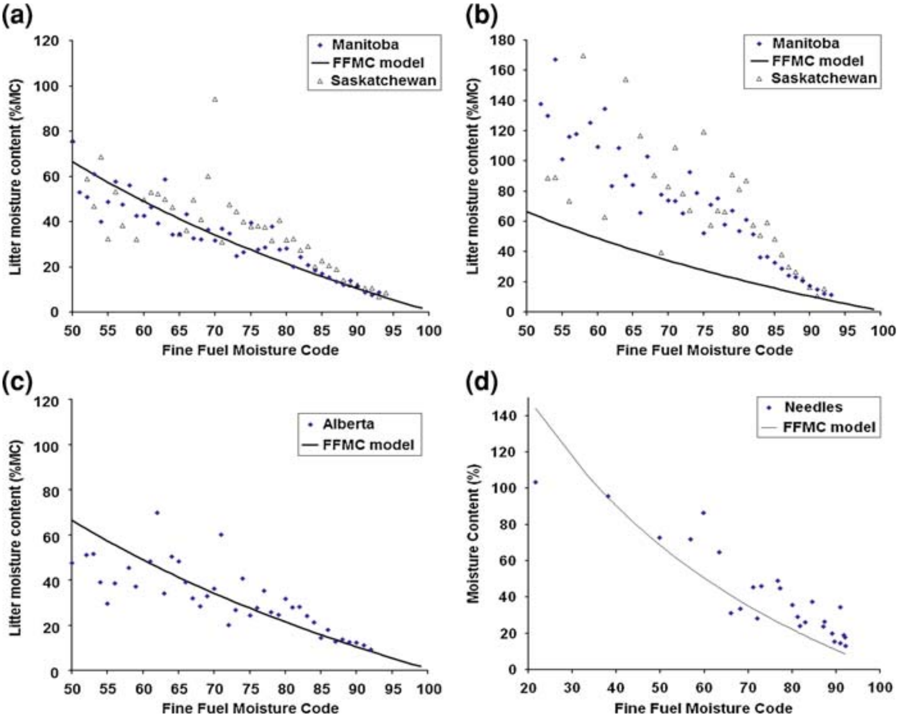

Fig. 3 Observed litter moisture in relation to FFMC for (**a**) pine stands in Manitoba and Saskatchewan, (**b**) aspen stands in Manitoba and Saskatchewan, (**c**) spruce stands in Alberta, and (**d**) a pine stand in northeastern Ontario with continuous feathermoss forest floor. The standard FWI System relationship between moisture content and FFMC (Eq. 1) is shown as a solid line

stands are shown in Fig. 3c. This plot shows that the FFMC relationship to moisture content in spruce forests is very similar to the relationships for pine forests. Figure 3d shows the correlation between moisture and FFMC value for pine litter from a jack pine stand sampled in northeastern Ontario in a recent field study (Wotton et al. 2005). Observations in Fig. 3d represent an average of three samples of litter collected daily during a short period in 2002 (results have not been grouped by FFMC class as was done in Fig. 3a–c due to the relatively small number of observations, and this is the source of increased variability in this plot). Here, the jack pine stand, while similar in structure to the FWI System standard, had a continuous carpet of feathermoss, on which pine needle litter lay. The plot shows that while the association between FFMC and absolute moisture content still exists, calculated FFMC values represent somewhat wetter litter than would be expected in the standard jack pine stand in the FWI System (the relationship in Eq. 1). In a recent paper, Wotton and Beverly (2007) developed stand type-specific equations relating FFMC and litter moisture content for a range of Canadian forest types and stand densities.

The FFMC is also reflective of litter moisture in small twigs, fuels which would also be consumed in flame front passage and contribute to the spread and intensity of a surface fire. Figure 4 shows the relationship between FFMC and moisture in small

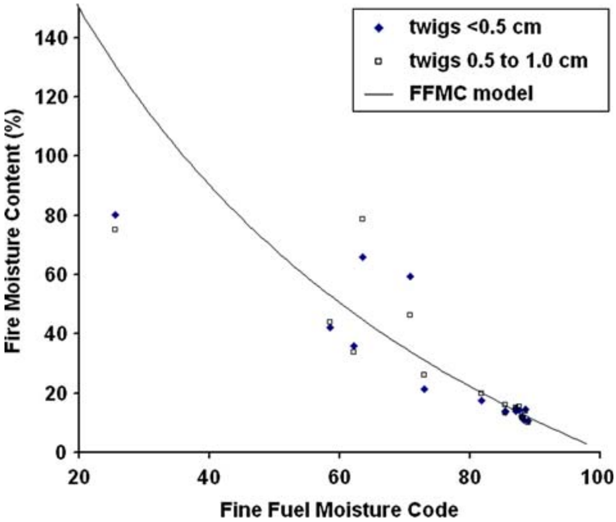

Fig. 4 An example of moisture in small twigs on the surface of the forest floor in relation to FFMC calculated at a nearby weather station

twigs (<1 cm diameter) from sampling in a jack pine stand near Sault Ste. Marie, Ontario during the spring and summer of 2005. Sampling here was carried out over a small number of days and does not represent a definitive study of the moisture content relationship (twig moisture was not the main purpose of this study); however, a trend with FFMC is evident. The two size classes shown in Fig. 4 represent twigs that would likely be completely consumed in the passage of the flaming front of a fire. In a recent study, DeGroot et al. (2005) also developed a calibration for the relationship between FFMC and grass moisture content in open fields in Indonesia.

