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Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System

B.M. Wotton, M.E. Alexander, S.W. Taylor

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Great Lakes Forestry Centre
Sault Ste. Marie, Ontario

Canada

UPDATES AND REVISIONS TO THE 1992 CANADIAN FOREST FIRE BEHAVIOR PREDICTION SYSTEM

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ABSTRACT

This report documents a number of changes to the 1992 release of the Canadian Forest Fire Behavior Prediction (FBP) System, and addresses several mathematical and physical inconsistencies in its underlying models that have been identified over the last 15 years of its operational use throughout Canada. Several additional equations are included to allow calculations of a few elements not included in the original release of the system. However, these updates and revisions do not represent significant changes to the structure of the FBP System, but are largely modifications and clarifications of some of the models within the system. The implementation of these mathematical changes to the FBP System into existing technology transfer products (e.g., field guides and aids, software products), should be virtually transparent to most users. Finally, 20 formal test cases are presented to allow the developers of applications based on the FBP System to test their products against known benchmarks. It is important to understand that this document does not represent a new version of the Canadian FBP System (described in ST-X-3 "The Development and Structure of the Canadian Forest Fire Behavior System"), but is rather a supplement to that publication. A correct and up-to-date implementation of the FBP System must rely on the information contained in both these reports.

Wotton, B.M.; Alexander, M.E.; Taylor, S.W. 2009. Mises à jour et révisions de la Méthode canadienne de prévision du comportement des incendies de forêt de 1992. Ressources naturelles Canada, Service canadien des forêts, Centre de foresterie des Grands Lacs, Sault Ste. Marie (Ontario), Canada. Information Report GLC-X-10, 45p.

RÉSUMÉ

Le présent rapport décrit un certain nombre de modifications apportées à la version de 1992 de la Méthode canadienne de prévision du comportement des incendies (PCI) de forêt et porte sur plusieurs anomalies mathématiques et physiques qui ont été décelées dans les modèles sous-jacents au fil des 15 dernières années d'utilisation opérationnelle de la méthode au Canada. Il présente également plusieurs équations additionnelles permettant de calculer quelques éléments qui ne faisaient pas partie de la version originale de la méthode. Ces mises à jours et révisions ne constituent toutefois pas des modifications importantes à la structure de la méthode PCI et viennent surtout rectifier et clarifier certains modèles de la méthode. La plupart des utilisateurs pourront sans difficulté appliquer ces modifications mathématiques de la méthode PCI aux produits de transfert de la technologie actuellement disponibles (p. ex., guides et outils de terrain, produits logiciels). Pour terminer, le rapport présente 20 jeux d'essai officiels grâce auxquels les développeurs d'applications basées sur la méthode PCI pourront vérifier leurs produits en regard de repères connus. Il est important de bien comprendre que le présent document ne constitue pas une nouvelle version de la Méthode canadienne de prévision du comportement des incendies de forêt (décrite dans le rapport d'information ST-X-3F intitulé Élaboration et structure de la Méthode canadienne de prévision du comportement des incendies de forêt), mais plutôt un supplément à cette publication. Pour que l'application de la méthode PCI soit adéquate et à jour, il faut s'appuyer sur l'information contenue dans ces deux rapports.

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1.0 INTRODUCTION

The Canadian Forest Fire Danger Rating System (CFFDRS), as developed by the Canadian Forest Service, consists of two major subsystems, the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System (Taylor and Alexander 2006). The FWI System outputs are six relative numerical ratings of fire potential in a single standard fuel type. The FBP System (Figure 1) is a complex set of empirical equations that integrate the major factors influencing wildland fire spread and intensity producing quantitative predictions of potential fire behavior in a number of major Canadian fuel types (Table 1). The fundamental principles on which the FBP System was developed date back to the conception of forest fire research in Canada in the mid 1920s (Van Wagner 1990). The bulk of the system's formal development took place in the 1970s and 1980s (Lawson et al. 1985; Van Wagner 1989). The details of this development and the mathematical structure of the FBP System were published formally in 1992 as Forestry Canada Information Report ST-X-3, entitled "The Development and Structure of the Canadian Forest Fire Behavior Prediction System"(Forestry Canada Fire Danger Group 1992)[1]. This report is referred to in this document simply as "ST-X-3". The FBP System is currently used operationally across Canada, in a number of U.S. states (e.g., Alaska, Minnesota) and in New Zealand (Seli 1999; Pearce and Anderson 2008).

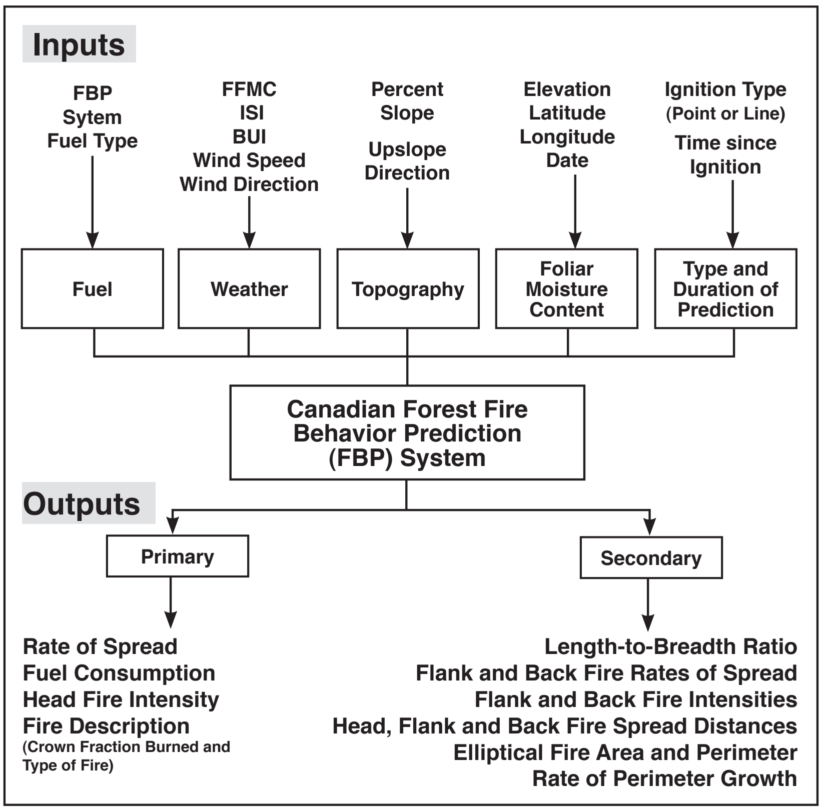

Figure 1. Structure of the Canadian Forest Fire Behavior Prediction (FBP) System.

CFFDRS technology and information transfer has, over the last several decades, used a number of media from field aids and guides to wall posters (Alexander and Stocks 1998), to, more recently, interactive media such as CD-ROM training courses and web pages[2](Taylor and Alexander 2006). These efforts continued with a focus on the FBP System following the publication of ST-X-3, including overview articles (e.g., Hirsch 1993; Alexander et al. 1996). Taylor et al. (1997) developed a field guide to the FBP System. This guide, commonly called the "Red Book" provides a simplified version of the FBP System, suitable for use in field applications of the system (e.g., near-real time prediction of wildfire behavior). System outputs are presented in a tabular, look-up format. It was prepared to assist staff in making first approximations of FBP System outputs when computer-based applications are not readily available. Hirsch (1996) developed a self-guided workbook that provides diagrams, examples and exercises that help explain the basis of the FBP System in a user-friendly manner. A CD-ROM-based interactive training and reference program developed by Hirsch (1998) uses multimedia (video, audio, text, graphics, photos, and animation) to teach users about the FBP System. A wall poster presenting color photographs of representative stands of each of the 16 FBP System fuel types has also been prepared

[1] As presented in ST-X-3, the FBP System was developed by the following members of the former federal forest service Fire Danger Group over approximately 10-years beginning in 1981: C.E. Van Wagner and R.S. McAlpine (Petawawa National Forestry Institute, Chalk River, ON), B.J. Stocks and T.J. Lynham (Great Lakes Forestry Centre, Sault Ste. Marie, ON), M.E. Alexander (Northern Forestry Centre, Edmonton, AB), and B.D. Lawson (Pacific Forestry Centre, Victoria, BC).

[2] http://www.nofc.forestry.ca/fire/research/environment/cffdrs/cffdrs_e.htm

Table 1. List of fuel types presently included in the Canadian Forest Fire Behavior Prediction (FBP) System

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[a]	Coniferous plantation
C-7	Ponderosa pine/Douglas-fir
Deciduous	
D-1	Leafless Aspen
Mixedwood	
M-1[b]	Boreal mixedwood-leafless
M-2[b]	Boreal mixedwood-green
M-3[c]	Dead balsam fir mixedwood-leafless
M-4[c]	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[d]	Matted grass
O-1b[d]	Standing grass

[a]Can vary crown base height.
[b]Must specify percent conifer composition.
[c]Must specify percent dead fir.
[d]Must specify degree of curing and can specify fuel load.

(de Groot 1993). Stocks and Hartley's (1995) poster highlights the range in fire intensity of some of the experimental fires that contributed to the development of the C-3 (mature jack or lodgepole pine), C-4 (immature jack or lodgepole pine) and S-1 (jack or lodgepole pine logging slash) FBP System fuel types, similar to Alexander and Lanoville's (1989) presentation for the spruce-lichen woodland (C-1) fuel type. Cole and Alexander's (1995) poster for the boreal spruce (C-2) fuel type presents a graph for determining one of six head fire intensity classes, type of fire[3](surface, intermittent crown or continuous crown), and crown fraction burned based on the Initial Spread Index and Buildup Index components of the FWI System. An accompanying table offers additional information on fire potential and management implications (Alexander and Cole 1995). Fogarty and Alexander (1999) constructed a "grassland fire behavior pocket card" based on

[3] These six fire intensity classes (i.e., < 10, 10-500, 500-2000, 2000-4000, 4000-10 000, and > 10 000 kW/m) have come to be regarded as a national standard.

the natural standing O-1b grass fuel type that provides a quick means of judging near-worst case fire behavior potential in grasslands (Alexander and Fogarty 2002). Models of probability of sustained flaming ignition have been developed for several FBP System fuel types (Lawson and Dalrymple 1996). Additional interpretive material on the FBP System is included in the revised edition of CFFDRS weather guide (Lawson and Armitage 2008).

The developers of the FBP System had the expectation that the individual fire management agencies would develop FBP System fuel type maps utilizing forest inventory and other information (e.g., remote sensing imagery). This has been the case with each of the Canadian fire management agencies developing FBP System fuel type maps for their fire management zones in varying levels of resolution (e.g., Tymstra and Ellehoj 1994; Wilson et al. 1994; Hawkes et al. 1995; Power 1996; Ember Research Services Ltd. 2000; Pelletier et al. 2002; Nadeau et al. 2005; Nadeau and Englefield 2006).

Fire management agencies in Canada and elsewhere have made extensive use of the FBP System (Beck 2005; Taylor and Alexander 2006), incorporating it into a wide variety of computerized decision-support systems for operational use. Some examples include: fire prevention measures (Ontario Ministry of Natural Resources 2008); presuppression preparedness system (Beck 2004); firefighter safety alerts (Beck et al. 2002); firebreak breaching (Alexander et al. 2004, 2006); fire growth projections (Tymstra 2002; Anderson et al. 2007a; Tymstra et al. 2009); and wildfire threat rating (Hawkes and Beck 1997). The FBP System has also been directly and indirectly used in a host of research and development studies. Examples of these include: fire danger classification schemes and guidelines (Pearce and Alexander 1994; de Groot et al. 2004; Alexander 1994, 2008); modelling of carbon emissions (Amiro et al. 2001; de Groot 2006; de Groot et al. 2007, Lavoué et al. 2007); climate change (Parisien et al. 2005a); fire regime analyses (Flannigan 1993; Flannigan and Wotton 1994); fire effects (de Groot et al. 2003); fire behavior potential assessments (Taylor et al. 1998; Anderson and Englefield 2001; Hely et al. 2001; Lavoie 2004); climatologies (Kafka et al. 2000; Amiro et al. 2004); fire and fuel management strategies (Sanchez-Guisandez et al. 2002, 2007; Hirsch et al. 2004; Parisien et al. 2003, 2005b, 2007; Beck and Simpson 2007); mathematical modelling of fire growth (Richards 1994, 1999; Anderson et al. 1998, 2007b; Anderson 2002); modelling of fire behavior in relation to firefighter safety (Baxter et al. 2004; Alexander et al. 2005); and fire management decision support systems (Trevis 2005).

The FBP System has been used essentially without modification since the publication of ST-X-3 in 1992. Some internal inconsistencies in the system gradually became apparent, particularly in recent years, as more computer applications of the system were developed. The purpose of this publication is two fold. First to document the problems that have arisen to date and to present solutions along with new or revised equations where necessary. The second goal of this document is to present an extensive test dataset that can be used by software developers as a preliminary check that their programming of the FBP System equations and structure is correct.

