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Current status and future needs of the BehavePlus Fire Modeling System

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Abstract. The BehavePlus Fire Modeling System is among the most widely used systems for wildland fire prediction. It is designed for use in a range of tasks including wildfire behaviour prediction, prescribed fire planning, fire investigation, fuel hazard assessment, fire model understanding, communication and research. BehavePlus is based on mathematical models for fire behaviour, fire effects and fire environment. It is a point system for which conditions are constant for each calculation, but is designed to encourage examination of the effect of a range of conditions through tables and graphs. BehavePlus is successor to BEHAVE, which was developed in 1977 and became available for field application in 1984. It was updated to BehavePlus in 2002. Updates through version 5 have added features and modelling capabilities. It is becoming increasingly difficult to expand the system. A redesign will address the need for consolidation with other systems and make it easier to incorporate new research results. This paper describes the development history and application of BehavePlus. The design, features and modelling foundation of the current system are described. Considerations for the next generation are presented.

Additional keywords: crown fire, fire behaviour, fire effects, fire management, fuel, spotting distance, surface fire.

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Introduction

Fire behaviour and fire effects modelling systems play an important supporting role in many facets of wildland fire management. When used in conjunction with personal fire experience and a basic understanding of fire models, predictions can be successfully applied to wildfire behaviour prediction, prescribed fire planning and fuel hazard assessment. Scenarios representing conditions beyond common experience can be modelled and alternatives can be examined. Fire modelling systems support fire and land management at scales from small area prescribed burns to national seasonal fire potential assessments and to global climate change evaluation. A multitude of systems address various aspects of wildland fire. For example, McHugh (2006) described the applicable spatial scale for six systems available for fuel treatment analysis and Stratton (2006) provided guidance on use of seven systems for spatial wildland fire analysis. A summary of 40 tools for management of vegetation and fuels was compiled by Peterson *et al.* (2007).

BehavePlus is among the most widely used fire management systems in the US, with a significant use outside of the US (Andrews 2010). A study designed to gain an understanding of the information needs of wildland fire and fuel managers found that BehavePlus was used by 95% of the 143 responders (Miller and Landres 2004). A comprehensive study of issues related to software systems in the fire and fuels subject area reported that BehavePlus 'is by far the single most widely used software tool' (Rauscher 2009). Among the reasons that BehavePlus is so widely used is that it is not designed for a specific application such as wildfire prediction or fuels management. It is used for those applications, and also to give people a basic understanding of wildland fire, to communicate fire management alternatives to the public, to gain an understanding of the mathematical fire models, to develop fire prescriptions, to do post-fire investigations, to support research analyses and more.

BehavePlus is used for prescribed fire planning (USDA and USDOI 2008) and is a component of US fire behaviour and prescribed fire courses (NWCG 2012). Examples of application are found in Technical Fire Management (TFM), a professional mid-career program for US fire and fuels managers (www.washingtoninstitute.net, accessed 2102) in which some participants use BehavePlus to prepare a final project that addresses an issue in their home unit (e.g. Bannister 2001; Dustin 2002; Goodman 2006; Ramirez 2006; Cagle 2008; Sanchey 2011). BehavePlus serves as a research tool to examine potential fire behaviour for various fuel and weather conditions (Hély *et al.* 2000; Fulé *et al.* 2001; Brose and Wade 2002; Dimitrakopoulos 2002; Sargis and Adams 2004; Glitzenstein *et al.* 2006; Cronan and Jandt 2008; Diamond *et al.* 2009; Fontaine *et al.* 2012). It is used to develop custom fire behaviour fuel models (Grabner *et al.* 2001; Wu *et al.* 2011) and to exercise and evaluate the Rothermel surface fire spread model (Sauvagnargues-Lesage *et al.* 2001; Streeks *et al.* 2005; Jolly 2007).

The original application of the BEHAVE Fire Behavior Prediction and Fuel Modeling System was wildfire prediction by an individual, now called Fire Behavior Analyst (FBAN) (NWCG 2011), who has both extensive fire experience and fire modelling training. BEHAVE has been updated and expanded and is now called the BehavePlus Fire Modeling System to reflect its expanded scope (Andrews 1986, 2007). The user base has expanded to include some who have neither fire experience nor access to the formal courses that teach fire behaviour modelling (NWCG 2012). Proper use of any fire modelling system relies on an educated user who recognises model limitations and understands the assumptions of the models on which predictions are based (Alexander and Cruz 2012; Jolly *et al.* 2012).

BehavePlus provides a means of modelling fire behaviour (such as rate of spread and spotting distance), fire effects (such as scorch height and tree mortality) and the fire environment (such as fuel moisture and wind adjustment factor). BehavePlus is a point fire modelling system made up of over 40 deterministic mathematical models. BehavePlus consists not only of the models, but also model linkages, the user interface, method of defining a worksheet, source and method of supplying input values, context-sensitive help system, table and graph output, and user options.