It is clear from Figs. 3 and 4 that variability in the association between FFMC and actual moisture content increases with increasing moisture content (that is, decreasing FFMC value). This increasing variability is commonly observed in moisture sampling and is a result of small-scale variability in stand structure (e.g., stand density and canopy structure), surface vegetation and forest floor composition; modellers should be aware of this non-homogenous variability when developing models of these processes and incorporate appropriate transformations of their data. After a rainfall, small differences in stand structure can lead to large differences in water that has reached the surface of the forest floor (throughfall). This in turn affects the moisture content of those fuels on and just below the surface of the forest floor. As the forest dries in the days after a rainfall the influence of these small scale differences disappear. The speed at which these microsite differences in moisture content disappear depends on the drying rate of the fuel being studied. Fine fuels dry rapidly and micro-site variability in moisture content across reduces quickly (over just 1 or 2 days), while fuels in the organic layer, like those represented by the Duff Moisture Code, change more slowly and hence can display considerable small scale spatial variability until a lengthy period of drying has occurred (on the order of several weeks duration).

2.2 Duff Moisture Code

The Duff Moisture Code (DMC) describes the moisture content of the upper layers of the forest floor where litter is beginning to decay. The DMC model nominally tracks moisture in the top 7 cm of the forest floor in a mature jack or lodge pole pine stand and represents a fuel load of 5 kg/m^2. As with the FFMC, moisture in this layer increases from a code value of 0 (which corresponds to a saturation moisture content of 300%). The DMC has no upper bound, however values above 150 are rarely seen. At the centre of the DMC model is a simple exponential model of moisture exchange similar to many other operational fuel moisture models used today. Moisture content can be found from the code value through the equation

$$\mathrm{mc} = 20 + \ln\left(\frac{\mathrm{DMC} - 244.73}{-43.43}\right) \tag{2}$$

The DMC layer gains moisture directly only from rainfall and dries to a constant equilibrium moisture content of 20%. The rate at which drying occurs (which corresponds to the time lag coefficient in the exponential drying model) depends on both relative humidity and temperature. For a July day with a temperature of 25°C and a relative humidity of 30%, drying rate is approximately 10 days.

Although the DMC models a fuel layer in the standard jack pine stand of the FWI System, like the FFMC, it is used throughout a range of forest types across the country. The relationship between DMC and the upper 6 cm of the forest floor topped by a layer of feathermoss in a mature jack pine stand northeast of Sault Ste. Marie, Ontario is shown in Fig. 5. The forest floor at this site was somewhat different than that of the FWI System standard, with the presence of a thick feathermoss layer at the surface;

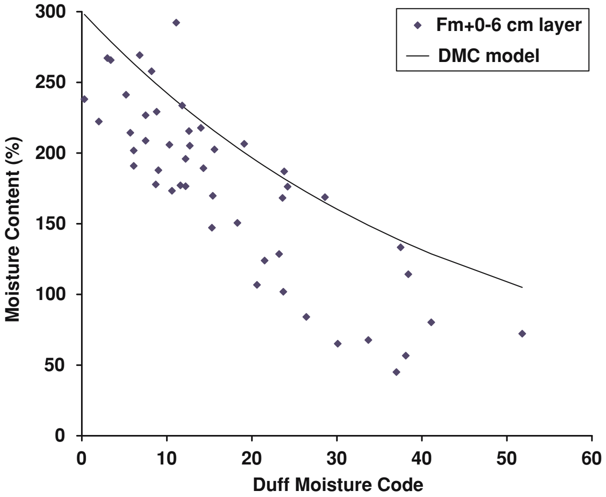

Fig. 5 Observed duff moisture content in a mature jack pine stand in north eastern Ontario related to DMC calculated at a nearby weather station. The standard FWI System relationship (Eq. 2) is shown as a solid line

however there is a clear correlation between DMC and the observed moisture content of this layer. The DMC has also been found to be correlated with moisture content in a number of different forest types and several relationships have been developed linking DMC value to specific forest floor moisture content in different forest types (Lawson et al. 1997; Wilmore 2001).

2.3 Drought Code

The Drought Code (DC) is a simple index to account for the influence of long term drying on the fuels on the forest floor. It is similar to other drought models such as the Keetch–Byram Drought Index (Keetch and Byram 1968) and the Palmer Drought Index (Palmer 1988). The DC is often used as an indicator of the moisture content of deep layers of the forest floor and the moisture content of large down and dead woody debris on the forest floor. In the FWI System the DC nominally tracks moisture in a 18 cm thick organic layer with a fuel load of 25 $\mathrm{kg/m^2}$, though many forests in Canada (east of the Rockies) do not achieve organic layers of this depth. This layer does not interact with the atmosphere directly but absorbs moisture only through rainfall. It dries through the same exponential drying mechanism used in the FFMC and DMC models; however the DC dries toward a constant equilibrium moisture content of 0%. Its drying rate is dependant on temperature alone. For a day in July with a temperature of 25 °C the DC's response time is approximately 50 days.

As with the DMC and FFMC, the moisture content of the layer modelled by the DC is converted to a code value where increasing values mean increasing levels of dryness of the deep forest floor or of the large woody material on the forest floor. In the current FWI System a DC value of 0 corresponds to a saturation moisture content of 400% (Van Wagner 1987). The DC has no real maximum, though values over 1,000 are extremely rare. The conversion between DC and moisture content takes the form

$$\mathrm{MC} = 400 \cdot \mathrm{e}^{\frac{-\mathrm{DC}}{400}} \tag{3}$$

Equation 3 differs slightly in one term from the equation often used for conversion between moisture and DC, which comes directly from Van Wagner 1987. It should be noted that the original equation (Eq. 22 in Van Wagner 1987) refers to the conversion between DC and a unitless 'moisture equivalent'. This moisture equivalent is not defined as the equivalent to gravimetric moisture content however. It has a maximum value of 800 when DC is 0. Given that the DC layer in the FWI System is defined as having a maximum moisture holding capacity of 400% moisture content (Van Wagner 1987), the two are clearly not equivalent. This difference can be seen by examining data from several studies of moisture content in deep duff layers (Lawson et al. 1996b; Wilmore 2001). In the layout of the FWI System (Van Wagner 1987) it is implicit in the formulation of the DC conversion that moisture content must be equivalent to one half of the moisture equivalent term at saturation. This simple relationship between the two is carried over the range of the DC scale, and the formulation presented in Eq. 3 agrees well with observations of forest floor moisture (as can be seen in the functional forms of Lawson et al. (1996b)) for west coast forest types. Drought Code values have been shown to be associated with occurrence of drought (Girardin et al. 2004).