The revisions to the FBP System's models presented here do not represent significant changes to the structure of the FBP System, but are modifications and clarifications of some of the models within the system. The implementation of these mathematical changes into existing technology transfer products (e.g., revision of the Taylor et al. (1997) field guide) will be virtually transparent to the user. A good familiarity with the FBP System and ST-X-3 on the part of the reader is presumed.

2.0 ERRATA TO INFORMATION REPORT ST-X-3

Shortly after the publication of ST-X-3 a few typesetting errors were found and several textual clarifications were deemed necessary. These errors and clarifications were documented and put out in the form of an errata sheet distributed informally in April 1994. A formal documentation source for these errata has not existed until now. These errata were as follows:

- Page 19, Table 4: The No. of yrs. sampled by Springer and Van Wagner (1984) at Kapuskasing was 4.
- Page 22: The title for the Fuel Type C-3 & C-4 portion of Figure 3 should read "...Mature and Immature Jack or Lodgepole Pine."
- Pages 26 and 54: Equation 32 should have read:

$$a = 140 \times e^{\left(\frac{-33.5}{PDF}\right)} \qquad \textbf{(32)}$$

- Pages 31 and 55, Equation 42 should read:

$$ISF = \frac{\ln\left[1 - \left(\frac{100 \times RSF}{PC \times a}\right)^{\frac{1}{c}}\right]}{-b} \qquad \textbf{(42)}$$

- Page 39, left-hand column, first full paragraph: The crown fraction burned for continuous crown fire should read " $\geq$0.9".
- Page 40, right column, last paragraph: Line 8 should read "types (C-1, O-1, S-1, S-2, S-3, D-1)".
- Pages 43 and 58: Equation 77 should be replaced by the appropriate rate of spread equation for the fuel type in question. The rate of spread equation would simply have the ISI term replaced by the BISI term to derive the back fire spread rate.
- Page 44 (and the figure list on page 5): Figure 22 caption should read "Length-to-Breadth ratio of elliptically shaped fires as a function of wind speed for grass fuels (equations 80 and 81)".
- Pages 44 and 58: Equation 80 should read,

$$LB = 1.1 \times WSV^{0.464}, \; WSV \geq 1.0 \qquad \textbf{(80)}$$

- Pages 46, 59 and 61: The flank fire rate of spread should be designated as FROS rather than FRS.
- Page 53, (middle of the page), under the 'General Rate of Spread Equation' it should read: C-1 to C-5, C-7, D-1 and S-1 to S-3.
- Page 58: Under Length-to-Breadth ratio "Open fuel types (O-1)" should read "Grass fuel type (O-1)".

Please note that the errata associated with Equations 32, 42 and 80 given above are now being replaced by subsequent revisions as documented elsewhere in this report.

3.0 REVISIONS AND ENHANCEMENTS

Over time, a number of inconsistencies have been discovered in the system. Canadian Forest Service fire researchers have periodically prepared solutions to these problems as a result of interactions with fire managers, researchers and commercial FBP System software developers. These problems and their solutions are documented in this section. The numbers of new or replacement equations to ST-X-3 are denoted in bold. At the end of this section, a summary of all changes to ST-X-3 equations is presented. All symbols and abbreviations defined in the text are listed in Appendix 1 and a complete summary of the equations presented here can be found in Appendix 2.

Lawson et al. (1996) developed and updated an earlier model of diurnal variation in the Fine Fuel Moisture Code (FFMC) complete with equations and a new look-up table, which has been incorporated into the FBP System field guide (Taylor et al. 1997). The new diurnal FFMC model described by Lawson et al. (1996) incorporates the FF-scale linking the FFMC to fine fuel moisture content (Van Wagner 1987) and extends the prediction to around the clock and to the nearest minute, allowing, for example, the forecasting of diurnal variation in fire intensity (Beck et al. 2002).

3.1 Surface Fuel Consumption

3.1.1 Surface Fuel Consumption Model for Fuel Type C-1

Problem

The surface fuel consumption (SFC) model for the spruce-lichen woodland fuel type (C-1) in the FBP System (Equation 9 in ST-X-3) has a lower bound when the Fine Fuel Moisture Code (FFMC) equals 81 (Figure 2). However, the equivalent rate of spread equation for fuel type C-1 has no such bound and therefore the system can be used to estimate spread rates with no corresponding SFC for this fuel type, which clearly does not make physical sense.

Solution

The lower bound is simply an artefact of the form of the regression equation used in the original SFC model for fuel type C-1. To add a slower decrease in SFC with FFMC, a new equation, similar to Equation 9 in ST-X-3, was created. This equation still passes through the SFC data points available for this fuel type (Alexander et al. 1991). The new SFC model for FBP System fuel type C-1 consists of two equations:

$$SFC = 0.75 + 0.75 \times (1 - e^{-0.23 \times (FFMC - 84)})^{0.5} \qquad \text{if } FFMC > 84 \qquad \textbf{(9a)}$$

$$SFC = 0.75 - 0.75 \times (1 - e^{-0.23 \times (FFMC - 84)})^{0.5} \qquad \text{if } FFMC \le 84 \qquad \textbf{(9b)}$$

This new form of the SFC equation for the C-1 fuel type for can be seen, along with the original curve and data points, in Figure 2.

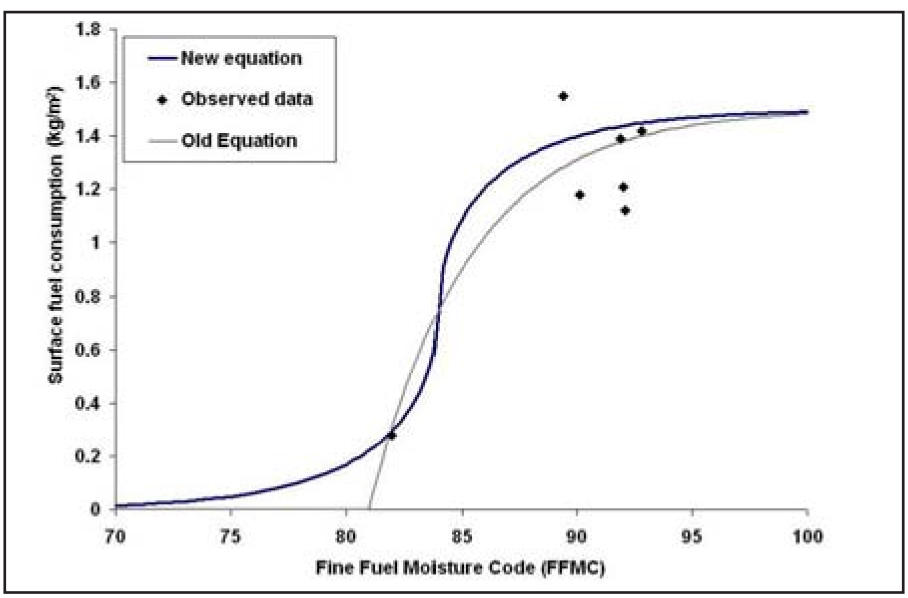

Figure 2. The new surface fuel consumption model for the spruce-lichen woodland FBP System fuel type (C-1) in relation to the original formulation and the existing empirical data.

3.1.2 Default Value for Grass Fuel Load

Problem

The grass fire rate of spread equations included in ST-X-3 were derived from data collected by Cheney et al. (1993) in the Northern Territory of Australia. For the 1984 interim edition of the FBP System, a nominal grass fuel load (GFL) of 3.0 t/ha (0.3 kg/m^2) was selected based on a review of the existing Canadian literature on the subject, although no expected natural range or variability were presented. However, in New Zealand, a nominal fuel load of 3.5 t/ha has been used in modelling grassland fire danger and fire behavior using the FBP System (Alexander 1994, 2008; Fogarty and Alexander 1999; Alexander and Fogarty 2002) on the grounds that this represented the average fuel load of the experimental fires carried out by Cheney et al. (1993). The mean (and range) in fuel load in the cut or grazed (n = 52) and natural undisturbed (n = 70) pastures were 3.55 (2.26-5.66) and 3.41 (1.17-5.85) t/ha, respectively. Baxter (2006) reported on grass fuel loads on linear disturbances (e.g., powerline right-of-ways, pipelines, seismic lines, railroads and roads) in north-central Alberta. He found that the mean fuel load in the spring (n = 64) was 3.47 t/ha and in the fall at the same location it was 5.42 t/ha.

Solution

The grass fuel load default value has been modified to match the observations upon which the FBP System grass fuel type rate of fire spread models are based. The GFL (and consequently SFC) for fuel types O-1a and O-1b should be set to 3.5 t/ha or 0.35 kg/m^2. However, it's worth stressing that users of the grass fire behavior models in the FBP System should use measured values of grass fuel load in place of this average value, if such observations exist.

3.2 Rate of Spread Calculations

3.2.1 Fire Behavior Models for Fuel Types M-3 and M-4

Problem

Experimental data describing fire behavior in mixedwood stands with a dead balsam fir component killed by spruce budworm is limited to a small set of fires carried out in northeastern Ontario (Stocks 1987). It thus became necessary to apply some "art" (Van Wagner 1985) to the process of formulating rate of spread relationships for this fuel complex. Figure 7 of ST-X-3 shows that as the Percent Dead Fir (PDF) decreases, the predicted rate of spread for FBP System fuel types M-3 and M-4 becomes very similar. The curves for 30% dead fir (PDF=30%) in the lower two graphs in Figure 7 of ST-X-3 show little difference in the predicted rate of spread between leafless (M-3) and green (M-4) variants of the dead balsam fir mixedwood fuel types: this is not physically correct. Furthermore, as PDF approaches zero, the rate of spread predicted by the model also diminishes to zero: this is also illogical.

Solution

As the PDF in M-3 and M-4 decreases, a mixedwood stand with dead balsam fir should come to resemble a pure deciduous or hardwood stand (e.g., FBP System fuel type D-1). The assumption in the M-3 and M-4 models is that all of the coniferous component of this fuel type was killed by insects. Thus, a new spread rate model was developed for FBP System fuel types M-3 and M-4 that was a blend of FBP System fuel type D-1 and the existing M-3 and M-4 model with 100% dead fir.

The following two sub-sections (3.2.1.1 and 3.2.1.2) document the new formulations of Equations 29 through 32 in ST-X-3 for calculating rate of spread in the M-3 and M-4 fuel types; Equations 33 and 34 in ST-X-3 are no longer used.

3.2.1.1 Fuel Type M-3: Dead Balsam Fir Mixedwood-Leafless

The rate of spread equation for this fuel type has been reformulated so that at 100% dead fir, the resulting curve matches the current FBP System fuel type M-3 equation and at 0% dead fir, the resultant rate of spread is equivalent to FBP System fuel type D-1. For values of PDF between 0% and 100%, rate of spread is determined by blending these equations in a manner similar to that used for the boreal mixedwood-leafless fuel type (M-1) as given by Equation 27 in ST-X-3. This new equation is:

$$RSI = \frac{PDF}{100} \times RSI_{M\text{-}3(100\%)} + \left(1 - \frac{PDF}{100}\right) \times RSI_{D\text{-}1} \qquad \textbf{(29)}$$

where RSI is the initial spread rate without the BUI (Buildup Index) effect and RSID-1 is the rate of spread calculated for leafless aspen fuel type (D-1). $RSI_{M\text{-}3(100\%)}$, which represents the rate of spread when PDF=100 is given by:

$$RSI_{M\text{-}3(100\%)} = 120 \times \left[1 - e^{(-0.0572 \times ISI)}\right]^{1.4} \qquad \textbf{(30)}$$

Equation 30 follows the form of the general rate of spread equation given by Equation 26 in ST-X-3. In this case, the *a*, *b* and *c* coefficients are explicitly included based on calculations using Equations 29, 30 and 31 in ST-X-3 with PDF = 100%. The new model for the dead balsam fir mixedwood-leafless fuel type (M-3) is shown in Figure 3 for a range of PDF values.

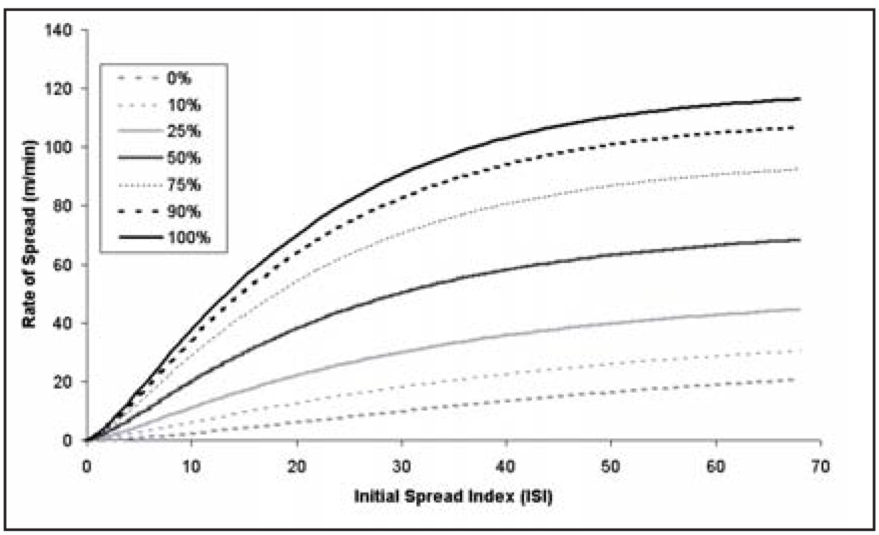

Figure 3. Rate of spread curves for the new dead balsam fir mixedwood-leafless FBP System fuel type (M-3) for a range of percent dead fir (PDF) values.