Although the spatial systems FARSITE (Finney 1998), FlamMap (Finney 2006) and FSPro (Finney *et al.* 2011) are based on essentially the same mathematical models as BehavePlus, there remains a need for point-based modelling. Many fire management applications do not require the detailed information provided by spatial systems and are, in fact, better satisfied by simple tables and graphs. BehavePlus can also complement the spatial systems. A person who learns about the models using BehavePlus is better able to interpret the results of the spatial systems, where the modelling that occurs at each pixel is less evident. A user can run BehavePlus to examine, for example, the effect of fuel model, live fuel moisture or canopy base height on modelled fire behaviour. It is difficult to see specific cause and effect relationships in a landscape of thousands of model calculations.

The term 'model' is used in this paper for the equations and algorithms that form the foundation of fire modelling systems. Independently developed models are grouped into 'modules' based on rules and assumptions. A 'system' is a packaging of models into a tool that is useful for a task. A system might be a computer program, nomographs, tables or photo series. 'Collaborative systems' link the capabilities of several systems and data sources with a common user interface, such as BlueSky for smoke (Larkin *et al.* 2009), Wildland Fire Decision Support System (WFDSS) for wildfire (Pence and Zimmerman 2011) and Interagency Fuels Treatment Decision Support System (IFTDSS) for fuels (Wells 2009). Other authors have used the terms 'model' and 'system' in various other ways (Scott and Reinhardt 2001; Peterson *et al.* 2007; Reinhardt and Dickinson 2010; Keane *et al.* 2011).

This paper describes the development history of BehavePlus and the design and features of the current system. The modelling foundation of BehavePlus is reviewed and considerations for the future are presented.

Background

The initial BEHAVE system was developed after the 1976 S-590 'Fire Behavior Officer' course, to automate the nomographs and tables taught in the course (Albini 1976*a*; Rothermel 1983; Andrews 2007). The first presentation of the BEHAVE system was given in September 1977 at the Missoula Fire Sciences Laboratory. BEHAVE was first available in computer card batch mode. The six characters on the header card for the card deck became the name of the program. An interactive version could be used only at night when the Missoula Fire Laboratory had access to the LBL (Lawrence Berkeley Laboratory) computer in California.

With improvement of computer access, BEHAVE was available to the field as an interactive program through remote access. An early version of the program started with a question 'Are you using a computer with a screen?' The answer was 'no' if the person was using a Silent 700 terminal, which printed questions and answers on paper. A 'terse' option shortened the text. People who had a 'screen' ran the program under the 'wordy' option.

The fire modelling portion of BEHAVE was expanded and renamed FIRE1, and fuel modelling programs were included to make it the BEHAVE Fire Behavior Prediction and Fuel Modeling System. BEHAVE was formally accepted by the US Forest Service, Fire and Aviation Management, Washington Office as a nationally supported system in 1984. It was the first system to formally go through their process of transferring a system from research to application.

BEHAVE eventually consisted of five FORTRAN programs that ran in interactive mode under the DOS operating system on personal computers. The fire modelling portion was the BURN subsystem (FIRE1 and FIRE2 programs) (Andrews 1986; Andrews and Chase 1989). Custom fuel models were developed and tested using the FUEL subsystem (NEWMDL and TSTMDL programs) (Burgan and Rothermel 1984; Burgan 1987). The RXWINDOW program was designed for prescribed fire planning; the user specified acceptable fire behaviour and effects and the program found the associated fuel moisture and wind speed (Andrews and Bradshaw 1990).

A major update from BEHAVE to BehavePlus was funded by the Joint Fire Science Program and released in 2002. BehavePlus version 1.0 offered the same fire modelling capabilities as BEHAVE, with a new look and feel, as well as a new internal coding structure (Andrews and Bevins 1998). Each subsequent version has added additional features and modelling capabilities (Heinsch and Andrews 2010). Updates through version 5 have been supported by the US Forest Service Fire and Aviation Management and the Rocky Mountain Research Station.

System design and features

BehavePlus is organised according to calculation modules, each of which is based on related mathematical fire models (Fig. 1, Table 1). Modules can be used independently or linked together with results from one being used as input to another. Following is a summary of the modules. An overview of all of the models in BehavePlus is given in the next section.

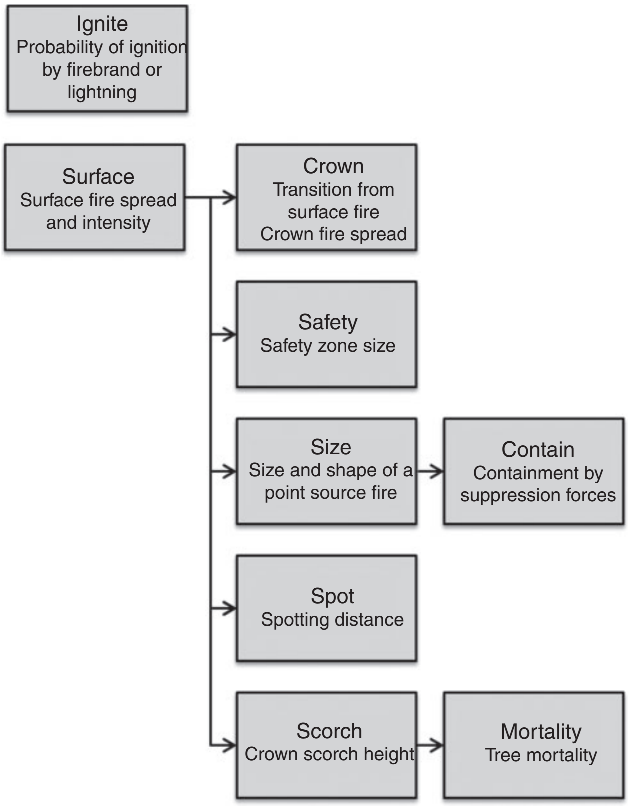

Fig. 1. BehavePlus modules are based on related models. Modules can be either used independently or linked, with output from one used as input to another (Table 1).