Understanding the level of drought influencing the forest is important because it gives an indication of the amount of fuel that will be consumed in fires: both on the surface and within the forest floor. It further is used by fire managers as an indicator of the difficulty of mop-up of a fire, that is, the difficulty in finally extinguishing all areas where the fire is smouldering, though it is probably more typical that a fire management agency would use the Build-Up Index (BUI) for this purpose (the relationship between DC and BUI is described in the next section).

2.4 Build-Up Index

The Build-Up Index (BUI) accounts for moisture levels in the fuels tracked by the DMC and the DC. In its simplest sense it is a harmonic mean of DMC and DC, with DC being weighted to reduce its influence. While the calculation is slightly more complex than this, for the purposes of this discussion the simple understanding that it is a weighted mean of DMC and DC is sufficient. Further details on the exact formulation of the BUI are given in Van Wagner (1987).

The BUI is a unitless index used as a relative indicator of potential fuel available for surface fuel consumption (consumption of material on and in the forest floor by the passing fire front). Figure 6 shows the clearly positive relationship between total surface fuel consumption and BUI for a series of experimental fires in jack pine. In the FBP System this relationship is assumed to roll over to a constant value of about 5 kg/m^2 (representing nearly complete consumption of surface fuels) at high BUI levels, though this roll over is not reflected in the data here. These fires form the basis of

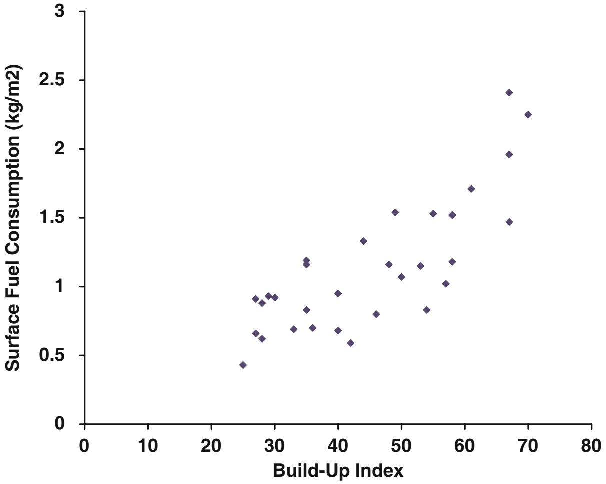

Fig. 6 Total surface fuel consumption (surface litter, down and dead wood and forest floor consumption) for experimental fires in jack pine as a function of BUI

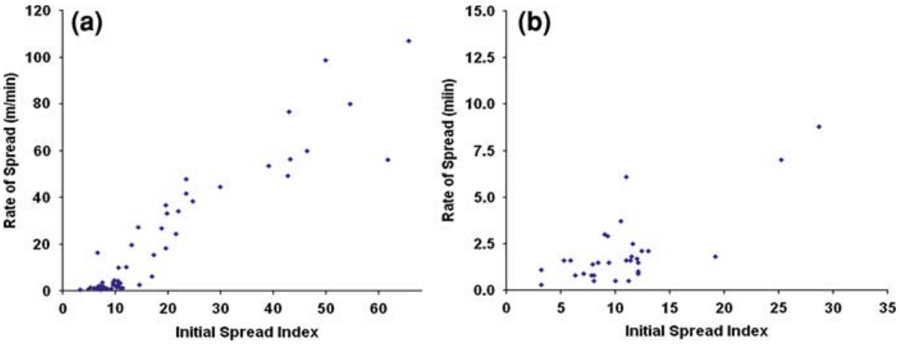

Fig. 7 Rate of spread as function of ISI for (**a**) jack pine and lodge pole pine forests and (**b**) aspen forests (data is from experimental fires and well-documented wildfires)

the mature Jack Pine/Lodge Pole Pine fuel type in the FBP System (called the C-3 fuel type) and derive mainly from fires reported in Lawson (1973), Quintilio et al. (1977) and Stocks (1987, 1989). It is important to understand that the BUI does not take into account the actual fuel load on the ground for any particular stand type. It implicitly assumes a standard load and fuel arrangement (that of the standard FWI System forest stand) and further assumes that this fuel load would be adequate to maintain fire spread. Thus it is a weather-based indicator only.

The BUI is often used by forest fire management agencies as an indicator of the potential difficulty in extinguishing smouldering fire, or the tendency of a fire to remain smouldering deep in the ground or in large woody material. Higher BUIs indicate a higher potential for this kind of smouldering fire and thus potentially indicate a longer time for mop-up of the fire.

2.5 Initial Spread Index

The Initial Spread Index (ISI) integrates the moisture content of surface fuels (through the FFMC) and the observed wind speed to give a unitless indicator of the potential rate of spread of a fire (details of its calculation can be found in Van Wagner 1987). The ISI has been found to be a good indicator of rate of spread in a range of forest types. All of the rate of spread models in the FBP System are non-linear functions of ISI; however a certain value of ISI can correspond to quite different expected rates of spread for different fuel types. Figure 7a shows the positive relationship between observed rate of spread and ISI for a series of experimental and wildfires in jack pine and lodge pole pine that make up the FBP System's mature jack pine/lodge pole pine fuel model (FBP fuel type C-3) and Fig. 7b shows a similar set of points for experimental fires in aspen (FBP fuel type D-1). While both plots show an increasing rate of spread with increasing ISI, the difference in the magnitude of the rate of spreads predicted should be noted. At an ISI value about 30 the plot for the jack pine/lodge pole pine fuel type indicates an expected rate of spread of just over 40 m/min while the plot for the aspen fuel type indicates a rate of spread of approximately 8 m/min.