3.2.1.2 Fuel Type M-4: Dead Balsam Fir Mixedwood-Green

The rate of spread equation for this fuel type has been reformulated so that at 100% dead fir the resulting curve matches the current FBP System M-4 fuel type equation and at 0% dead fir the resultant rate of spread is equivalent to one fifth of the rate of spread for the leafless aspen fuel type (D-1). For values of PDF between 0% and 100%, rate of spread is determined by blending the calculations in a manner similar to that used in the boreal mixedwood-green fuel type (M-2) given by Equation 28 in ST-X-3. This new equation is:

$$RSI = \frac{PDF}{100} \times RSI_{M\text{-}4(100\%)} + 0.2 \times \left(1 - \frac{PDF}{100}\right) \times RSI_{D\text{-}1} \quad \textbf{(31)}$$

where, RSI is the initial spread rate without the BUI effect and $RSI_{D\text{-}1}$ is the rate of spread calculated for the leafless aspen fuel type (D-1). $RSI_{M\text{-}4(100\%)}$, which represents the rate of spread when PDF=100, is given by:

$$RSI_{M\text{-}4(100\%)} = 100 \times \left[1 - e^{(-0.0404 \times ISI)}\right]^{1.48} \quad \textbf{(32)}$$

Equation 32 follows the form of the general rate of spread equation given by Equation 26 in ST-X-3. In this case, the *a*, *b* and *c* coefficients are explicitly included based on calculations using Equations 32, 33 and 34 in ST-X-3 with PDF=100. The new model for the boreal mixedwood-green fuel type (M-4) is shown in Figure 4 for a range of PDF values.

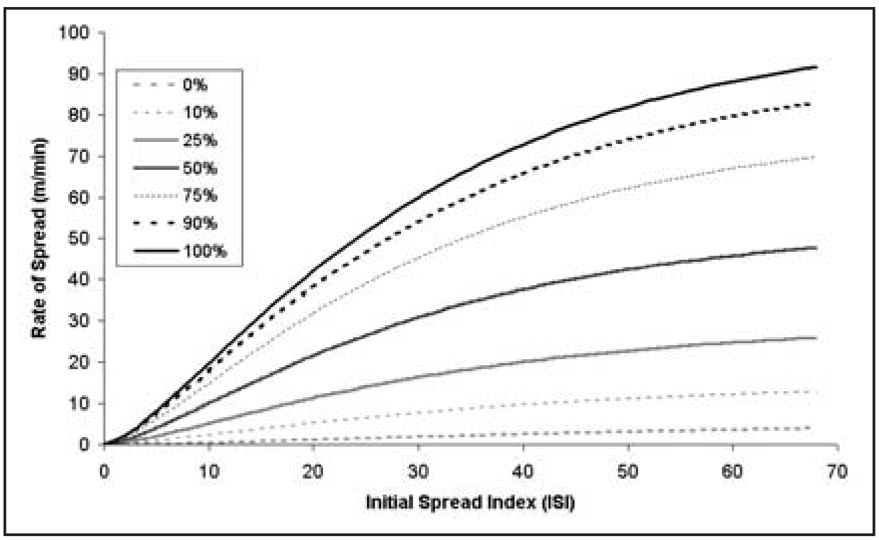

Figure 4. Rate of spread curves for the new dead balsam fir mixedwood-green FBP System fuel type (M-4) for a range of percent dead fir (PDF) values.

3.2.2 Degree of Curing Effect on Rate of Spread in the Grass Fuel Types O-1a and O-1b

Problem

The degree of grass curing, expressed as a percentage of dead material versus the total standing crop, has a major effect on fire spread in grasslands. As a general rule of thumb, it is widely believed that fires will not spread in grasslands when the degree of curing is less than about 50% (Cheney et al. 1993, 1998; Cheney and Sullivan 1997). However, observations of outdoor experimental fires have indicated that fire spread is indeed possible at and below this level (Parrott and Donald 1970; Sneeuwjagt and Frandsen 1977; Clark 1983; Marsden-Smedley and Catchpole 1995).

At the time that ST-X-3 was being finalized for publication, no accepted relationship for grassland degree of curing and relative fire spread existed. In the absence of any definitive research on the subject, a conservative approach was adopted: fire spread in grass was assumed to be negligible when the degree of curing was less than 50% and to increase linearly as degree of curing increased above 50%. Since the publication of ST-X-3, Australian fire researchers have published a sigmoid function (Cheney and Sullivan 1997) relating degree of grass curing to relative fire spread for degree of curing between 50 and 100% (Figure 5) as follows (after Cheney et al. 1998):

$$\mathrm{CF} = 1.120/(1 + 59.2 \times e^{(-0.124\times(C\ -\ 50))}) \qquad C \geq 50$$

where CF is the curing factor and C is the degree of curing (%). This relationship is based on the authors' field experience and is not based on formal experimentation or data analysis relating degree of curing to relative rate of fire spread.

Solution

A new CF relationship has been developed that limits rate of spread at 50% degree of curing to 10% of the maximum value attained when fuels are 100% cured. Below 50% degree of curing, the new CF relationship simply drops off exponentially toward a value of zero. The new function is composed of two separate equations that join at a degree of curing value of 58.8% as follows:

$$\mathrm{CF} = 0.005 \times (\mathrm{e}^{0.061 \times C} - 1) \qquad \text{if } C < 58.8 \qquad \textbf{(35a)}$$

$$\mathrm{CF} = 0.176 + 0.02 \times (C - 58.8) \qquad \text{if } C \geq 58.8 \qquad \textbf{(35b)}$$

This new function, as shown in Figure 5, retains the original linear relationship above a degree of curing of about 60% but now allows for the possibility of limited fire spread below a degree of curing of 50%.

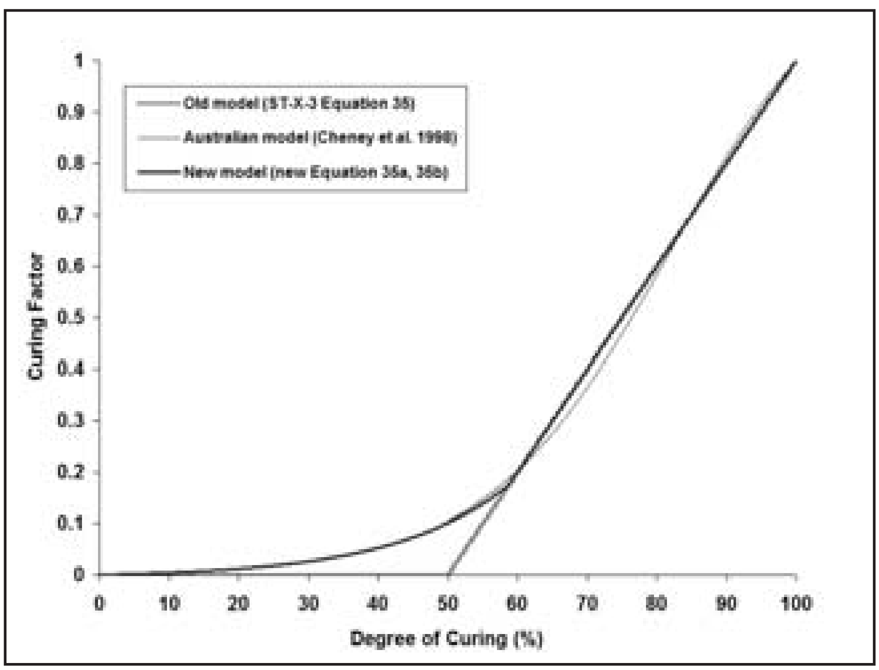

Figure 5. The new grassland degree of curing-relative rate of fire spread function ("new model") compared with the original formulation in ST-X-3 ("old model") along with the relationship presently used in grassland fire danger rating in Australia.

3.2.3 Slope Effect on Rate of Spread

3.2.3.1 Maximum for Ground Slope

Clarification

There has been some confusion regarding the implementation of the spread factor model in the calculation of the slope effect on fire spread. Equation 39 in ST-X-3 is not recommended for a ground slope (GS) in excess of 70% (Van Wagner 1977a). Van Wagner (1977a) observed that, "Above this limit flames would tend to bathe the slope directly, and fire behaviour would become very intense and unstable". In addition, Cheney (1981) suggested that it was questionable to extend such models to very steep conditions "as fuel discontinuities usually occur on steep slopes".

For slopes greater than 70%, the SF value equivalent to a ground slope of 70% (i.e., 10.0) should be used. To clarify its implementation, Equation 39 in ST-X-3 is now written as:

$$SF = e^{3.533\times\left(\frac{GS}{100}\right)^{1.2}} \qquad \text{if } GS < 70\% \qquad \textbf{(39a)}$$

$$SF = 10.0 \qquad \text{if } GS \geq 70\% \qquad \textbf{(39b)}$$

3.2.3.2 Slope Equivalent Initial Spread Index Calculation for All Fuel Types Except Mixedwood (M-1/2 and M-3/4)

Problem

Extreme wind and slope conditions can lead to a negative value within the logarithm in the slope equivalent Initial Spread Index (ISF) calculation, (Equations 41, 42 or 43 in ST-X-3). This problem can arise in all FBP System slope effect calculations when conditions are extreme. The problem is due to the application of the slope factor (SF) to the zero wind rate of spread (RSZ) in the calculation of slope adjusted zero wind rate of spread (RSF) represented by Equation 40 in ST-X-3. When using the FBP System equations for situations with extreme slopes during periods with extremely high FFMC values, it is possible for RSZ×SF to exceed the maximum rate of spread value for a fuel type as defined by the a parameter in Table 6 of ST-X-3. In these cases a value of RSF/a > 1 results, causing the argument to the natural logarithm to become negative, and hence undefined.

Solution

The problem can be solved by placing a limit on the argument inside the logarithm in Equations 41 and 43 of ST-X-3. In the Canadian Forest Service C language computer source code for the FBP System, the value inside the logarithm is limited to a value of 0.01. Thus, the equation for the conifer (C-1 to C-7), deciduous (D-1), and slash (S-1 to S-3) FBP System fuel types should change to the following :

$$ISF = \frac{\ln\left[1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right]}{-b} \qquad \text{if } 1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}} \geq 0.01 \qquad \textbf{(41a)}$$

$$ISF = \frac{\ln(0.01)}{-b} \qquad \text{if } 1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}} < 0.01 \qquad \textbf{(41b)}$$

For the grass FBP System fuel types (O-1a and O-1b), the following equations should now be used:

$$ISF = \frac{\ln\left[1-\left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}}\right]}{-b} \qquad \text{if } 1-\left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}} \geq 0.01 \qquad \textbf{(43a)}$$

$$ISF = \frac{\ln(0.01)}{-b} \qquad \text{if } 1-\left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}} < 0.01 \qquad \textbf{(43b)}$$

where, CF is the curing factor defining the relative rate of spread in grasslands as estimated from the degree of curing (*C*) based on Equations 35a and 35b.

Approximate maximum values of the ISF, limited by the introduction of Equations 41b and 43b, are given for each FBP System fuel type in Table 2 below. All values are well beyond the maximum ISI value within the original datasets on which the equations are based.

Table 2. Approximate maximum slope equivalent Initial Spread Index (ISF) values for all the FBP System fuel types, excluding the four mixedwood fuel types (M-1, M-2, M-3 and M-4)

Fuel type	C-1	C-2	C-3	C-4	C-5	C-6	C-7	D-1	O-1a	O-1b	S-1	S-2	S-3
Maximum ISF	71	163	103	157	66	58	151	198	148	132	155	105	56

3.2.3.3 Slope Equivalent Initial Spread Index Calculation for Fuel Types M-1 and M-2

Problem

Fire behavior characteristics in the boreal mixedwood FBP System fuel types (M-1 and M-2) are calculated by blending predictions from the boreal spruce (C-2) and the leafless aspen (D-1) fuel types. This approach appears reasonable for rate of spread based on a small number of well-documented fires (Stocks 1988; Hely et al. 2001); however a thorough validation of this model has not yet been carried out.

In the slope calculations for FBP System fuel types M-1 and M-2, the form of Equation 42 in ST-X-3 causes the ISF to increase as the percent conifer (PC) decreases. Final ISF values for fuel types M-1 or M-2 can therefore be greater than either the ISF for fuel types C-2 or D-1 under similar conditions; this is not a logical result given the FBP System's current boreal mixedwood fuel type rate of spread formulations.

The problem exists because Equation 42 in ST-X-3 scales the slope equivalent rate of spread (RSF) value by dividing it by PC, which eliminates the contribution of the D-1 fuel type to the RSF value. This is a problem because the zero wind rate of spread (RSZ) component of the RSF has been calculated as a weighted average of the non-slope influenced rates of fire spread for FBP System fuel types C-2 and D-1 in Equations 27 and 28 of ST-X-3.