- IGNITE – Probability of ignition.
- SURFACE – Surface fire behaviour.
- CROWN – Crown fire behaviour.
- SAFETY – Safety zone size.
- SIZE – Point source fire size and shape.
- CONTAIN – Fire containment due to suppression action.
- SPOT – Maximum spotting distance.
- SCORCH – Crown scorch height.
- MORTALITY – Probability of tree mortality.

BehavePlus is a point modelling system; each calculation is based on the assumption of uniform conditions in both time and space. However, runs are rarely based on a single calculation. The system is designed to encourage comparison and evaluation through examination of graphs and tables (Figs 2, 3). The example in Fig. 3 involved calculation of tree mortality from calculated fireline intensity and crown scorch (SURFACE-SCORCH-MORTALITY); the user can instead choose to specify values for fireline intensity (SCORCH-MORTALITY) or enter observed or estimated values for scorch height (MORTALITY). BehavePlus can also produce simple diagrams that aid interpretation of results (Fig. 4).

The BehavePlus worksheet is determined by selection of modules, options and output variables. Only required values are requested, organised by category (fuel moisture, weather, etc.) rather than by module. Options include selections such as whether wind speed is entered as midflame, 20-ft or 10-m wind and whether wind adjustment factor is entered or calculated. Another option allows surface fuel to be entered as a fuel model or as individual fuel parameters (load, depth, moisture of extinction, etc.). There are over 180 variables in BehavePlus including input and output, as well as intermediate values for those interested in model understanding (Andrews 2009). The context-sensitive help system provides definitions, diagrams, guidance and information on the role that the variable plays.

The design of BehavePlus is an attempt to address a balance between simplicity and flexibility. Diverse user groups have different requirements. A person whose needs are satisfied by a simple calculation can use pre-selected options and ignore many of the program features. A person who is doing more complex analyses can change modelling options, units and decimals, table and graph format and so on (Heinsch and Andrews 2010).

BehavePlus is driven by interactive user input, which allows for experience and judgment in determining values. There are no default values for input parameters, based on the feeling that a user should think about every required input. Worksheets, runs and custom fuel models can be saved for later use. Tables can be exported for further analysis or alternate presentation using other software.

Model foundation

BehavePlus5 includes over 40 fire models, described in 58 reference papers (Table 2). The 53 standard fire behaviour fuel models and custom fuel models are counted as one 'model'. BehavePlus or BEHAVE has sometimes incorrectly been used as a synonym for the Rothermel surface fire spread model, which is only one of many models in the system. Following is an overview of the fire models in BehavePlus5 with reference to associated modules. Details can be found in the referenced documents.

Surface fire

The core of the SURFACE module is the Rothermel (1972) surface fire spread model, with some minor adjustments (Albini 1976*b*), which calculates head fire rate of spread in surface fuels. The model describes fires advancing steadily, independent of the source of ignition (quasi steady-state). Fire behaviour in the flaming front is primarily influenced by fine fuels. The fuel bed is assumed to be horizontally uniform and continuous, within ~1.8 m of the ground. Fireline intensity and flame length are based on models developed by Byram (1959), using Albini's (1976*b*) method for using those models with the Rothermel model. The fuel consumed in the active flaming front is based on flame residence time (Anderson 1969) calculated from the characteristic surface-area-to-volume ratio of the Rothermel model. The relationship among rate of spread, heat per unit area, fireline intensity and flame length is displayed in the fire characteristics chart (Andrews and Rothermel 1982). A simple chart is available in BehavePlus; a supplemental program gives more options (Andrews *et al.* 2011). Calculation of surface fire spread rate and intensity requires a description of the surface fuel, midflame wind speed, slope and fuel moisture.

Table 1. BehavePlus modules are groupings of related mathematical fire models
Possible linkages indicate values that can come from other modules rather than direct user input