2.6 Fire Weather Index

Byram (1959) gave a simple equation for estimating the intensity of a spreading fire per unit of fire perimeter (I_B) that has become ubiquitous in forest fire management. It can be written as,

$$I_B = H \cdot W \cdot R \tag{4}$$

where H represents the heat release through combustion of fuel, W represents the weight of fuel consumed, and R represents the rate of spread of a fire. Byram's fireline intensity represents the energy release per metre of fire perimeter of a spreading fire. This quantity has been found to be correlated with flame length from a spreading fire, with flame length scaling at roughly the square root of fireline intensity (Byram 1959). Byram's fireline intensity is used by fire managers as an indicator of the difficulty of suppression and as a guide to the type of suppression resources that might be successful in holding a spreading fire. For fires in Canadian forests, general ranges have been laid out for typical suppression resources (e.g., Alexander and Lanoville 1989). For intensities under 500 kW/m crews with hand tools and pumps can be effective at suppressing the spreading fire. Between 500 and 2,000 kW/m, bulldozers and airtankers become necessary. Between 2,000 and 4,000 kW/m only airtankers can effectively build fireline. Above 4,000 kW/m control of the spreading head fire is extremely difficult by any direct means.

The Fire Weather Index (FWI) is the final index of the FWI System and is analogous to Byram's fireline intensity. The FWI is formed using a formulation similar to Eq. 4 where W is represented by the BUI (the fuel consumption indicator) and R is represented by the ISI (the rate of spread indicator) and is a unitless indicator of expected fire intensity.

The FWI provides a general summary of fire weather and fuel moisture in a region and can be useful when a single indicator of general fire potential is needed, for instance when communicating fire danger to the public (it is the FWI that is used in setting the levels on the well known roadside fire danger signs). Fire management agencies today rely on the more basic elements of the FWI System (such as BUI, ISI and FFMC) in their daily operational planning. Given that modern fire agencies have detailed forest fuel type information about their forests, the FBP System outputs are also used operationally, assessing potential fire growth and resource requirements for successful fire suppression.

Given that the FBP System is the second major component of the CFFDRS and outputs can be used to provide physically realistic predictions of fire behaviour, I will briefly describe its primary outputs in the following section.

3 The Fire Behaviour Prediction System

The FBP System takes the relative indices of the FWI System and converts them to stand specific, physically recognizable and interpretable predictions of fire behaviour. The system produces predictions for 16 major fuel types and accounts for influences of topography, location, and time of year on fire behaviour. In its secondary outputs the system employs a simple elliptical model of expected fire growth to estimate head, flank and back fire rates of spread and fire shape. Using a model of acceleration it can also model fire spread from either a single point or an ignition line.

The three main primary outputs of the FBP System are analogous to the three relative fire behaviour indices of the FWI system. Surface fuel consumption (SFC) is analogous to the BUI (see Fig. 6) and indeed the FBP System fuel types include a method of converting a BUI value (or in one case FFMC) into an actual estimate of surface fuel consumption based on extensive field measurements during experimental fires. The head fire rate of spread (ROS) is analogous to the ISI as was discussed earlier (see Fig. 7). In the FBP System, Byram's fireline intensity is calculated as the head fire intensity (HFI: the intensity of the fire at the head of the spreading fire) using the fuel consumed (SFC in the case of surface fires only) and ROS. For a surface fire this intensity is then calculated by

$$\mathrm{HFI} = 300 \cdot \mathrm{SFC} \cdot \mathrm{ROS}$$

where SFC is in kg/m^2 and ROS is in m/min. The fourth primary output of the FBP System is a descriptive output of the fire type. This is dependant on the fire intensity where a fire can be described as either: surface, intermittent crowning, or fully crowning.

The FBP System is a complex set of empirical models that have been developed over years of experimental burning. In some ways the FBP System is much more complex than the FWI System and an entirely separate paper could be dedicated to a basic description of its inputs and outputs and their use in fire management. In contrast to the FWI System, however, FBP System outputs represent physically understandable quantities, such as rate of spread in m/minute or fuel consumption in kg/m^2. For this reason, this I have chosen to limit the description of the FBP System (more detail can be found in Forestry Canada Fire Danger Group 1992) and focus mostly on the interpretation of the unitless codes and indices output from the FWI System.

4 Applications

Outputs of the CFFDRS have been used by fire researchers for the development of a number of applications relevant to fire management. This section will describe some of these applications and present some raw data showing the relationships between fire activity and outputs of the FWI System.

4.1 Depth of burn

The depth of burn, the amount of the forest floor consumed during a fire, can be important for determining ecological impacts of a fire. For instance, removing organic material can help create a more viable seedbed. Moisture level in the duff layer is an important factor influencing the depth of burn that occurs during spreading fires. Figure 8 shows the relationship between DMC and depth of burn from two sets of

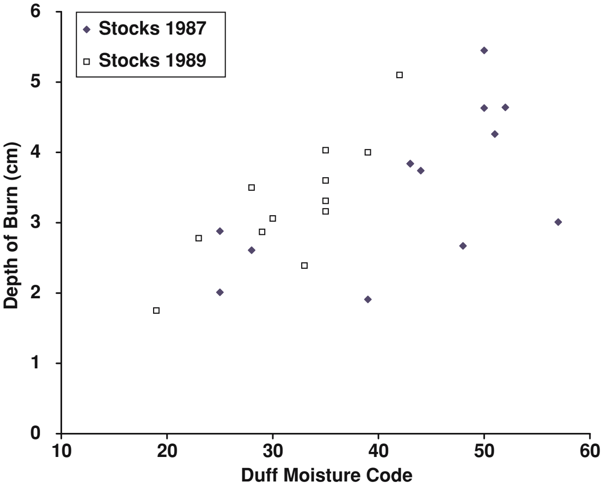

Fig. 8 Depth of burn measured on experimental fires in jack pine as a function of DMC

experimental fires (Stocks 1987, 1989). The correlation between DMC and depth of burn was $r = 0.60$ ($n = 21$, $P = 0.0037$) for the data in the immature jack pine burning experiment (Stocks 1987) and $r = 0.82$ ($n = 12$, $P = 0.0011$) for the mature jack pine experiment (Stocks 1989). Difference in depth of burn with DMC between these two experiments was due to differences in the forest floor at the two sites. There is a great deal of variability in these measurements because forest floor density and moisture content can vary considerably throughout a stand. DMC is also correlated with woody fuel consumption in medium to large sized down and dead woody material on the forest floor.