Solution

The new approach is to apply the weighted average to the ISF calculation. Hence, Equation 42 in ST-X-3 now becomes:

$$ISF = \frac{PC}{100} \times ISF_{C\text{-}2} + \left(1 - \frac{PC}{100}\right) \times ISF_{D\text{-}1} \qquad \textbf{(42a)}$$

where, $ISF_{C\text{-}2}$ and $ISF_{D\text{-}1}$ are ISF values calculated via Equation 41 for FBP System fuel types C-2 and D-1, respectively. This value of ISF should then be used to calculate the WSE using Equation 44 in ST-X-3.

3.2.3.4 Slope Equivalent Initial Spread Index Calculations for Fuel Types M-3 and M-4

As with the boreal mixedwood fuel types M-1 and M-2, the slope equivalent wind speed (WSE) for the dead balsam fir mixedwood fuel types M-3 and M-4 should be calculated by blending the slope equivalent Initial Spread Index (ISF) calculated for the leafless aspen fuel type (D-1) and 100% PDF in a similar manner to the new Equation 42a as follows:

$$ISF = \frac{PDF}{100} \times ISF_{M\text{-}3(100\%)} + \left(1 - \frac{PDF}{100}\right) \times ISF_{D\text{-}1} \qquad \textbf{(42b)}$$

$$ISF = \frac{PDF}{100} \times ISF_{M\text{-}4(100\%)} + \left(1 - \frac{PDF}{100}\right) \times ISF_{D\text{-}1} \qquad \textbf{(42c)}$$

This value of ISF should then be used to calculate the WSE using Equation 44 in ST-X-3.

3.2.3.5 Calculation of Wind Speed Equivalent Under Extreme Conditions

Problem

In the FBP System a wind speed function (Equation 53a in ST-X-3) that differs from the standard wind speed function defined in the FWI System (Van Wagner 1987) is used to calculate ISI when wind speeds exceed 40 km/h. This calculation is needed to restrict the ISI from becoming too large at high wind speeds. The equation is described in footnote 2 on page 32 of ST-X-3.

In the calculation of the slope equivalent wind speed (WSE) by Equation 44 in ST-X-3, high slope equivalent ISI (ISF) values (due to steep slopes and dry fine fuel conditions) can result in WSE values that will exceed 40 km/h. Thus, this limiting function applied in the calculation of the ISI should also be used in back-calculating the WSE value as it will be subject to the same conditions (i.e., the final ISI will be calculated using either Equation 53 or Equation 53a in ST-X-3); there is however no description of how this calculation should be carried out in ST-X-3.

Solution

To solve this problem, Equation 44 of ST-X-3 was renumbered Equation 44a and Equation 44b was introduced. Equation 44b is the solution of Equation 53a for wind speed. The form of Equations 52 and 53a in ST-X-3 lead to a maximum possible ISI value for each particular value of FFMC. This maximum ISI value is equivalent to 2.496 × f(F), where f(F) is the fine fuel moisture function in the ISI (Van Wagner 1987). To avoid the situation where the term inside the logarithm in Equation 44b goes to zero or becomes negative, a limit was introduced such that when ISF > 0.999 × ISI_{MAX} then ISF = 0.999 × ISI_{MAX}. This leads to a maximum WSE of 112.45 in all cases. Thus, we have the following equations:

$$WSE' = \frac{1}{0.05039}\ln\left(\frac{ISF}{0.208 \times f(F)}\right) \quad \textbf{(44a)}$$

$$WSE'' = 28 - \frac{1}{0.0818}\ln\left(1 - \frac{ISF}{2.496 \times f(F)}\right) \quad \text{if ISF} < 0.999 \times 2.496 \times f(F) \quad \textbf{(44b)}$$

$$WSE'' = 112.45 \quad \text{if ISF} \geq 0.999 \times 2.496 \times f(F) \quad \textbf{(44c)}$$

where f(F) is calculated as per Equation 45 in ST-X-3.

The final calculation methodology for WSE is now as follows:

$$WSE = WSE' \quad \text{if } WSE' \leq 40 \quad \textbf{(44d)}$$

$$WSE = WSE'' \quad \text{if } WSE' > 40 \quad \textbf{(44e)}$$

3.2.4 Estimating Crown Base Height in Fuel Type C-6

Each of the FBP System fuel types susceptible to crowning incorporate a unique characterization of the height to live crown base associated with that fuel type, with the exception of the conifer plantation FBP System fuel type (C-6). This is due to the relatively homogenous stand structure in conifer plantations (Van Wagner 1986) and flexibility of the dual-equation rate of spread model. In this model, the user may input a specific height to live crown base of the stand, if one is known. Since publication of ST-X-3, McAlpine and Hobbs (1994) have developed equations for predicting height to live crown base from stand height and stand density for plantations of four commonly planted boreal tree species (red pine, jack pine, black spruce and white spruce). McAlpine and Hobbs (1994) found that the height to live crown base in red pine plantations could be predicted from the following equation:

$$CBH = -11.2 + 1.06 \times SH + 0.00170 \times SD \quad \textbf{(91)}$$

where, CBH = height to live crown base (m), SH = stand height (m) and SD = stand density (stems/ha).

3.2.5 Dual-equation Rate of Spread Model for Fuel Type C-6

Clarification

Two minor points of clarification regarding the documentation of the conifer plantation FBP System fuel type (C-6) as described in ST-X-3 are necessary:

- Page 35, Figure 15 and page 36, Equation 58: In the case of FBP System fuel type C-6, the final or equilibrium head fire rate of spread (ROS) is replaced by the surface fire rate of spread for the C-6 fuel type (RSS). This point of clarification was originally included in the 1994 Errata to ST-X-3 (see Section 2.0).
- Page 36, Equation 58: In using Equation 58, if RSO > RSS then CFB = 0.

The dual equilibrium method of modeling fire spread from surface through to active crowning (Van Wagner 1989) is applied to one fuel type in the FBP System, namely conifer plantation (C-6). The equations presented by Van Wagner (1993), illustrating the application of the two-equation method in immature and mature jack pine stands, are not currently part of the FBP System.

3.3 Crown Fuel Consumption

Clarification

In terms of the crown or canopy fuels in a forest stand, it is assumed in the FBP System, that if intermittent or continuous crowning is predicted to occur, only the consumption of coniferous fuels contribute to frontal fire intensity. For the conifer FBP System, fuel types crown fuel consumption is calculated by Equation 66 in ST-X-3 as follows:

$$CFC_{\text{C-1 to C-7}} = CFL \times CFB \quad \textbf{(66a)}$$

where, CFC is the crown fuel consumption, CFL is the crown fuel load and CFB is the crown fraction burned. As described in Section 7.3 of ST-X-3, for the boreal mixedwood fuel types M-1 and M-2, the CFC is multiplied by a factor (PC/100, where PC is the percent conifer) to scale it the amount of coniferous composition in the stand as follows:

$$CFC_{\text{M-1/M-2}} = CFL \times CFB \times PC/100 \quad \textbf{(66b)}$$

Similarly, the dead balsam fir fuel types M-3 and M-4 fuel types must be scaled in the same manner based on the percent dead fir (PDF):

$$CFC_{\text{M-3/M-4}} = CFL \times CFB \times PDF/100 \quad \textbf{(66c)}$$

3.4 Diurnal Variation in Fire Behavior Potential

Problem

Fire behavior potential varies substantially throughout the day. This variation has important implications for fire suppression tactics and firefighter safety (Beck et al. 2002) and for fire growth simulation modeling (Tymstra et al. 2008). In this regard, a user may wish to forecast the time of day that a significant fire behavior threshold would be reached such as the critical surface fire intensity for crowning or certain fire intensity class.

To compute the time of day for any particular value, the FBP System must be applied "in reverse". The procedure is generally as follows. Because surface fuel consumption and the Buildup Index (BUI) effect on spread rate (BE) are assumed to have a constant value throughout the day (assuming no precipitation occurs) for all fuel types except C-1, one can use Equation 57 or 69 in ST-X-3 to obtain the spread rate for a particular fire intensity and fuel type. The critical ISI can then be determined by reversing the appropriate spread rate equation. Then, for a given forecasted wind speed, the f(W) parameter is obtained algebraically from Equation 53 in ST-X-3 and in turn the f(F) parameter from Equation 52. The problem is that there is no exact algebraic solution for m component of Equation 45 in ST-X-3.

Solution

A numerical approximation of the FFMC for a particular f(F) value was developed to enable estimation of FFMC without having to rely on Equations 45 and 46 (Figure 6):

$$\text{FFMC} = 71.7069 + 6.375 \times \ln(f(F) - 2.0737) \quad \textbf{(93)}$$

When an FFMC value is obtained from Equation 93, the time of day that a certain predicted or forecasted fire behavior value will be reached for a given wind speed in a particular fuel type can then be estimated from the diurnal (Lawson et al. 1996) or hourly FFMC (Van Wagner 1977b).

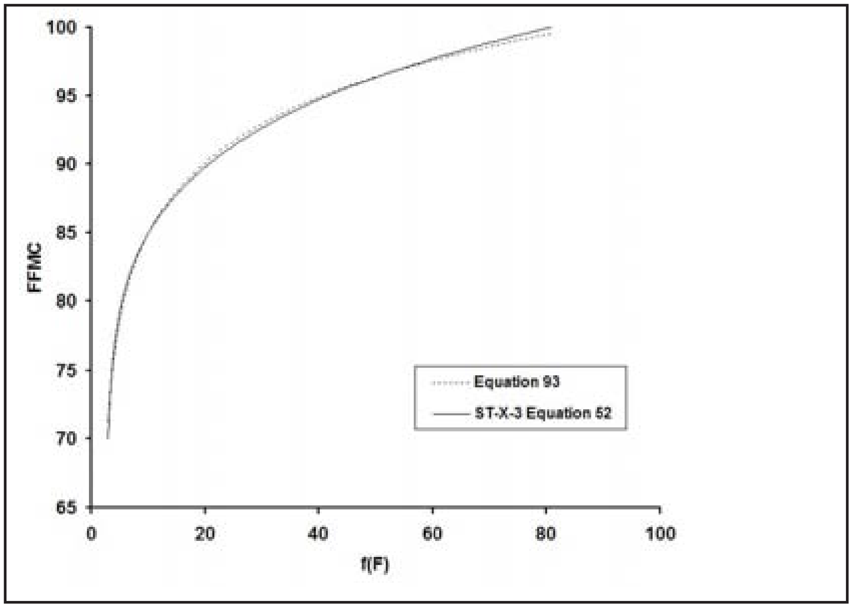

Figure 6: The relationship between the fuel moisture parameter f(F) used to compute the FFMC as defined in the FWI System as represented by Equation 52 versus that estimated by Equation 93.

3.5 Acceleration of a Point Source Fire in Closed Canopy Fuel Types

Problem

Because it is mathematically possible to calculate separate values of crown fraction burned (CFB) for the head as well as the flanks and back of a fire (and indeed for any point along the perimeter of a fire), it is also possible to calculate a separate acceleration parameter at each of these points because acceleration depends on the CFB as defined in Equation 72 of ST-X-3. However, the functional form of Equation 72 leads to the possibility of varying acceleration rates for different parts of the fire, which can in turn lead to computational irregularities. For example, if the head fire CFB is approximately 0.3 it is quite possible that both the flank fire crown fraction burned (FCFB) and the back (or rear) fire crown fraction burned (BCFB) will be equal to zero. This situation will lead to a head fire that accelerates more slowly toward equilibrium than either the flank or back fire. Under low wind conditions this can lead to flank ($FROS_t$) and back ($BROS_t$) fire spread rates that are greater than the head fire rate of spread at elapsed time t (ROS_t) during the acceleration phase of a fire's development from a point source ignition.

Solution

For a particular fire, one value for the acceleration parameter (α) should be calculated using the CFB obtained from the equilibrium head fire rate of spread (ROS). This α value should then be applied to the acceleration of both the back and flank fire rates of spread. The equation to calculate α from CFB for closed canopy fuel FBP System types[4] remains the same as in ST-X-3:

$$\alpha = 0.115 - 18.8 \times CFB^{2.5} \times e^{(-8 \times CFB)}$$

where, CFB is calculated from Equation 58 in ST-X-3 using the equilibrium head fire rate of spread.

3.6 Elliptical Fire Growth

3.6.1 Length-to-Breadth Ratio for the Acceleration Phase of Point Source Fire Growth

Problem

Currently within the FBP System, the length-to-breadth ratio (LB) estimated for a point source fire (Alexander 1985) does not change during its acceleration towards equilibrium spread following ignition, rather the fire assumes a final LB immediately upon ignition. Field and laboratory experimentation (Peet 1967; McAlpine 1989; Bilgili and Methven 1990; Alexander et al. 1991; Cheney and Gould 1995; McRae 1999) suggest that a point source fire's LB should increase as it accelerates to its final, equilibrium state (McAlpine and Wakimoto 1991). The constant LB problem was briefly discussed in Section 8.4.2 of ST-X-3.