Module name	Calculations	Possible linkages
SURFACE	Surface fire rate of spread Fireline intensity and flame length Reaction intensity and heat per unit area Intermediate values: heat source, heat sink, characteristic dead fuel moisture, relative packing ratio, etc. Standard, custom and special case fuel models Wind adjustment factor	
CROWN	Transition from surface to crown fire Crown fire rate of spread Crown fire area and perimeter Fire type: surface, torching, conditional crown or crowning Crown fire intensity and flame length Power of the fire, power of the wind	Surface fireline intensity or flame length can come from SURFACE Surface fire heat per unit area can come from SURFACE
SAFETY	Safety zone size based on flame height Area, perimeter and separation distance	Head fire flame length can come from SURFACE
SIZE	Elliptically shaped point source fire Area, perimeter and shape	Head fire rate of spread and effective wind speed can come from SURFACE
CONTAIN	Fire containment success for single or multiple resources given line construction rate, arrival time, resource duration, head or rear attack, and direct or parallel attack Final area and perimeter, fire size at initial attack and fireline constructed	Head fire rate of spread can come from SURFACE Length-to-width ratio and fire size at report can come from SIZE
SPOT	Maximum spotting distance from torching trees, burning piles or wind-driven surface fire	Head fire flame length can come from SURFACE for wind-driven surface fire
SCORCH	Crown scorch height from surface fire flame length	Surface fireline intensity or flame length can come from SURFACE
MORTALITY	Probability of mortality from bark thickness and crown scorch	Scorch height can come from SCORCH
IGNITE	Probability of ignition by firebrands Probability of ignition from lightning strikes	

Surface fuel

Surface fuel can be input to the SURFACE module in several ways: as standard fire behaviour fuel models; fuel parameters; custom fuel models; two fuel models; and special case fuel models. In all cases, the fuel descriptors apply specifically to requirements of the Rothermel model, and do not represent all components of the fuel complex. Large diameter fuels, ground fuels (duff) and overstorey are not included. Fuel component size classes are quantified by surface-area-to-volume ratio (SAV) of live and dead fuel. The fire model does not limit the number of classes, although standard fuel models (described below) have at most three sizes of dead fuel and two of live. A single fuel bed depth represents the fuel complex. Dead fuel moisture of extinction is an input; live fuel moisture of extinction is calculated.

Fuel is commonly described for the surface fire spread model by means of fuel models, which are sets of values required by the fire model. Eleven fuel models were published with the spread model (Rothermel 1972); all had dead fuel moisture of extinction of 30%. In developing his nomographs, Albini (1976*a*) added two fuel models and assigned appropriate moisture of extinction values to each fuel model. Anderson (1982) described those 13 fuel models with photographs. An additional set of 40 fuel models was developed by Scott and Burgan (2005) to represent a wider range of conditions. There are now 53 (13 + 40) standard fire behaviour fuel models. In total, 17 of the 40 fuel models are dynamic, meaning that fuel is transferred from the live to the dead category to represent curing. The dynamic load transfer model was developed for fire danger rating (Burgan 1979) and was incorporated into the fuel modelling portion of BEHAVE (Burgan and Rothermel 1984). Live herbaceous fuel moisture is used to determine load transfer portion. Because of weaknesses in that relationship and sensitivity of the fire model and dynamic fuel models to live fuel moisture, BehavePlus includes the option of direct entry of fuel load transfer portion (percent cured) (Andrews *et al.* 2006; Jolly 2007).

BehavePlus allows entry of the basic fuel model parameters, permitting examination of how changes in various fuel variables (fuel bed depth, fine fuel SAV, live fuel load, heat content, etc.) affect modelled fire behaviour. Given the variability that exists in any fuel bed and the uniformity assumptions and fuel weighting formulation of the fire model, fuel parameters are generally adjusted to achieve measured or expected fire behaviour (Burgan and Rothermel 1984; Burgan 1987; Keane 2013).

A custom fuel model can be developed for cases not satisfied by any of the 53 standard fuel models. Developing a custom fuel model is truly a ‘modelling’ exercise involving testing and modifying parameters of a standard fuel model or of field