4.2 Fire occurrence

4.2.1 Human-caused fire

The FFMC is used by fire managers as an indicator of the receptivity of surface fuels to ignition and has a strong influence on the vigour of spread of a surface fire; thus it is an important element in predicting fire occurrence on the landscape. Figure 9 shows the relationship between observed human-caused fire occurrence and FFMC for two ecoregions in Ontario. Here a single daily FFMC stream has been interpolated to the centre of each of the ecoregions and human-caused fire is summarized across each ecoregion for each day during the fire seasons of 1976–2004. The number of fires occurring on days with the same integer FFMC value over the entire study period are summed and divided by the total number of days in the region at that same FFMC value. The two ecoregions shown in Fig. 9, which are virtually the same size ($<0.1\%$ difference in area), represent areas with different forest fuels (Ecological Stratification Working Group 1996). Ecoregion 90, the Lac Seul Upland, is dominated by coniferous forests, mainly black spruce and jack pine. Ecoregion 97, the Lake Timiskiming

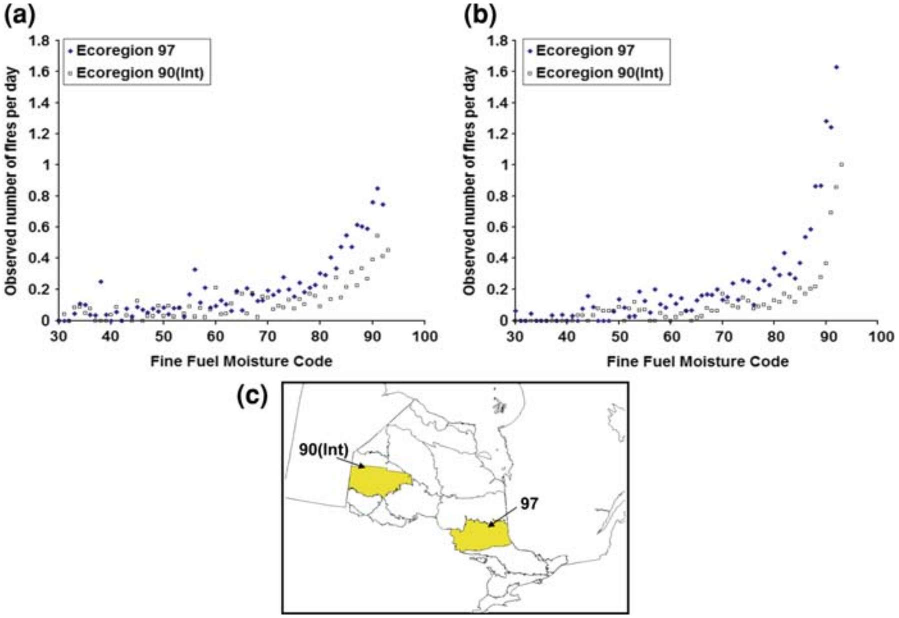

Fig. 9 Observed number of human-caused fires per day in each integer FFMC class for two Ontario ecoregions (the y-axis has been adjusted for differences in the total number of days in each FFMC class). Fires have been seperated into two cause groups, (**a**) Recreational, Industrial, and miscellaneous cause type fires that have a peak in the mid-summer and (**b**) residential, railway and incendary which have a peak in spring. The map (**c**) shows the locations of these two ecoregions (shaded) with the province of Ontario. The study period spans 1976–2003

Lowland, contains a mix of coniferous (pines and spruces) and deciduous (aspen, birch) types. For this current analysis only the areas from within the Intensive and Measured Zone of ecoregion 90 are included so that the study area received relatively consistent fire detection effort. The province of Ontario has traditionally broken its fire management area down into three zones: an intensively protected zone where fires are aggressively suppressed; a measured zone where fires receive aggressive initial attack but if they escape are re-evaluated for extended attack; an extensive zone where fires are simply monitored and not attacked unless they threaten communities or other values. In addition human-caused fires have been broken up into two different cause groups: group 1 includes fire cause types that tend to occur relatively consistently throughout the fire season, with a peak during the mid to early summer; and group 2 includes those fires that tend to occur most frequently in the spring.

Clearly from Fig. 9 fire occurrence increases with increasing FFMC (as fuels dry) in a non-linear way for both cause groups. It is difficult to determine visually if the number of fires expected at a certain level of FFMC is influenced by both cause and by ecoregion. As a simple test a log transform was applied to the data in Fig. 9 and the significance of terms in a simple model of the form,

$$\log(\mathrm{FIREOCC}) = \beta 0 + \beta 1 \times \mathrm{FFMC} + \beta 2 \times \mathrm{ECOREGION} + \beta 3 \times \mathrm{CAUSE}$$

was tested using analysis of variance (full model: $n = 164$, $F = 120$, $P < 0.0001$). This revealed ecoregion did have a significant influence on the number of fires occurring (for ecoregion: $F = 66.9$, $P < 0.0001$) while cause did not ($F = 1.4$, $P = 0.24$). No interaction terms between FFMC and ecoregion or cause were found to be significant.

Differences in fire occurrence between these two ecoregions are most likely due to two main factors: differences in forest type, and even more importantly, differences in human activity. Fire managers use their understanding of the relationships between fire occurrence and FFMC along with their understanding of potential human activity in the forests in their area to make predictions of the number of human-caused fires expected to occur each day. The relationship shown in Fig. 9 has been used in past to model fire occurrence (e.g., Cunningham and Martell 1973; Martell et al. 1989; Poulin-Costello 1993; Wotton et al. 2003) using logistic and Poisson regression (McCullagh and Nelder 1989)

It is important to remember that expected human-caused fire occurrence in an area depends on the receptivity of forest fuels to ignition and sustainable spread (e.g., moisture content of surface fuels) as well as the number of ignition sources in the forest: without ignition sources receptive forest fuels are unimportant. The presence of ignition sources depends on human activity in the forest. This activity can have very clear spatial structure with fires occurring in clusters close to populated areas, roads and railways. To demonstrate this Fig. 10 shows historical human-caused fires in Ontario (1976–2004). The structure of roads, railways and high population areas is clearly evident in this map.