Solution

The form of the fire spread acceleration function in the FBP System, represented by Equation 70 in ST-X-3, is applied to LB causing it to vary from a value of 1.0 at time zero, to a final equilibrium value defined by Equation 79 (for standing timber and slash fuel types) or Equation 80 (for grass fuel types). During the acceleration phase of point source fire growth, LB should be calculated by the following equation:

$$LB_t = (LB - 1) \times (1 - e^{-\alpha \cdot t}) + 1 \qquad \textbf{(81)}$$

where, t is the elapsed time since ignition, LB is the equilibrium LB as calculated by Equation 79 or 80, LB_t represents the LB after elapsed time t since ignition, and α is the acceleration parameter from Equation 72 in ST-X-3.

Implications

The introduction of this new equation into the FBP System has a number of consequences that should be noted.

a) Fire Shape

For all fuel types except O-1a and O-1b, LB should be calculated using Equation 79 in ST-X-3. For the FBP System grass fuel types, LB is calculated using the following equations (formerly Equations 80 and 81 in ST-X-3):

$$LB = 1.1 \times WSV^{0.464} \qquad \text{if } WSV \geq 1.0 \qquad \textbf{(80a)}$$

$$LB = 1.0 \qquad \text{if } WSV < 1.0 \qquad \textbf{(80b)}$$

[4] This includes all the conifer fuel types except C-1, all of the mixedwood fuel types (M-1 to M-4), and the leafless aspen (D-1) fuel type.

b) Perimeter Computations

The model for calculating the perimeter growth rate (PGR) of a point source fire, as represented by Equation 88 in ST-X-3, is found by calculating the instantaneous rate of change of the total elliptical fire perimeter; that is, by taking the derivative with respect to time of the estimate of perimeter length obtained from Equation 87 in ST-X-3. When LB varies with time during the acceleration phase of point source fire growth, the derivative of Equation 87 leads to a very complex final form. However, this increase in complexity does not lead to large differences from the result using Equation 88 to calculate PGR with LB_t instead of LB. Thus, during the acceleration phase of point source fire growth, the PGR value should be calculated using Equation 88 with LB_t in place of LB. The result, however, should be viewed only as an approximation.

Equation 87 in ST-X-3 is given as a method for estimating the perimeter of an elliptically shaped fire. This formulation relies on the value of LB and the total distance spread along the major axis of the ellipse (DT). It should be noted that under acceleration these terms should be LB_t and DT_t, respectively

c) Flank Fire Rate of Spread and Spread Distance

On page 46 of ST-X-3, the authors suggest that Equation 70 (the ROS acceleration function) be used to calculate the flank fire rate of spread after time t ($FROS_t$)[5] . This is not correct. Equation 89 in ST-X-3 should be used to calculate the $FROS_t$ and LB_t should be used instead of LB. The flank fire spread distance after elapsed time t since ignition (DF_t) should be calculated using the new Equation 92 as follows:

$$DF_t = \frac{DH_t + DB_t}{LB_t \times 2} \quad \textbf{(92)}$$

where, DH_t and DB_t are the head and back fire spread distances after elapsed time t since ignition, respectively.

3.6.2 Point Source Fire Acceleration and the Dual-equation Rate of Spread Model for Fuel Type C-6

Problem

The sequence of steps involved in the application of the acceleration function in the calculation of rate of spread, particularly the flank fire surface spread rate (FRSS), within the dual-equation rate of spread model for the C-6 (conifer plantation) FBP System fuel type is not clearly detailed in ST-X-3, which has caused some confusion.

Solution

In the following discussion all rate of spread terms and the elliptical shape parameter LB are defined and used with the subscript t, to denote the elapsed time since ignition, explicitly included. In calculating these values for the equilibrium state, equilibrium terms should be used in the place of time-dependent terms (e.g., RSS_t replaced with RSS, LB_t replaced with LB)

a) Surface Head and Back Fire Rates of Spread

During the acceleration phase of point source fire growth, the head and back fire rates of spread at time t are calculated using Equation 70 as described in ST-X-3 using the appropriate equilibrium rate of spread. Note that for back fire surface

[5]Note that in ST-X-3, the final flank fire rate of spread was defined as FRS, however to be consistent with the labelling convention we use here (e.g., BRSS, BROS) we refer to it as FROS.

rate of spread, the ISI associated with back fire spread (BISI) is used in Equation 62 in place of the ISI. Calculation of the BISI is done using Equations 75 and 76, as described in Section 8.3 of ST-X-3.

b) Surface Flank Fire Rate of Spread

The flank fire rate of spread should always be calculated on the basis of the head and back fire rates of spread and LB using Equation 89 in ST-X-3. To make this explicitly clear for the surface fire case involving FBP System fuel type C-6, a new equation (similar to Equation 89) is presented here:

$$\mathrm{FRSS}_t = \frac{\mathrm{RSS}_t + \mathrm{BRSS}_t}{2 \times \mathrm{LB}_t} \qquad \textbf{(90)}$$

where, RSS_t, FRSS_t and BRSS_t are the surface fire rate of spread after elapsed time *t* at the head, flanks and back of a point source fire, respectively, and LB_t is the LB of an elliptical shaped fire at elapsed time *t* as defined in Section 3.5.1.

c) Final Head Fire Rate of Spread

For fuel type C-6, the final head fire rate of spread is calculated using Equation 65 in ST-X-3, which blends the RSS_t and a crown fire rate of spread (RSC), the latter value being calculated from Equation 64 in ST-X-3. Note that the RSC is not influenced by the acceleration function.

d) Final Back Fire Rate of Spread

The final back fire rate of spread is also calculated using the same blending technique as described above for the final head fire rate of spread (i.e., the use of Equations 62 through 65 in ST-X-3). ST-X-3 does not explicitly describe the use of the BISI in this calculation, and for clarity we will describe this here.

As was stated above for the BRSS_t, the BISI is used in place of the ISI in Equation 62. The BISI should also be used in place of the ISI in Equation 64 to calculate a backing crown fire rate of spread (BRSC). The BRSC should then be used in Equation 65 along with values for BRSSt and crown fraction burned by the back fire after elapsed time *t* (BCFB_t: calculated using Equation 58 in ST-X-3) to calculate a final back fire rate of spread (BROS_t).

e) Final Flank Fire Rate of Spread

As with the FRSS_t, FROS_t should always be calculated using the final head and back fire rates of spread (ROS_t and BROS_t, respectively) and the LB_t. FROS_t should be calculated using Equation 89 in ST-X-3. For clarity we present this explicitly using the elapsed time *t* subscript in the following equation:

$$\mathrm{FROS}_t = \frac{\mathrm{ROS}_t + \mathrm{BROS}_t}{2 \times \mathrm{LB}_t} \qquad \textbf{(89)}$$

3.6.3 Calculation of Rate of Spread Around an Elliptically Shaped Fire Perimeter

Problem

Methods to calculate the rate of spread (ROS) at any point around the perimeter of an elliptically shaped fire are not presented in ST-X-3. Calculation of rate of spread, and other fire behavior characteristics such as fire intensity, at any point on the perimeter of a fire is necessary however, for proper application of the FBP System to fire growth modelling. Some published methods for calculating ROS at any point on the perimeter of an elliptically shaped fire use one of the ellipse's foci as the fire's point of origin to simplify the geometry. This assumption is used, for example, in the U.S. BehavePlus fire behavior prediction system (Andrews et al. 2008) and other applications (e.g., Scott 2007); however, the fire origin location does not necessarily correspond to one of the foci of the ellipse (Catchpole et al. 1982). In the final 1992 version of the FBP System an explicit back fire rate of spread (BROS) relationship was developed that eliminated the need for 'foci as the origin' as assumption; this was discussed in Section 8.3 of ST-X-3. An estimate of the BROS, together with the prediction of the head fire rate of spread, defines the location of the point of origin of the fire on the semi-major axis of the ellipse (Figure 7). Catchpole et al. (1982) provide a method for calculating rate of spread at any point P around an ellipse; however this functional form gives rate of spread in the direction perpendicular to the tangent to the ellipse at that point. We, however, define rate of spread at point P on the perimeter of an ellipse as the rate of spread in the direction defined by a line between the origin of the fire and point P (Figure 7). Thus a modified formulation was considered necessary.

Solution

A method for calculating rate of spread at any point along the perimeter of an elliptically shaped fire using the FBP System's head, flank and back fire spread rates of spread as outputs is presented below as Equation 94. The idealized elliptically shaped fire and pertinent properties are shown in Figure 7.

It should be noted from Figure 7 that the flank fire rate of spread (FROS) is defined within the FBP System as the lateral rate of spread of the fire or the spread rate in the direction perpendicular to the spread direction of the head fire. The direction of spread at point P as shown Figure 7 in follows the line that joins the ignition point or origin of the fire to point P on the ellipse. The rate of fire spread at point P on the ellipse at an angle θ off of the head fire spread direction is given by the following equation:

$$\mathrm{ROS}(\theta) = \frac{\mathrm{ROS} - \mathrm{BROS}}{2 \times \cos\theta} + \frac{\mathrm{ROS} + \mathrm{BROS}}{2 \times \cos\theta} \times \left(\frac{\mathrm{FROS} \times \cos\theta \times \left[\mathrm{FROS}^2 \times \cos^2\theta + (\mathrm{ROS} \times \mathrm{BROS}) \times \sin^2\theta\right]^{\frac{1}{2}} - \dfrac{\left(\mathrm{ROS}^2 - \mathrm{BROS}^2\right)}{4} \times \sin^2\theta}{\mathrm{FROS}^2 \times \cos^2\theta + \left(\dfrac{\mathrm{ROS} + \mathrm{BROS}}{2}\right)^2 \times \sin^2\theta} \right) \tag{94}$$

From this value of ROS(θ), it then follows that the value of any related fire behavior descriptor or characteristic, such as fire intensity, can be calculated at any point on the ellipse using the relations found in ST-X-3. A sample calculation from Equation 94 is given in Table 3. One important special condition to make note of is the situation when θ= 90°. In this case Equation 94 reduces to an undefined value (i.e., 0/0). This equation, however, is only undefined at exactly θ= 90°; it displays no asymptotic behaviour as θ approaches a value of 90°. Thus, if θ is offset by some small amount (e.g., θ= 90.001°), an accurate estimate of ROS(θ= 90°) can be made.

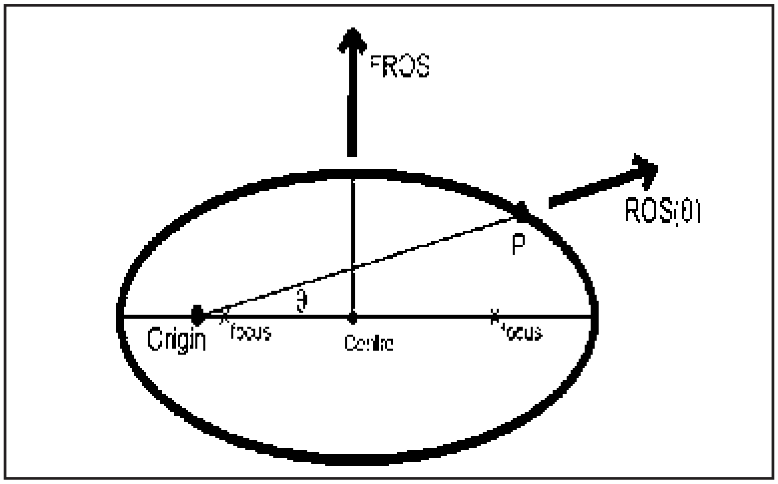

Figure 7: Schematic representation of an elliptically shaped fire with directions of spread at the flank (FROS) and at an arbitrary point P on the perimeter (ROS(θ)).

Table 3. An example of rate of spread calculations about an elliptically shaped fire. These calculations are based on a fire burning in FBP System fuel type C-2 (boreal spruce) on level terrain with an FFMC of 92, a wind speed of 15 km/h, and a BUI of 64. This set of conditions gives: LB = 1.98, ROS = 17.16, FROS = 4.88, and BROS = 2.16

θ (degrees)	ROS(θ) (m/min)
0	17.16
15	14.29
30	9.72
45	6.6
60	4.78
75	3.71
90	3.07
105	2.67
120	2.43
135	2.28
150	2.20
165	2.17
180	2.16

3.7 Summary of Revisions to ST-X-3

The following list summarizes the changes made in the previous section. All equations referenced in this document are listed in Appendix 2.

- Equations 9a and 9b replace ST-X-3 Equation 9.
- Equations 29 to 32 replace ST-X-3 Equations 29-32; ST-X-3 Equations 33 and 34 are no longer used.
- Equations 35a and 35b replace ST-X-3 Equation 35.
- Equations 39a and 39b replace ST-X-3 Equation 39.
- Equations 41a and 41b replace ST-X-3 Equation 41.
- Equation 42a replaces ST-X-3 Equation 42.
- Equations 42b and 42c are additions.
- Equations 44a, 44b, 44c, 44d, 44e replace ST-X-3 Equation 44.
- Equations 66a, 66b, 66c replace ST-X-3 Equation 66.
- Equations 80a, 80b and 81 replace ST-X-3 Equations 80 and 81.
- Equations 90 to 94 are new.