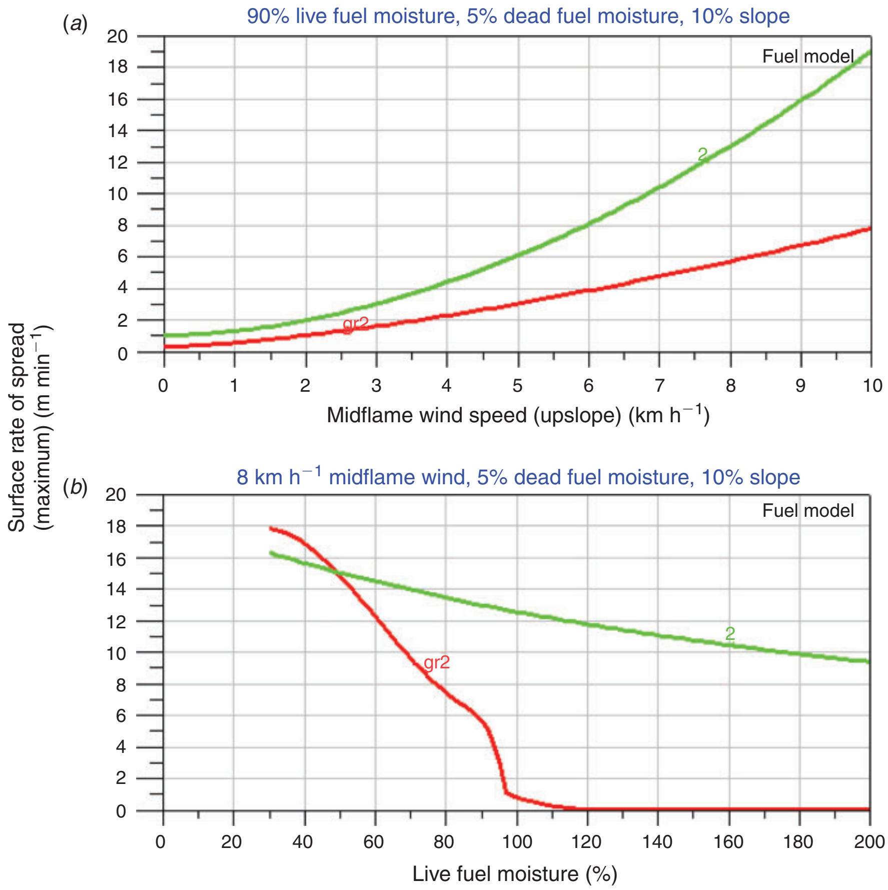

Fig. 2. BehavePlus facilitates examination of the effect of input values on results. This example output from the SURFACE module compares rate of spread for fuel models 2 and GR2 for ranges of (*a*) midflame wind speed and (*b*) live fuel moisture.

Midflame wind speed (km h^{-1})	Fireline intensity (kW m^{-1})	Flame length (m)	Scorch height (m)	Prob of mortality (%)
3	130	0.7	3.7	0
6	293	1.1	5.4	15
9	497	1.3	6.5	25
12	733	1.6	7.3	29

Fig. 3. Example BehavePlus table output from the SURFACE, SCORCH and MORTALITY modules shows probability of tree mortality for a range of midflame wind speed, with all other conditions held constant: fuel model TU2, 5% dead moisture, 50% live moisture, 10% slope, 30°C air temperature, Douglas-fir, 25 m tall, diameter at breast height 35 cm, crown ratio 0.8.

measurements. Custom fuel models developed in BehavePlus are saved in a format for later use by BehavePlus, or in a format required by FARSITE and other systems.

As a means of dealing with the horizontal fuel uniformity assumption of the fire spread model, two fuel models and the percent cover of each can be specified. Three modelling approaches are available in BehavePlus: two-dimensional expected spread (Finney 2003), harmonic mean (Fujioka 1985) and area weighted (Rothermel 1983).

BehavePlus also includes 'special case fuel models', for which additional mathematical models are used to define fuel parameters and for which restrictions of the standard fuel models (such as number of size classes and constant particle density) are not imposed (Hough and Albini 1978; Brown and Simmerman 1986).

Fuel moisture

The moisture content of surface fuels is used to calculate spread rate and intensity in the SURFACE and CROWN modules; and foliar moisture, representing the moisture of live conifer needles, is used to calculate transition to crown fire in the CROWN module (see the crown fire section below). In addition, there is a fine dead fuel moisture tool that is not directly linked to any of the calculation modules.

Rothermel's surface fire spread model requires fuel moisture content for each size class of fuel. Weighting factors are used to find characteristic moisture for live and dead fuel, putting most of the weight on fine fuels. If the characteristic dead fuel moisture is greater than the specified dead fuel moisture of extinction, the fire will not spread. If the characteristic live fuel moisture is less than the calculated live fuel moisture of extinction, live fuel contributes as a heat source; otherwise, it serves only as a heat sink.

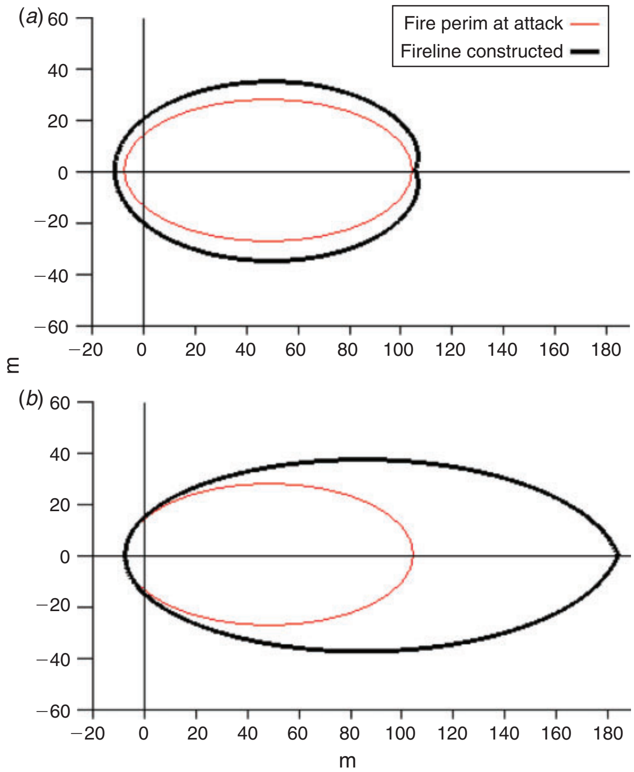

Fig. 4. Example diagram from the BehavePlus CONTAIN module shows results of (*a*) head and (*b*) rear attack. Forward rate of spread is 3 m min^{-1}, fire size at attack 0.5 ha, length-to-width ratio 2.0, line production rate 1000 m h^{-1}. Head attack contained the fire in 0.3 h at 0.7 ha with 303 m of fireline constructed. Rear attack contained the fire in 0.4 h at 1.1 ha with 434 m of fireline constructed.