4.2.2 *Lightning-caused fire*

Moisture in the upper organic layer is important for determining the probability of ignition from lightning strikes; lightning discharges tend to run down tree boles and possibly ignite the surface or organic material near the base of the tree (see for example Fig. 11). Each day across Canada, fire managers examine the previous day's (or

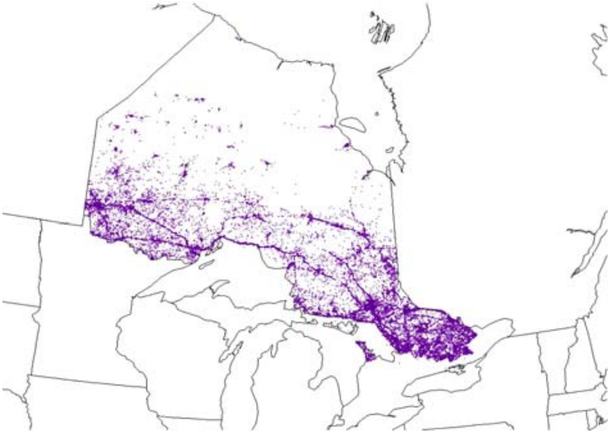

Fig. 10 The locations of human-caused fires in Ontario (1976–2003)

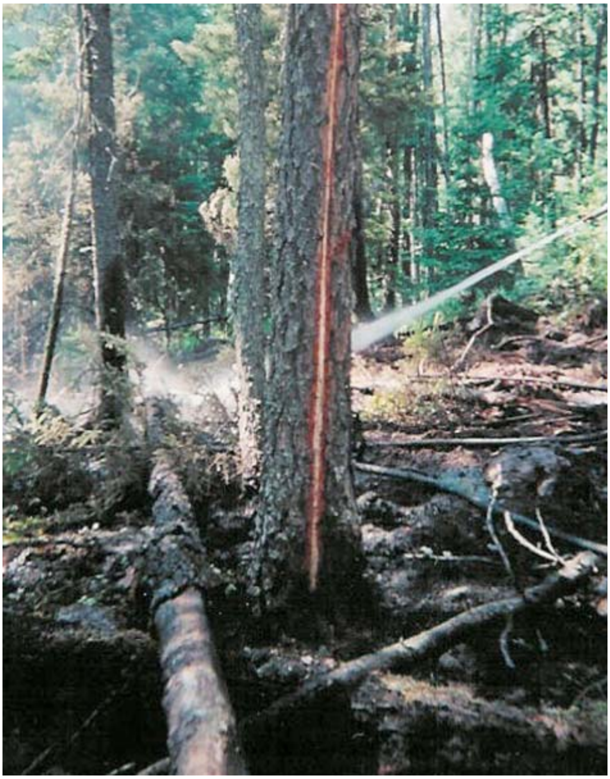

Fig. 11 The discharge path to electrical ground, indicated by the strip without bark, of a strike that started a fire (Fort Frances District Fire #39) in Ontario during the 2002 fire season. (Photo by J. Beverly on August 4, 2002, Quetico Provincial Park, Ontario)

perhaps 1/2 or 1/4 day's) lightning strike location records along with maps of the DMC to estimate the location of expected pockets of lightning fire occurrence. The DMC has become the standard indicator of landscape receptivity to ignition by lightning, with lightning expected to ignite fires when DMC exceeds a value of approximately 20. Figure 12a shows the raw probability of ignition (number of lightning fires per lightning strike in each integer DMC class) for the intensively protected area of northeastern and northwestern Ontario (1992–2004). Here daily lightning and observed fire ignition have been grouped into 20 km by 20 km cells and DMC interpolated to the centre of each cell from Ontario's daily fire weather station network according to the standard method used operationally in the province. The rise in expected ignition frequency with rising DMC is quite clear, though visually it seems a there is a difference in the rate of increase of fires per lightning strike between eastern and western Ontario; this is most likely due to the difference in forest type in these two regions (northwestern Ontario (west of Lake Nippigon) being dominated more by coniferous forests than northeastern Ontario, which has a larger mixedwood component (a stand level mixture of coniferous and deciduous trees)). A similar trend can be seen for lightning and fire information collected over the forested area of Alberta (Fig. 12b).

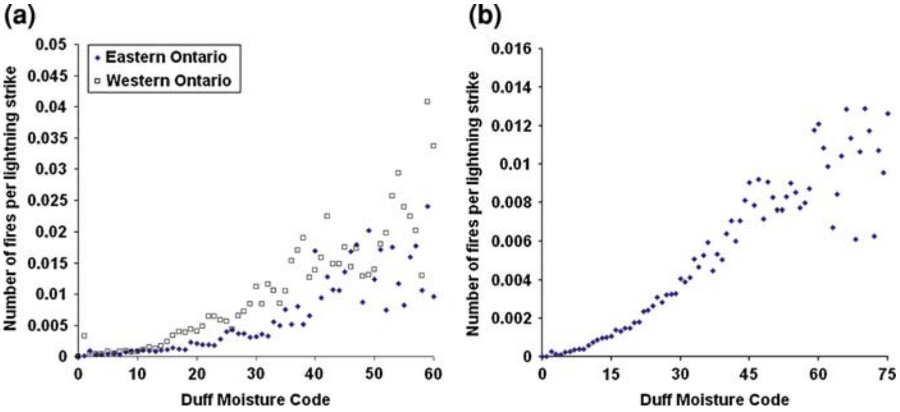

Fig. 12 Raw number of fires resulting from a lightning strike as a function of DMC for (**a**) Eastern and western Ontario (1992–2004) and (**b**) the forested area of Alberta (1984–2004)