4.0 TEST DATASETS

4.1 Description

In 1992, the mathematical routines that made up the FBP System were programmed into computer code in the C language and rigorously tested. It was hoped and is still hoped, that software developers would use this code as a core component for their implementation of the system, thus ensuring that calculations were performed according to one standard method. The C source code is freely available[6] and a number of software developers as well as others have used it as the core component in their specific application of the FBP System. However, a number of computer applications of the system have been developed without the use of this C-code library. Thus, we have developed a formal dataset to be used as a benchmark to enable testing of each individual fuel type and various sub-models of the FBP System (e.g., foliar moisture content calculation, or the calculations of slope equivalent wind speed). In practice, software developers should use this test dataset in their computer applications of the FBP System to check their outputs for accuracy against the outputs of the "official" code maintained by the Canadian Forest Service.

We designed this set of FBP System inputs to produce a short test dataset so that software developers could test a limited number of examples and still be able to effectively test all of the important effects and interactions involved in the FBP System. The test dataset, consisting of 20 cases or scenarios, exhibits the following features:

- All of the fuel types are represented, which was considered necessary to test for errors in the various fuel type specific constants and equations comprising the FBP System (e.g., see Tables 6, 7 and 8 of ST-X-3).
- A range of latitudes and longitudes are given to test the equations for estimating foliar moisture content and, in turn, their effect on the critical surface intensity for crowning.
- A large number of the scenarios have wind/slope interactions and test a range of wind direction and slope aspect combinations.
- All of the cases or scenarios are treated as point source ignitions to test the acceleration and elliptical fire spread functions in the FBP System (i.e., calculation of the length-to-breadth ratio and the rates of spread at the head, flank and back of an elliptical-shaped fire after elapsed time *t* since ignition).

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[6]Electronic copies of the input dataset and a detailed output list as well as the C code for the FBP System are available upon request. Requests should be directed to: B.M. Wotton, Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, Ontario P6A 2E5 (e-mail: mwotton@nrcan.gc.ca).

A description of the interactions examined in the 20 cases compiled for testing is given in Section 4.2. The precise inputs and outputs are detailed in Section 4.3.

4.2 Fuel Type Examples and Effects Tested

Each individual fuel type example tests a number of equations and interactions. Outputs from each of these test cases are presented in the next section.

Test Case 1: Fuel Type C-1

- Low range of wind/slope interaction (wind is at a right angle to slope)
- High BUI value should increase rate of spread (BE > 1.0)
- Acceleration function in open canopy
- The new SFC function

Test Case 2: Fuel Type C-2

- Extreme rate of spread conditions (high wind speed and dry fine fuels)
- Addition of slope and wind vectors at off angles
- Wind speed > 40 km/h: testing the inclusion of the alternate ISI formulation (Equation 53a in footnote 2 on page 32 of ST-X-3)
- GS > 70%: to test for the upper slope limit using the new Equations 39a and 39b
- RSF ~ 110: testing for the inclusion of the new Equations 41a and 41b

Test Case 3: Fuel Type C-3

- Low BUI: should lead to BE < 1.0 and a reduction in rate of spread
- Wind speed > 40 km/h: testing the inclusion of the alternate ISI formulation (Equation 53a in footnote 2 on page 32 of ST-X-3)
- Short time period: testing the new LB_t relationship (Equation 81)

Test Case 4: Fuel Type C-4

- Zero wind and low FFMC: very low rate of spread conditions
- GS > 70%: testing for the upper slope limit of 70% (new Equations 39a and 39b)
- Elevation present in the FMC calculation: this should use the second component of the FMC model (Equations 3 and 4 in ST-X-3)
- BUI is high: so BE > 1.0 and there should be an increased rate of spread

Test Case 5: Fuel Type C-5

- Low intensity spread conditions
- BUI = BUI_0: therefore BE should equal 1.0
- Slope and wind vectors are in opposite directions and equivalent: therefore their magnitudes cancel each other out with resulting in WSV = 0

Test Case 6: Fuel Type C-6

- FMC < 97%: testing effect of FME on crown fire rate of spread
- ROS is at the point of continuous crowning (CFB ≈ 0.9) but is sensitive to FMC differences
- BUI close to BUI_0: so BE equals approximately 1.0.
- Dual equilibrium model or two-equation method with crown involvement: testing flank fire CFB, rate of spread, and intensity calculations using the equation for calculating crown fire rate of spread in fuel type C-6 (Equation 64 in ST-X-3)
- Wind and slope are opposing: test for proper WSE vectoring

Test Case 7: Fuel Type C-7

- Moderate FFMC (to one decimal place to test accuracy of input)
- Wind speed accuracy also to one decimal
- Slope and wind direction are perpendicular: testing for proper WSE vectoring
- Very low BUI: so BE < 1.0 and rate of spread should be reduced

Test Case 8: Fuel Type D-1

- Dry and windy conditions
- High BUI so BE > 1.0 and rate of spread should be increased
- Wind speed > 40 km/h again to test for inclusion of footnote 2 on page 32 in ST-X-3 (Equation 53a)

Test Case 9: Fuel Type M-1

- Wind and slope interaction: testing the new Equation 42
- Middle range of PC
- BUI < BUI_0: BE < 1.0 and rate of spread should be reduced

Test Case 10: Fuel Type M-2

- Extremely dry and windy conditions
- Wind and slope interaction: testing the new Equation 42 again.
- Low PC
- Wind speed > 40 km/h again to test for inclusion of footnote 2 on page 32 in ST-X-3 (Equation 53a)

Test Case 11: Fuel Type M-3

- Low BUI: BE < 1.0 and rate of spread should be reduced
- Close to surface fire and intermittent crown fire transition point (CFB ≈ 0.10)
- High PDF
- Wind and slope are perpendicular: testing proper WSE vectoring

Test Case 12: Fuel Type M-4

- Extremely dry and windy conditions
- Low PDF
- FMC is at a maximum
- Wind and slope are almost perpendicular: testing proper WSE vectoring

Test Case 13: Fuel Type O-1a

- Extremely dry and windy conditions
- Wind and slope interaction testing for the inclusion of new Equations 43a and 43b
- Lack of a BUI effect
- C = 90%
- High wind: testing grass fire length-to-breadth (LB) model
- Short elapsed time since ignition: testing LB_t using the new Equation 81

Test Case 14: Fuel Type O-1b

- Very mild burning conditions
- Grass curing just above the critical threshold of 50%
- Winds < 1 km/h limit but not zero: testing grass fire LB model using the new Equation 80b
- No slope

Test Case 15: Fuel Type O-1b

- Extremely dry and windy conditions
- *C* < 50%: testing the new rate of spread CF model (Equation 35a) for grass fuel types at *C* < 50%

Test Case 16: Fuel Type S-1

- Extremely dry and windy conditions
- Moderate slope steepness with wind interaction
- Very high BUI: BE > 0 and rate of spread should be increased

Test Case 17: Fuel Type S-2

- Moist fuel conditions: should lead to low rates of spread
- No wind and no slope
- BUI = BUI_0: therefore BE = 1.0

Test Case 18: Fuel Type S-3

- Moderate burning conditions
- Moderate slope steepness and no wind
- Low BUI: BE < 1.0 and rate of spread should be reduced

Test Case 19: Fuel Type C-6

- FMC ~ 97%: therefore there should be no FME influence on rate of spread
- Burning conditions have been chosen so there should be no crowning: testing the dual equilibrium model or two-equation method

Test Case 20: Fuel Type C-6

- FMC > 97%: therefore FME should reduce rate of spread
- Burning conditions have been chosen to correspond to an intermittent crown fire: testing the dual equilibrium model or two-equation method

4.3 Inputs and Outputs of the Test Datasets

The inputs and outputs for the 20 test cases as described in section 4.2 appear in Tables 4 to 6. Note that outputs for each of the test cases in most instances present quantities to an apparent high degree of precision (i.e., several decimal places). This degree of precision is beyond the true accuracy of the FBP System's models and would not be used operationally. Outputs have been presented to this high degree of precision for the purpose of allowing software testers the opportunity to examine the accuracy of their programming implementation of the FBP System.

5.0 DISCUSSION

The FBP System, and the numerous decision aids developed from it, has been readily accepted by all wildland fire management agencies in Canada. Favorable evaluations of model predictions and observed wild and prescribed fire behavior have been documented in both published reports (e.g., Alexander 1991, 1992, 2000; Alexander et al. 1993; Fogarty et al. 1996; Rasmussen and Fogarty 1997; Quintilio et al. 2001; Mottus 2001; Cruz and Plucinski 2007) and in approximately 200 case studies prepared as part of the requirements for the national Wildland Fire Behavior Specialist training course sponsored by the Canadian Interagency Forest Fire Centre (CIFFC) (see Alexander and Thomas 2003b, p. 7). Watts (1987) however makes some pertinent comments concerning the validation of fire models in general and the need for further model testing that are worth repeating:

Table 4. Inputs for each of the test cases described in section 4.2. Column headings correspond to the list of FBP System symbols and abbreviations found in Appendix II of ST-X-3 or as defined in Appendix 1 of this document unless otherwise noted.

Test Case	Fuel Type	FFMC	BUI	WS (km/h)	WDIR[a] (°)	WAZ (°)	GS (%)	SAZ (°)	Lat.[b] (°)	Long.[b] (°)	Elev.[b] (m)	D_j	D_0 [c]	t (min)	PC (%)	PDF (%)	GFL (kg/m^2)	C (%)
1	C-1	90	130	20	0	180	15	90	55	110	-	182	-	20	-	-	-	-
2	C-2	97	119	20.4	0	180	75	135	50	90	-	121	-	20	-	-	-	-
3	C-3	95	30	50	0	180	0	0	55	110	-	182	-	5	-	-	-	-
4	C-4	85	82	0	-	171	75	135	55	105	200	182	-	30	-	-	-	-
5	C-5	88	56	3.4	0	180	23	0	55	105	-	152	145	30	-	-	-	-
6	C-6	94	56	25	0	180	10	0	55	105	-	152	132	60	-	-	-	-
7	C-7	88.8	15	22.1	270	90	15	180	50	125	-	152	-	20	-	-	-	-
8	D-1	98	100	50	270	90	35	180	45	100	-	152	-	60	-	-	-	-
9	M-1	90	40	15.5	180	0	25	0	47	85	-	182	-	20	55	-	-	-
10	M-2	97	150	41	180	0	50	20	63	120	100	213	-	20	10	-	-	-
11	M-3	87	25	10.7	180	0	8	93	56	90	10	130	-	20	-	70	-	-
12	M-4	97	80	35	180	0	50	90	56	90	-	258	-	20	-	30	-	-
13	O-1a	95	20	35	180	0	50	90	56	90	-	244	-	5	-	-	1	90
14	O-1b	85	40	0.5	180	0	0	-	50	90	-	152	-	10	-	-	0.2	55
15	O-1b	95	40	35	180	0	10	90	50	90	-	152	-	20	-	-	1	45
16	S-1	95	130	15	180	0	20	45	50	90	-	152	-	20	-	-	-	-
17	S-2	87	63	0	0	180	0	0	50	90	-	182	-	20	-	-	-	-
18	S-3	89	20	0	0	180	30	90	50	90	-	213	-	20	-	-	-	-
19	C-6	90	80	15	0	180	10	90	46	77	-	171	-	10	-	-	-	-
20	C-6	91	100	20	0	180	30	90	46	77	-	213	-	10	-	-	-	-

[a] Wind direction (i.e., the direction the wind is coming from).
[b] Lat., Long. and Elev. correspond to latitude (north), longitude (west) and elevation, respectively.
[c] D_0 in the input section corresponds to a user identified date of minimum FMC.

Table 5. Primary FBP System outputs for the test cases defined in section 4.2. Column headings correspond to the list of FBP System symbols and abbreviations found in Appendix II of ST-X-3 or as defined in Appendix 1 of this document unless otherwise noted.