The SURFACE module offers the option of specifying a moisture scenario as an alternative to entering moisture content for each size class. The concept of moisture scenario is similar to that of fuel model in that a code is used to reference a set of values assigned to parameters required by the fire spread model. Two sets of fuel moisture scenarios used in comparing fuel models are included in BehavePlus (Burgan and Rothermel 1984; Scott and Burgan 2005). A user can also define fuel moisture scenarios to represent local conditions for applications such as prescribed fire planning.

Fine dead fuel moisture tables (Rothermel 1983) are in BehavePlus as a stand-alone tool. They are based in part on expert opinion and not on a well defined mathematical model foundation, so are not programmed as part of the SURFACE module.

Wind

Wind is an important influence on wildland fire and plays a role in several modules of BehavePlus:

- SURFACE – midflame wind is used to calculate surface fire spread rate. Models are available to reduce 10-m or 20-ft wind to midflame wind.
- CROWN – 20-ft wind is used to calculate crown fire spread rate.
- SIZE – effective wind speed determines the shape of a point source fire.
- SPOT – 20-ft wind is used to find maximum spotting distance.
- SCORCH – midflame wind affects flame tilt in calculating crown scorch height.

BehavePlus includes models for vertical adjustment of wind speed, from 10-m to 20-ft to midflame height. Wind speed at 10 m above the vegetation is assumed to be 1.15 times the wind at the 20-ft height (Turner and Lawson 1978; Lawson and Armitage 2008). Rothermel (1972) coined the term 'midflame' wind to differentiate the wind that affects surface fire from the free wind at 20 ft (or 10 m) above the top of the vegetation. The Rothermel surface fire spread model was designed to use the fuel and environmental conditions in which the fire is expected to burn; prior knowledge of the fuel's burning characteristics is not required. Flame dimensions are not needed to determine the wind speed for calculating spread rate. In application, hand-held measurements of wind at 'eye-level' are often used for midflame wind (Andrews 2012). Effective midflame wind speed is the combined effect of wind and slope according to the Rothermel model equations (Albini 1976*a*).

Albini and Baughman's (1979) models for wind adjustment factor reduce 20-ft wind to midflame wind. For surface fuels that are unsheltered by overstorey, midflame wind speed is defined as the average wind from the top of the fuel bed to twice that height, based on a log wind profile. The model for sheltered fuel assumes constant wind with height under the canopy, with the reduction based on canopy density.

The Rothermel (1972) model includes a wind speed limit, above which the predicted rate of spread is constant. The results are apparent in the plots comparing the 40 fuel models (Scott and Burgan 2005). BehavePlus includes the option of not imposing the wind limit, based on a reanalysis of the McArthur (1969) data from which the wind limit function was derived and on recent data that do not support the limit (Andrews *et al*. 2013).

Crown fire

The CROWN module in BehavePlus includes models for spread rate and intensity (Byram 1959; Thomas 1963; Rothermel 1991), transition from surface to crown fire (Van Wagner 1977, 1989, 1993; Finney 1998; Scott and Reinhardt 2001), conditions for active crown fire (Van Wagner 1977) and fire type (Van Wagner 1993; Finney 1998; Scott and Reinhardt 2001). The models were developed independently and, although not specifically designed to work together, the CROWN module provides a means of modelling the range of fire behaviour (Finney 1998; Scott and Reinhardt 2001). Many important factors that affect crown fire are not included (Werth *et al.* 2011). It is especially important for a user to be aware of model limitations in predicting extreme fire behaviour (Cruz and Alexander 2010).

The model for crown fire rate of spread is a simple correlation based on seven crown fires (Rothermel 1991). The inputs are only 20-ft wind speed and surface fuel moisture. The model does not utilise a description of either the surface or the crown fuels. It was designed to predict an average crown fire spread rate over several hours. Due to the nature of the model, spotting is included as a mechanism of spread. BehavePlus does not include a reduction to spread rate based on crown fraction burned as does