While the rate of increase in probability of lightning fire ignition with increasing DMC visually seems different for the two regions of Ontario and in Alberta, a simple statistical comparison was carried out to test this hypothesis. A logistic regression model was used of the form

$$\begin{aligned}\mathrm{LOGIT}(\mathrm{FIRE}_{\mathrm{DMC}}/\mathrm{LTG}_{\mathrm{DMC}}) = {} & \beta 0 + \beta 1 \times \mathrm{DMC} + \beta 2 \times \mathrm{REGION} \\ & + \beta 3 \times \mathrm{DMC} \times \mathrm{REGION}\end{aligned}$$

where REGION was a 3 level categorical variable that represented (1) the west and (2) east region in Ontario (from Fig. 12a) and (3) the forested area of Alberta (from Fig. 12b). Results of the regression (PROC GENMOD, SAS Institute 2002) showed that both REGION ($df = 2$, Wald $\chi^2 = 164$, $P < 0.0001$) and the interaction term DMC × REGION ($df = 2$, Wald $\chi^2 = 41.8$, $P < 0.0001$) had a significant influence on the probability of ignition from lightning.

The high variability that is evident at high values of DMC in the plots in Fig. 12 exists because very dry forest floor conditions are quite rare in these regions, and thus there are considerably fewer days with these high DMC values and correspondingly fewer fires in these categories from which to create a reliable estimates of the fire per lightning strike value.

Logistic regression (McCullagh and Nelder 1989) can be used to develop models of the probability of lightning fire ignition as was shown in Wotton and Martell (2005). In understanding lightning-caused fires and attempting to model lightning fire occurrences it is important to understand that a lightning fire can go through a number of phases in its life: it is ignited from a lightning strike, it can then smoulder for a period, change between a smouldering ignition to a spreading surface fire, and perhaps change back again to a smouldering fire. In terms of importance to a fire management agency, a lightning fire occurrence can be reduced to two very important phases (Wotton and Martell 2005): (1) the ignition of the fire from a lightning strike, this can be either an immediately spreading surface fire or, more likely in Canadian boreal

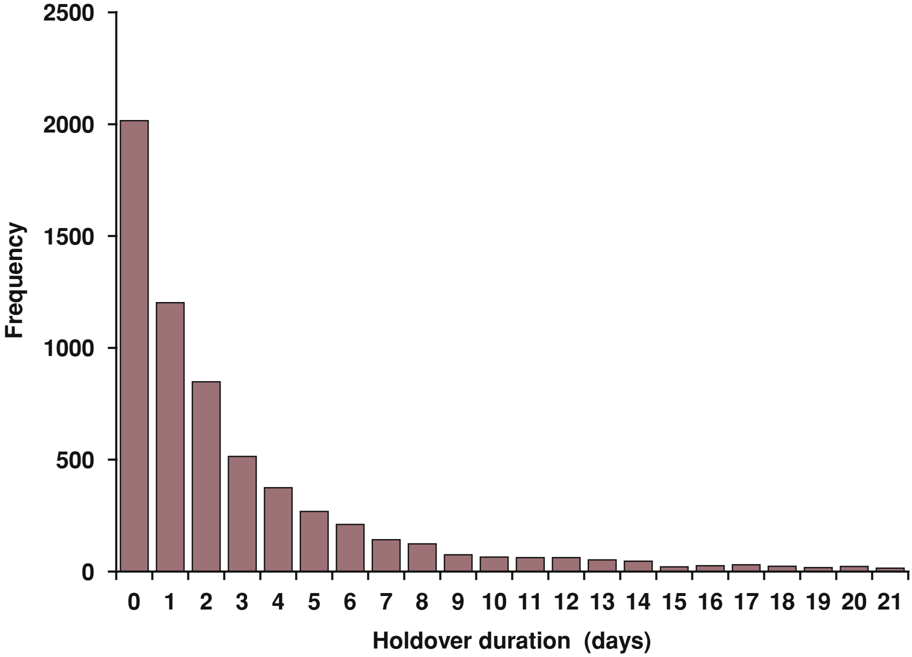

Fig. 13 Holdover duration for lightning fires across Ontario 1992–2004

forests, a smouldering fire in the forest floor; and (2) the detection and reporting of that fire too the management agency, which can occur when the fire is consuming enough material to create a smoke column that can be seen. The latter event is most important to a fire management agency, as this is the trigger for fire management action to begin; however, the number of ignitions smouldering on the landscape undetected is also of interest to the management agency in terms of planning for fire occurrence several days in the future. The time between these two events is called the holdover time. Figure 13 shows holdover times for fires from 1992 to 2004. From this plot it is clear that some fires can “holdover” for several days before being detected by the agency and suppressed.

4.3 Area burned

The area burned by fire is an important statistic to forest fire managers in any region, even more so in areas with many high values (homes and cottages, infrastructure, merchantable timber). Several studies of the correlation between fire weather, FWI indices and area burned have been carried out for a number of regions in Canada. Harrington et al. (1983) examined correlations between monthly provincial area burned and mean and maximum indices from the FWI System. They found correlations that explained 33% of the variability in area burned in provinces west of Ontario. Monthly means and maxima of the DMC and the daily severity rating (DSR, an exponentially

Table 1 Correlation of annual area burned (1976–2004, $n = 28$) with annual mean and 99th percentile of several FWI System outputs and the number of fires occurring in the region