Case	WSV (km/h)	RAZ (°)	BE	SF	ISI	FMC (%)	D_0	RSS (m/min)	SFC (kg/m^2)	SFI (kW/m)	CFC (kg/m^2)	RSO (m/min)	CSI (kW/m)	TFC (kg/m^2)	CFB	FD[a]	ROS[b] (m/min)	HFI (kW/m)
1	20.086	174.7	1.033	1.437	11.796	93.33	161	5.569	1.399	2336.99	0.485	1.04	436.56	1.884	0.647	I	5.569	3147.82
2	127.689	141.5	1.137	10.00	136.138	107.39	155	121.104	3.728	135426.4	0.8	0.857	958.88	4.528	1	C	121.104	164491.3
3	50	180	0.781	1	86.707	93.33	161	80.517	0.602	14536.5	1.15	19.345	3492.44	1.752	1	C	80.517	42314.89
4	32.997	135	1.034	10.00	11.113	94.15	160	16.657	2.543	12705.28	1.162	1.637	1248.34	3.705	0.968	C	16.657	18512.26
5	0.004	0	1	1.832	3.219	85.93	145	0.049	1.218	17.88	0	29.082	10627.79	1.218	0	S	0.049	17.88
6	22.939	180	0.981	1.25	23.963	92.56	132	18.261	1.218	6673.44	1.64	7.74	2828.67	2.858	0.911	C	42.809	36704.87
7	22.429	99.8	0.628	1.437	11.175	89.84	136	2.358	2.107	1490.59	0	7.359	4652.24	2.107	0	S	2.358	1490.59
8	52.425	107.5	1.118	2.725	134.432	0	0	31.212	1.259	11792.25	0	0	0	1.259	0	S	31.212	11792.25
9	24.753	0	0.946	1.953	14.924	108.57	147	13.307	1.364	5446.63	0.343	6.72	2750.68	1.708	0.78	I	13.307	6817.05
10	65.616	7.7	1.16	4.654	129.9	118.7	165	18.057	1.674	9069.43	0.075	6.149	3088.24	1.749	0.935	C	18.057	9474.8
11	10.861	13.3	0.8	1.186	4.822	112.73	169	9.366	1.249	3510.38	0.178	7.704	2887.5	1.427	0.318	I	9.366	4010.24
12	48.639	44	1.087	4.654	111.007	120	174	36.098	3.007	32568.84	0.240	3.472	3132.31	3.247	0.999	C	36.098	35166.5
13	46.175	40.7	1	4.654	80.396	0	0	134.693	1	40407.98	0	0	0	1	0	S	134.693	40407.98
14	0.5	0	1	1	2.161	0	0	0.402	0.2	24.14	0	0	0	0.2	0	S	0.402	24.14
15	35.135	5	1	1.25	50.849	0	0	13.299	1	3989.59	0	0	0	1	0	S	13.299	3989.59
16	22.511	16.9	1.307	1.669	26.915	0	0	45.111	7.797	105514.8	0	0	0	7.797	0	S	45.111	105514.8
17	0	180	1	1	2.789	0	0	1.012	11.454	3478.58	0	0	0	11.454	0	S	1.012	3478.58
18	6.224	90	0.775	2.3	5.083	0	0	1.399	10.249	4301.89	0	0	0	10.249	0	S	1.399	4301.89
19	15.105	173.3	1.041	1.25	9.178	96.81	146	4.395	2.038	2687.57	0	4.896	2993.79	2.038	0	S	4.395	2687.57
20	21.207	160.6	1.071	2.3	14.399	120	146	10.279	2.654	8184.36	1.271	4.957	3947.16	3.925	0.706	I	17.637	20766.53

[a] Fire description (type of fire): S = surface; I = intermittent crown; and C = continuous crown.
[b] This represents final equilibrium head fire rate of spread in this case.

Table 6. Secondary FBP System outputs for the test cases defined in section 4.2. Column headings correspond to the list of FBP System symbols and abbreviations found in Appendix II of ST-X-3 or as defined in Appendix 1 of this document unless otherwise noted.

Test Case	LB	LB(t)	A (ha)	P (km)	PGR (m/min)	Head Fire[a] ROS$_t$ (m/min)	Head Fire[a] D$_t$[d] (m)	CFB	FD[e]	Flank Fire[b] ROS (m/min)	Flank Fire[b] FI (kW/m)	Flank Fire[b] ROS$_t$ (m/min)	Flank Fire[b] D$_t$[d] (m)	CFB	FD[e]	Back Fire[c] ROS (m/min)	Back Fire[c] FI (kW/m)	Back Fire[c] ROS$_t$ [a](m/min)	Back Fire[c] D$_t$[d] (m)
1	2.581	2.423	0.149	0.16	12.73	5.011	67.808	0.009	S	1.079	455.03	1.034	14	0	S	0.002	1.04	0.002	0.03
2	9.326	8.379	19.292	2.91	245.89	107.33	1434.62	0.726	I	6.493	8392.74	6.405	85.609	0	S	0.001	1.63	0.001	0.017
3	6.066	3.124	0.213	0.19	166.26	33.758	92.003	0	S	6.637	1198.23	5.403	14.726	0	S	0.002	0.44	0.001	0.003
4	4.207	4.08	2.411	0.76	35.876	15.995	350.925	0.079	S	1.996	1579.9	1.977	43.375	0	S	0.143	108.89	0.137	3.008
5	1	1	0	0.01	0.31	0.047	1.056	0	S	0.049	17.86	0.047	1.055	0	S	0.049	17.85	0.047	1.054
6	2.939	2.935	125.83	4.84	95.92	42.729	2160.886	0	S	3.133	1144.81	7.304	369.388	0	S	0.152	55.67	0.152	7.69
7	2.874	2.686	0.025	0.07	5.36	2.121	28.708	0	S	0.416	263.08	0.401	5.421	0	S	0.034	21.8	0.031	0.42
8	6.289	6.283	32.207	3.31	64.45	31.18	1601.575	0	S	2.487	939.71	2.487	127.735	0	S	0.07	26.6	0.07	3.613
9	3.169	2.847	0.635	0.33	30.25	11.33	147.286	0	S	2.163	885.28	2.05	26.651	0	S	0.403	164.99	0.343	4.462
10	7.312	6.555	0.536	0.43	36.93	15.892	211.294	0	S	1.236	620.85	1.214	16.134	0	S	0.02	9.93	0.017	0.231
11	1.553	1.254	0.218	0.15	30.42	4.306	47.448	0	S	3.748	1404.85	2.134	23.515	0	S	2.28	854.39	1.048	11.548
12	5.936	5.375	2.713	0.89	75.22	31.991	427.593	0	S	3.064	2764.19	2.999	40.083	0	S	0.276	249.08	0.245	3.27
13	6.511	3.41	0.607	0.33	278.79	58.901	161.286	0	S	10.413	3123.82	8.695	23.808	0	S	0.911	273.24	0.398	1.091
14	1	1	0.001	0.01	2.42	0.275	1.633	0	S	0.38`6	23.19	0.264	1.568	0	S	0.37	22.23	0.253	1.503
15	5.736	5.261	0.398	0.34	27.80	11.965	161.926	0	S	1.169	350.71	1.147	15.519	0	S	0.113	33.86	0.102	1.374
16	2.885	2.696	10.265	1.33	109.19	40.588	549.273	0	S	8.45	19763.6	8.135	110.094	0	S	3.639	8511.65	3.274	44.309
17	1	1	0.048	0.08	6.36	0.911	12.326	0	S	1.012	3478.58	0.911	12.326	0	S	1.012	3478.58	0.911	12.326
18	1.192	1.173	0.027	0.06	4.78	1.259	17.036	0	S	0.693	2130.08	0.634	8.574	0	S	0.253	778.14	0.228	3.081
19	1.991	1.677	0.016	0.04	10.90	3.004	17.835	0	S	1.129	690.49	0.916	5.44	0	S	0.101	61.98	0.069	0.411
20	2.721	2.002	0.136	0.13	40.06	10.266	58.699	0	S	1.901	1513.65	2.574	14.718	0	S	0.066	52.48	0.038	0.219

[a] All quantities under this heading pertain to a description of the head fire (e.g., ROS is equivalent to rate of spread of the head fire after time *t*).
[b] All quantities under this heading pertain to a description of the flank fire (e.g., ROS is equivalent to flank fire rate of spread).
[c] All quantities under this heading pertain to a description of the back fire (e.g., FI is equivalent to back fire intensity).
[d] Distance travelled during elapsed time *t* for head fire, flank fire and back fire, respectively.
[e] Fire description (type of fire): S = surface; I=intermitted crown

> *… if validation is a process for determining that the outputs of a model conform to reality, no model can be validated in an absolute sense; i.e., a model can never be proved correct, it can only be proven wrong. Acceptance of a model does not imply certainty, but rather a sufficient degree of belief to justify further action. Thus, in practice, validating a fire model is really a problem of invalidation. The more difficult it is to invalidate the model, the more confidence we have in it.*

Watts' comments echo an earlier statement by the statistician George Box (1979) "All models are wrong, some are useful."

Despite the widespread acceptance and operational use of the FBP System, users should remain aware of the empirical approach and the reliance on expert opinion used in model development. Some of these assumptions are discussed in the following paragraphs.

Rate of Spread and Levelling Off in the ROS-ISI Equations

In the development of ST-X-3 the assumption was made that a fire's forward rate of spread levels off at very high wind speeds or more specifically, at very high ISI values. The authors felt this to be an appropriate, conservative approach in the absence of any definitive research on the subject. The maximum possible spread rates predicted for the O-1a and O-1b grass fuel types in the FBP System are 190 and 250 m/min, respectively. However, grassland fires with rates of spread exceeding these values have been observed. Cheney et al. (1998) lists six documented wildfires in grass that exhibited rates of fire spread above 250 m/min, including one incident where the spread rate reached 383 m/min (Noble 1991) burning in exceptionally dry (FFMC 99; Fogarty and Alexander 1999), fully cured grassland with 10-m open winds averaging 45 km/h), giving a FBP System modified ISI of 131. In addition, Cheney (1981) has pointed out that with respect to Australian grasslands, there is observational evidence from wildfires of a decrease in rate of fire spread at very high wind speeds but not in native Australian hardwood forests (eucalypts), although crowning activity maybe reduced in the latter.

While the maximum calculable rate of advance for the most crown-fire prone fuel types in the FBP System (i.e., C-2, C-3 and C-4) is 110 m/min, Keeves and Douglas (1983) have documented an observed spread rate of approximately 200 m/min in a South Australia radiata pine plantation over a 50-minute time interval, burning under critically dry fuel conditions (FFMC 99, BUI 199; Pearce and Alexander 1994) coupled with 10-open winds in excess of 80 km/h (Australian Bureau of Meteorology 1984), giving a FBP System modified ISI of about 175. There are a few reported cases of wildfires spreading in North American conifer forests at rates between 133-183 m/min (8-11 km/h) for short time intervals (Anderson 1968; Wade and Ward 1973; Simard et al. 1983); however there is no reliable wind speed data to match these "bursts" in fire spread.

Leveling Off in the Surface Fuel Consumption Models

The surface fuel consumption (SFC) models in the FBP System also contain a maximum possible value for fuel consumption, which is determined by the assumed maximum available fuel load. As a result of a post-burn investigation of the 2001 Chisholm Fire in central Alberta, which included the re-burning of a previous experimental burning study area (Quintilio et al. 1991) and the 1968 Vega Fire (Kiil and Grigel 1969), Ember Research Services Ltd. (2003a, 2003b) concluded that the SFC model for the FBP System D-1 fuel type (leafless aspen) would under-predict at high BUI values and where dead-down woody fuel loads were significant. It's important to keep in mind that with one exception (Alexander 1982), the experimental plots used in the development of the D-1 fuel type SFC model (Alexander and Sando 1989; Quintilio et al. 1991) did not contain appreciable quantities of dead-down woody fuels. In fact, the description for the D-1 fuel type includes the statement that "Dead and down roundwood fuels are a minor component of the fuel complex". The maximum possible value set for the D-1 fuel type SFC model (1.5 kg/m^2) was based on the total preburn fuel load. We clearly need further experimental burning and/or wildfire monitoring in trembling aspen stands with heavy downed woody fuel accumulations under exceptionally dry fuel conditions.

The Original 16 Fuel Types

The fuel types modelled in the FBP System (Table 1) represent a broad range of forest and vegetation types from across Canada. This set of fuel types was not intended to exhaustively cover all relevant fuel types in the country or to be the final set of models produced. The intention was that new research was to continue to extend the FBP System to other fuel types. Indeed, the CIFFC Fire Science and Technology Working Group (1999) pointed out that the FBP System lacks fire behavior models for many fuel types across Canada, including leafed-out deciduous stands, forests affected by insect outbreaks other than spruce budworm, and forests subject to stand management treatments such as thinning and pruning. The British Columbia Ministry of Forests and Range and the Canadian Forest Service's Pacific Forestry Centre are presently carrying out an experimental burning study in lodgepole pine forests affected by mountain pine beetle at a site near the community of Vanderhoof in central British Columbia. An experimental burning project to examine the validity of the fire behavior predictions from FBP System models for the boreal mixedwood-leafless fuel type (M-1) is also being carried out by the Ontario Ministry of Natural Resources and the Canadian Forest Service near Sault Ste. Marie in Ontario (Hely et al. 2001).

While some outdoor field trials have examined sustained smouldering ignition in trembling aspen stands during the summer (Otway et al. 2007), no formal experimental burning study involving line fire ignitions in such a fuel type has been undertaken to-date. Some users have assumed that a "D-2" (i.e., leafed-out aspen) effectively exists as a result of applying 100% hardwood to the M-2 FBP System fuel type (boreal mixedwood-green). However, it's worth reiterating the statement made in ST-X-3 (p. 26) with respect to this issue: "Although no rate of spread data exist for hardwood fuel types under summer or 'leaf-out' conditions, the assumption is made that the rate of spread is 20% of that achieved under leafless condition". This relatively conservative approach taken – i.e., 1/5 of the D-1 (leafless aspen) FBP System fuel type rate of spread model output -- was considered justified on the grounds that fire spread in hardwood stands in summer is indeed considered possible on the basis of past experimentation (e.g., Stocks and Walker 1968) and numerous informal observations and anecdotal accounts of wildfires burning in mixedwood stands of varying conifer and hardwood composition during the summer (e.g., Juday 1985). In fact it's hypothesized that a duff moisture content threshold exists that must be overcome in addition to the fundamental requirement that the surface fuels are sufficiently dry for the fire to propagate through the surface fuels.