Table 2. Mathematical models that are included in each of the BehavePlus modules

Module	Model	Reference
SURFACE	Surface head fire rate of spread, reaction intensity, characteristic dead fuel moisture, live fuel moisture of extinction, etc.	Rothermel (1972); Albini (1976*b*)
	Fireline intensity, flame length	Byram (1959); Albini (1976*a*)
	Surface fire flame residence time	Anderson (1969)
	Fire characteristics chart; relationship among rate of spread, heat per unit area, fireline intensity and flame length	Andrews and Rothermel (1982); Andrews *et al.* (2011)
	Direction of maximum spread	Finney (1998); Rothermel (1983)
	Spread in direction from ignition point of a point source fire	Andrews (1986)
	Effective wind speed	Albini (1976*a*)
	Wind adjustment factor	Albini and Baughman (1979); Baughman and Albini (1980); Rothermel (1983); Andrews (2012)
	Wind speed at 10 m adjusted to 20 ft	Turner and Lawson (1978); Lawson and Armitage (2008)
	13 standard fire behaviour fuel models	Rothermel (1972); Albini (1976*a*); Anderson (1982)
	40 standard fire behaviour fuel models	Scott and Burgan (2005)
	Custom fire behaviour fuel models	Burgan (1987); Burgan and Rothermel (1984)
	Dynamic fuel load transfer	Burgan (1979); Andrews (1986), Burgan and Rothermel (1984); Scott and Burgan (2005)
	Two fuel models, weighted rate of spread	Rothermel (1983)
	Two fuel models, harmonic mean	Fujioka (1985)
	Two fuel models, two-dimensional expected spread	Finney (2003)
	Palmetto-gallberry special case fuel model	Hough and Albini (1978)
	Western aspen special case fuel model	Brown and Simmerman (1986); Brown and Debyle (1987)
CROWN	Critical surface intensity needed for transition from surface to crown fire	Van Wagner (1977)
	Transition to crown fire, relationship of surface fire intensity and critical surface fire intensity	Van Wagner (1989; 1993); Finney (1998); Scott and Reinhardt (2001)
	Crown fire rate of spread, area and perimeter	Rothermel (1991)
	Critical crown fire rate of spread, needed for an active crown fire	Van Wagner (1977)
	Active crown fire condition	Van Wagner (1989, 1993); Finney (1998); Scott and Reinhardt (2001)
	Fire type: surface, torching, conditional crown or crowning	Van Wagner (1993); Finney (1998); Scott and Reinhardt (2001)
	Crown fire flame length	Thomas (1963)
	Crown fire intensity	Rothermel (1991)
	Power of the fire, power of the wind	Byram (1959); Rothermel (1991)
SAFETY	Safety zone size, separation distance, radius	Butler and Cohen (1996, 1998*a*, 1998*b*)
SIZE	Elliptical fire size and shape, area, perimeter, length-to-width ratio	Anderson (1983); Andrews (1986)
CONTAIN	Fire containment	Albini *et al.* (1978); Fried and Fried (1996)
SPOT	Spotting distance from torching trees	Albini (1979); Chase (1981)
	Spotting distance from a burning pile	Albini (1981)
	Spotting distance from a wind-driven surface fire	Albini (1983*a*, 1983*b*); Chase (1984); Morris (1987)
SCORCH	Crown scorch height	Van Wagner (1973)
MORTALITY	Tree mortality	Ryan and Reinhardt (1988); Ryan and Amman (1994); Reinhardt and Crookston (2003); Hood *et al.* (2007)
	Bark thickness	Ryan and Reinhardt (1988); Reinhardt and Crookston (2003); Lutes (2012)
IGNITE	Probability of ignition from firebrand	Schroeder (1969)
	Probability of ignition from lightning	Latham and Schlieter (1989)
Fine Dead Fuel Moisture Tool	Fine dead fuel moisture tables	Rothermel (1983)

FARSITE, which includes spotting as a separate influence in fire growth modelling (Van Wagner 1993; Finney 1998; Scott and Reinhardt 2001).

As defined by Rothermel (1991), crown fire flame length is calculated using Thomas' (1963) model. Flame length is a function of crown fireline intensity, which is computed using the same basic model that is used for surface fire (Byram 1959). Crown fireline intensity is found from crown fire rate of spread and heat per unit area from both crown and surface fuels. Whereas the contribution of surface fuels can be taken from the SURFACE module, BehavePlus also allows direct input from a table prepared by Rothermel (1991) using a Albini's (1976*b*) burnout model to account for heavy fuel.

Rothermel (1991) used Byram's (1959) relationships to model power of the fire and power of the wind. The power ratio (P_R) is an indication of whether the fire might be wind driven

($P_R < 1$) or plume-dominated ($P_R > 1$). Given the many influencing factors and unknowns in crown fire behaviour, the results are not to be taken as predictions. Rather these calculations are useful in encouraging a person to consider the possibility of extreme fire behaviour under low-wind conditions.

Critical surface fireline intensity is the value required for a surface fire to transition to crown fire (Van Wagner 1977). Surface fireline intensity is either calculated using the models in the BehavePlus SURFACE module or directly specified by the user. In addition to a binary indication of transition (yes or no), the ratio of surface fireline intensity to critical surface fireline intensity (transition ratio, T_R) quantifies the relationship. Although the magnitude of the dimensionless value has no specific interpretation, a value close to one indicates the need for more care in interpretation of results. The critical crown fire rate of spread is the rate at which a crown fire must spread to maintain itself as an active crown fire (Van Wagner 1977). Similar to T_R, active ratio (A_R) is the ratio of crown fire rate of spread to critical crown fire rate of spread.

Fire type is based on the results of modelling conditions for transition to crown fire (T_R) and for active crown fire (A_R). A fire is categorised as 'surface' if $T_R < 1$ and $A_R < 1$; the fire is expected not to transition from surface to crown, and if it does it would not sustain as an active crown fire. The fire is 'torching' or 'passive crown' if $T_R > 1$ and $A_R < 1$; the fire makes the transition to crown fire but cannot spread as an active crown fire. The fire is 'crowning' or 'active crown' if $T_R > 1$ and $A_R > 1$; the fire makes the transition to crown fire and can spread as an active crown fire. The fire is labelled 'conditional crown' if $T_R < 1$ and $A_R > 1$; the model indicates that the fire will not transition to crown, but if it does, it could spread as an active crown fire.