Fire weather variable	Ecoregion 90 Correlation (P-value)		Ecoregion 97 Correlation (P-value)	
	Mean	99th %ile	Mean	99th %ile
FFMC	0.249 (0.202)	−0.004 (0.98)	0.158 (0.423)	0.176 (0.370)
DMC	0.247 (0.206)	0.338 (0.08)	0.303 (0.117)	0.332 (0.084)
ISI	0.372 (0.051)	0.578 (0.0013)	0.340 (0.077)	0.475 (0.011)
FWI	0.0354 (0.065)	0.562 (0.0019)	0.334 (0.082)	0.524 (0.0042)
Number of fires	0.382 (0.045)		0.258 (0.186)	
Number of escape fires[a]	0.504 (0.0063)		0.527 (0.0039)	

[a] Number of escape fires is defined as fires over 4 ha in size occurring in a year

scaled version of the FWI) were the best predictors across the provinces in general. Flannigan and Harrington (1988) carried on this work but looked at the relationship of monthly area burned to fire weather variables. They found that sequences of dry days (days with < 1.5 mm of rain) and low RH's had reasonable explanatory power. Again roughly 30% of the monthly variability in area burned was explained by models for provinces west of Ontario, while 11% of the variance was explained through similar models in the east. Recently Flannigan et al. (2005) studied monthly area burned in each of the ecozones of Canada from 1959 to 1997. They found average or maximum air temperature to be a consistent indicator of area burned. Fuel moisture indices also provided some explanatory power. They developed linear models for predicting area burned based on these associations; explained variability ranged from 36% to 64%. In general air temperature would not be thought to have a strong influence on the spread of an individual fire on a single day (except that high temperature might accompany low relative humidities); however, monthly temperature averages or maxima might integrate a number of factors influencing spread and hence perform as a good indicator of overall area burned (e.g., temperature certainly has an important role in increasing the drying rate of forest fuels).

Table 1 shows the correlation of annual area burned with annual average and 99th percentile value for several FWI System indices for the two ecoregions used as examples in the fire occurrence section (See Fig. 9c). While one would not want to draw strong inferences from just these two example areas, it seems that the 99th percentile provides a stronger fit to the area burned data than the mean alone and both the FWI and the ISI were significantly and similarly (in terms of strength) correlated with area burned.

Development of correlations and good predictive models of area burned as a function of fire weather, fuel moisture and fire behaviour indices can be challenging however. Area burned of any individual fire is strongly dependant on fire weather conditions on the particular day it is spreading (the relationships in the FBP System show this). Many fires can be present on the landscape but if the weather is not conducive to fire spread (perhaps winds are low and humidities are high) then little area will be burned. Conversely however, if weather is conducive to rapid fire growth but there have been no ignitions on the landscape, then no area will be burned. Indeed many days of high fire growth potential occur each fire season without major area burned, simply because no fires were burning or ignited on those days. The fuel type in which ignition is spreading can also play a role in determining the extent of area burned (see for example the rates of spread for jack pine and aspen fuels in Fig. 7). Furthermore, area burned can be also dependant on the level of protection in an area (Ward et al. 2001). In areas with a very high level of protection some fires that ignite on days with high fire growth potential may be suppressed quickly at a small size thus eliminating a potentially large amount of area burned that would have occurred in the absence of suppression. There is, however, a limit to the number of new fires that can be effectively actioned by most fire management agencies; when fires occur at rates above this limit fires may escape and become large (see Martell 2001 for a more detailed description of the fire suppression process).

It is these relatively few escaped fires that become large and contribute considerably to total area burned during any year. Table 1 also shows the correlation between annual area burned (1976–2004) and an estimate of annual number of escaped fires, estimated from one common criteria used by fire management agencies which defines any fire that grows to more than 4 ha as escaped. These correlations are higher than those between area burned and total number of fires in the region however in general only a small number of fires that occur eventually escape, and these fires contribute almost exclusively to the total area burned in a region. The frequency distribution of fire size is extremely skewed. On average across the country in the managed forest the 97% of all area burned is caused by only about 3% of the forest fires (Stocks et al. 2002), these 3% of fires represent those that grow to greater than 200 ha. Modelling the probability of occurrence of these large escaped fires would useful element in improving the prediction of area burned.

5 Summary

Understanding and predicting forest fire activity is a very important part of natural resource management in Canada and many other countries around the world. With increases in fire activity expected to occur with greenhouse gas induced climate change and with the increased expansion of the wildland–urban interface, forest fire management will most likely increase in its importance to the public, both in terms of personal safety and protection of personal and natural resources. In fact, in Canada the provincial forest fire agencies and the federal government recently (in 2005) developed a new common vision for forest fire management (called the Canadian Wildland Fire Strategy). This initiative seeks to lay out a strategy to help fire agencies maintain and possibly improve their fire management capability under the environmental, economic and social pressures facing fire management today. This new vision for forest fire management includes an emphasis on science and innovation and therefore presents the prospect for increased research into forest fire activity and forest fire management and an opportunity for the application of modern statistical modelling techniques to expand our understanding of the relationship between fire and the environment and to develop models that can be used as decision aids for operational fire management.

In order to develop research products that will assist forest fire managers in making decisions, it is useful for researchers to understand the processes influencing forest fire activity at various scales across the landscape. It is also important to understand how fire managers use and synthesize their understanding of these processes to manage daily forest fire activity in their regions. This paper provides a review of the Canadian Forest Fire Danger Rating System, which fire managers throughout Canada use on a daily basis to synthesize information about the fire environment and help in the decision-making process. Through the use of the CFFDRS, fire managers can track moisture levels in forest fuels which are important in both flaming and smouldering combustion, and which also have a strong influence on probability of expected ignition of both human- and lightning-caused fires. The CFFDRS also helps managers to predict expected fire behaviour (fire spread rate, fuel consumption fire intensity) using either current or forecasted weather, and can be used to estimate individual fire growth and area burned by fire in a region.

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Author Biography

B. Mike Wotton works as Research Scientist with the Canadian Forest Service (Natural Resources Canada) and specializes in fuel moisture, fire occurrence and fire behaviour modelling. His PhD research in the Faculty of Forestry at the University of Toronto involved development of models of lightning and human-caused fire occurrence using generalized linear modelling techniques. He works frequently with forest fire management agencies in Canada to develop models for use as operational decision aids.