Adjustment of Crown Base Height

Forecasting or predicting fire behavior is often viewed as both an art and a science (Van Wagner 1985; Alexander and Thomas 2004). As such, the expectation of the system developers was that practitioners would make appropriate adjustments and other modifications in their various applications of the FBP System to specific situations. This should always be done with caution and with a thorough understanding of the underlying assumptions in the system's structure and development. For example, many users and software developers have wanted the ability to change the CBH in FBP System fuel types other than in C-6 (conifer plantation). This issue was discussed in ST-X-3 (p. 10) and the following text bears repeating here:

> *Crown base height is a critical factor in the crowning criterion; however, the theory on which the crown fire criterion is based was itself dependent on empirical data for its final quantitative form. The crown base height assigned to each fuel type is therefore the result of some trial. While the independent fuel type description incorporates some indication of the crown base height, the assigned value for each fuel type had to match the general pattern of crown involvement. The final assigned crown base height values represent the real forest structure as well as possible …*

Although a single CBH value has been assigned to each crown-fire susceptible FBP System fuel type, there is effectively a range in CBH associated with each because of the natural variability in the stands upon which the fire behavior models were developed. Modifying the crown base height in FBP System fuel types other than the C-6 (conifer plantation) is not recommended. There are, however, existing models that allow a user to examine the influence of varying crown base height on fire behavior in certain stand types (e.g., Cruz et al. 2003, 2004, 2007; Alexander et al. 2006).

6.0 CONCLUDING REMARKS

Development of the FBP System has continued for more than 30 years; the Canadian Forest Service fire research group, as part of its commitment to the fire science and operational communities, will continue to attempt to document and incorporate improvements into the FBP System on a regular basis in the form of publications such as the present report. The FBP System and the CFFDRS owe a great deal of their success to the blend of straightforward physical reasoning with extensive field measurement and empirical modelling (Van Wagner 1971, 1985; Alexander and Quintilio 1990; Stocks et al. 2004a). Research by the Canadian Forest Service and other scientists into the physical processes involved in wildland fire behavior (Stocks et al. 2004b; Taylor et al. 2004; Cruz et al. 2005, 2006a, 2006b, 2006c; Alexander and Cruz 2006; Beverly and Wotton 2007), including fuel moisture (Beck and Armitage 2004; Northcott 1999; Abbott et al. 2007; Wotton and Beverly 2007), and fuel complex characteristics (Alexander et al. 2004; Lavoie 2004; Whitehead et al. 2007) are ongoing and, the empirical and theoretical relationships within the FBP System are expected to evolve with this improved understanding.

User feedback and operational experiences will also continue to be critical to improving the system. Observation of the behavior of free-burning wildfires in the future by both fire researchers and fire operations staff in light of reflection on previous case study documentation (Alexander and Thomas 2003a, 2003b) and past fire research studies in the field and laboratory must also form an integral part of the whole process. While further field research is critically important, it is expensive and time consuming. It is therefore quite likely that further improvements and developments in the FBP System will have to incorporate new approaches to including the effects of variation in fuel properties on fire behavior such as physical modelling.

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[7]Please note that there is a typographical error in footnote a of Table 3 in Alexander and Lanoville (1989). The equations for calculating fire area should read: A (ha) = K_A x [ROS (m/min) x T (min)]^2 /10 000 *or* K_A x [ROS (km/h) x T (h)]^2 x 100

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APPENDIX 1: LIST OF SYMBOLS AND ABBREVIATIONS

The FBP System contains many abbreviations and symbols for both inputs and outputs. A large number of these have been used in this document, and a few new ones have been created; the latter are given in bold. This appendix defines the abbreviations used here and highlights the new ones created.

θ	Angle formed between an ellipse's semi-major axis and a direction of spread
α	Alpha function controlling the acceleration function
a,*b* and *c*	Rate of spread equation coefficients
BCFB	Crown fraction burned by the back fire
$\mathbf{BCFB}_t$	Crown fraction burned by the back fire after time *t*
BE	BUI effect on spread rate
BISI	ISI to compute the back fire rate of spread
BROS	Equilibrium back fire rate of spread
$\mathbf{BROS}_t$	Back fire rate of spread after elapsed time *t*
BRCS	Crown rate of spread of the back fire in fuel type C-6
BRSS	Surface rate of spread of the back fire in fuel type C-6
$\mathbf{BRSS}_t$	Surface rate of spread of the back fire after elapsed time *t*
BUI	Buildup Index
BUI_0	Mean BUI for a particular fuel type
C	Degree of curing
CBH	Height to live crown base
CF	Curing function for grass fuel types
CFB	Crown fraction burned by the head fire
CFC	Crown fuel consumed
CFL	Crown fuel load
$\mathbf{DB}_t$	Back fire spread distance after elapsed time *t*
$\mathbf{DF}_t$	Flank fire spread distance after elapsed time *t*
$\mathbf{DH}_t$	Head fire spread distance after elapsed time *t* (formerly DH in ST-X-3)
f(F)	Fine fuel moisture function in the ISI

f(W)	Wind function in the ISI
FCFB	Crown fraction burned by the flank fire
FCFC	Crown fuel consumed by the flank fire
FFMC	Fine Fuel Moisture Code
FMC	Foliar moisture content
FME	Foliar moisture effect
FROS	Equilibrium final flank fire rate of spread (formerly FRS in ST-X-3)
$FROS_t$	Final flank fire rate of spread after elapsed time *t*
FRSS	Surface rate of spread of the flank fire in fuel type C-6
$FRSS_t$	Surface rate of spread of the flank fire after elapsed time *t*
GFL	Grass fuel load
GS	Ground slope
ISF	Initial Spread Index, with zero wind upslope
ISI	Initial Spread Index
LB	Length-to-breadth ratio.
LB_t	Length-to-breadth ratio after elapsed time *t*
PC	Percent conifer
PDF	Percent dead fir
PGR	Perimeter growth rate
ROS	Final head fire rate of spread
ROS*t*	Head fire rate of spread after elapsed time *t*
ROS(θ)	Rate of spread at an angle θ off the direction of forward spread
RSC	Crown fire rate of spread in fuel type C-6
RSF	Surface spread rate with zero wind, upslope
RSI	Initial rate of spread (before BE adjustment)
RSO	Critical spread rate for crowning
RSS	Surface fire rate of spread
RSS_t	Surface fire rate of spread after elapsed time *t*
RSZ	Surface spread rate with zero wind on level terrain
SD	Stand density
SF	Slope factor (multiplier for rate of spread increase upslope)
SFC	Surface fuel consumption
SH	Stand height
t	Elapsed time since ignition from a single point source ignition
WSE	Slope equivalent wind speed
WSV	Net effective wind speed on fire based on both the wind and slope influences

APPENDIX 2: SUMMARY OF NEW AND MODIFIED EQUATIONS

$$SFC = 0.75 + 0.75 \times (1 - e^{-0.23 \times (FFMC - 84)})^{0.5} \qquad \text{if FFMC} > 84 \qquad \textbf{(9a)}$$

$$SFC = 0.75 - 0.75 \times (1 - e^{-0.23 \times (FFMC - 84)})^{0.5} \qquad \text{if FFMC} \leq 84 \qquad \textbf{(9b)}$$

$$RSI = \frac{PDF}{100} \times RSI_{M-3(100\%)} + \left(1 - \frac{PDF}{100}\right) \times RSI_{D-1} \qquad \textbf{(29)}$$

$$RSI_{M-3(100\%)} = 120 \times \left[1 - e^{(-0.0572 \times ISI)}\right]^{1.4} \qquad \textbf{(30)}$$

$$RSI = \frac{PDF}{100} \times RSI_{M-4(100\%)} + 0.2 \times \left(1 - \frac{PDF}{100}\right) \times RSI_{D-1} \qquad \textbf{(31)}$$

$$RSI_{M-4(100\%)} = 100 \times \left[1 - e^{(-0.0404 \times ISI)}\right]^{1.48} \qquad \textbf{(32)}$$

$$CF = 0.005 \times (e^{0.061 \times C} - 1) \qquad \text{if } C < 58.8 \qquad \textbf{(35a)}$$

$$CF = 0.176 + 0.02 \times (C - 58.8) \qquad \text{if } C \geq 58.8 \qquad \textbf{(35b)}$$

$$SF = e^{3.533 \times \left(\frac{GS}{100}\right)^{1.2}} \qquad \text{if GS} < 70\% \qquad \textbf{(39a)}$$

$$SF = 10.0 \qquad \text{if GS} \geq 70\% \qquad \textbf{(39b)}$$

$$ISF = \frac{\ln\left[1 - \left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right]}{-b} \qquad \text{if } 1 - \left(\frac{RSF}{a}\right)^{\frac{1}{c}} \geq 0.01 \qquad \textbf{(41a)}$$

$$ISF = \frac{\ln(0.01)}{-b} \qquad \text{if } 1 - \left(\frac{RSF}{a}\right)^{\frac{1}{c}} < 0.01 \qquad \textbf{(41b)}$$

$$ISF = \frac{PC}{100} \times ISF_{C-2} + \left(1 - \frac{PC}{100}\right) \times ISF_{D-1} \qquad \textbf{(42a)}$$

$$ISF = \frac{PDF}{100} \times ISF_{M\text{-}3(100\%)} + (1 - \frac{PDF}{100}) \times ISF_{D\text{-}1} \qquad \textbf{(42b)}$$

$$ISF = \frac{PDF}{100} \times ISF_{M\text{-}4(100\%)} + (1 - \frac{PDF}{100}) \times ISF_{D\text{-}1} \qquad \textbf{(42c)}$$

$$ISF = \frac{\ln\left[1 - \left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}}\right]}{-b} \qquad \text{if } 1 - \left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}} \geq 0.01 \qquad \textbf{(43a)}$$

$$ISF = \frac{\ln(0.01)}{-b} \qquad \text{if } 1 - \left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}} < 0.01 \qquad \textbf{(43b)}$$

$$WSE' = \frac{1}{0.05039} \ln(\frac{ISF}{0.208 \times f(F)}) \qquad \textbf{(44a)}$$

$$WSE'' = 28 - \frac{1}{0.0818} \ln(1 - \frac{ISF}{2.496 \times f(F)}) \qquad \text{if ISF} < 0.999 \times 2.496 \times f(F) \qquad \textbf{(44b)}$$

$$WSE'' = 112.45 \qquad \text{if ISF} > 0.999 \times 2.496 \times f(F) \qquad \textbf{(44c)}$$

$$WSE = WSE' \qquad \text{if } WSE' \leq 40 \qquad \textbf{(44d)}$$

$$WSE = WSE'' \qquad \text{if } WSE' > 40 \qquad \textbf{(44e)}$$

$$CFC_{C\text{-}1 \text{ to } C\text{-}7} = CFL \times CFB \qquad \textbf{(66a)}$$

$$CFC_{M\text{-}1/M\text{-}2} = CFL \times CFB \times PC/100 \qquad \textbf{(66b)}$$

$$CFC_{M\text{-}3/M\text{-}4} = CFL \times CFB \times PDF/100 \qquad \textbf{(66c)}$$

$$LB = 1.1 \times WSV^{0.464} \qquad \text{if WSV} \geq 1.0 \qquad \textbf{(80a)}$$

$$LB = 1.0 \qquad \text{if WSV} < 1.0 \qquad \textbf{(80b)}$$

$$LB_t = (LB - 1) \times (1 - e^{-\alpha \cdot t}) + 1 \qquad \textbf{(81)}$$

$$FROS_t = \frac{ROS_t + BROS_t}{2 \times LB_t} \qquad \textbf{(89)}$$

$$\mathrm{FRSS}_t = \frac{\mathrm{RSS}_t + \mathrm{BRSS}_t}{2 \times \mathrm{LB}_t} \tag{90}$$

$$\mathrm{CBH} = -11.2 + 1.06 \times \mathrm{SH} + 0.00170 \times \mathrm{SD} \tag{91}$$

$$\mathrm{DF}_t = \frac{\mathrm{DH}_t + \mathrm{DB}_t}{\mathrm{LB}_t \times 2} \tag{92}$$

$$\mathrm{FFMC} = 71.7069 + 6.375 \times \ln(f(F) - 2.0737) \tag{93}$$

$$\mathrm{ROS}(\theta) = \frac{\mathrm{ROS} - \mathrm{BROS}}{2 \times \cos\theta} + \frac{\mathrm{ROS} + \mathrm{BROS}}{2 \times \cos\theta} \times \left(\frac{\mathrm{FROS} \times \cos\theta \times \left[\mathrm{FROS}^2 \times \cos^2\theta + (\mathrm{ROS} \times \mathrm{BROS}) \times \sin^2\theta\right]^{\frac{1}{2}} - \frac{\left(\mathrm{ROS}^2 - \mathrm{BROS}^2\right)}{4} \times \sin^2\theta}{\mathrm{FROS}^2 \times \cos^2\theta + \left(\frac{\mathrm{ROS} + \mathrm{BROS}}{2}\right)^2 \times \sin^2\theta} \right) \tag{94}$$