Spotting distance

The SPOT module includes models for maximum spotting distance from torching trees (Albini 1979; Chase 1981), burning piles (Albini 1981) and wind-driven surface fires (Albini 1983*a*, 1983*b*; Chase 1984; Morris 1987). In each case, the lofting height of potential firebrands is found from the flame structure. The ambient wind then carries the firebrand, which is assumed to be a wood cylinder. Model predictions are for maximum spotting distance based on the assumption that firebrands are sufficiently small to be carried some distance, yet large enough to start a fire when they reach the ground.

Spotting distance from torching trees applies to passive crowning, either a single tree or a group of trees torching together if they produce one flame. Characteristics of a transitory flame are calculated from the tree description. Flame length of a wind-driven surface fire can either be entered directly or calculated in the SURFACE module. The model is applicable only for a head fire in surface fuels that are not sheltered by overstorey. The user must specify a value for the continuous flame height from a burning pile, determined by expert opinion. It is appropriate to use BehavePlus to examine a range of possible flame heights.

Neither the number nor size of firebrands that might be produced is modelled. The models predict intermediate-range spotting, which occurs when live embers land far enough from the main fire to ignite fuels and grow as independent fires. They are not valid for short-range spotting such as debris blowing just across a fire line or for spotting resulting from large firebrands carried into the combustion column.

Probability of ignition

The IGNITE module includes models for probability of ignition from a firebrand (Schroeder 1969) and from lightning (Latham and Schlieter 1989). The model for probability of ignition from a firebrand is based on an experiment in which matches were dropped on pine needles. The calculation uses fine dead fuel moisture, air temperature and fuel shading from the sun. This calculation is often done in conjunction with the SPOT module for distance that a firebrand might travel and the SIZE module for the area of the fire after it has been spreading for a specified time.

The model for probability of ignition from cloud-to-ground lightning flashes is based on laboratory experiments using different fuel types (litter, duff, etc.). Other inputs include depth of the litter and duff layer, fuel moisture and lightning discharge type (negative, positive or unknown).

Safety zone

The SAFETY module is based on a model for minimum separation distance between the fire and a person as a function of flame height (Butler and Cohen 1996, 1998*a*, 1998*b*). The model is based on radiant heating only. Convective energy transport in the form of gusts, fire whirls or turbulence is not included. A safety zone is an area to which firefighters can retreat and not have to deploy fire shelters to remain safe. The size of a safety zone also considers the number of people and equipment to be protected. Flame length calculated in the SURFACE module can be used as a worst case estimate of flame height, or the user can specify a value for flame height.

Crown scorch

The SCORCH module includes a model for the height above the ground that the temperature in a convection column reaches lethal temperature (60°C) to kill live crown foliage (Van Wagner 1973). The relationship between fire behaviour and crown scorch height was derived from measurements on 13 outdoor experimental fires. Calculations are based on fireline intensity and also include the influence of air temperature and of wind on flame tilt. Fireline intensity as calculated in the SURFACE module can be used, or the user can enter a value based on field observation or on another model.

Tree mortality

The MORTALITY module includes models for probability of mortality, the likelihood that a tree will be killed by a fire as a result of crown scorch and cambium damage from surface fire flames. There is no consideration of root damage due to ground fire. The models are statistical, based on field data. The mortality equations (listed in the BehavePlus help system) variously include bark thickness, tree crown length scorched and tree crown volume scorched (Ryan and Reinhardt 1988; Ryan and Amman 1994; Reinhardt and Crookston 2003; Hood *et al.* 2007). BehavePlus includes the pre-fire, but not the post-fire, mortality models that are in FOFEM (Reinhardt 2003; Lutes 2012). A mortality model is also available for the special case western aspen fuel model the SURFACE module (Brown and Debyle 1987).

Size of a point source fire

The SIZE module is used to calculate the size and shape of a fire burning from a point source ignition based on elliptical shape, with length-to-width ratio a function of effective midflame wind speed. The initial BEHAVE system used a double ellipse model (Anderson 1983). A simple ellipse model was used in later versions of BEHAVE and in BehavePlus to meet the requirements of the fire containment model (Andrews 1986). The ignition point is the focus of the ellipse. Backing spread distance, maximum width of the fire and perimeter are determined by the ellipse equations. The user can specify effective wind speed and forward rate of spread, or those values can come from the SURFACE module. A slightly different simple ellipse model is in the CROWN module for area and perimeter of a crown fire (Rothermel 1991).

Containment

A model for fire containment in the CONTAIN module of BehavePlus (Fried and Fried 1996) replaced a simpler model in BEHAVE (Albini *et al.* 1978; Albini and Chase 1980). The model estimates fire suppression resources necessary for containment of a fire growing from a point source. Multiple resources with various arrival times can be defined. The fire spread rate, shape and size at attack can either be user input or calculated by the SURFACE and SIZE modules.

The shape of the free-burning point source fire is assumed to be that of an ellipse, with rate of spread constant over the time that line construction occurs. The rate of line construction is constant and work takes place simultaneously on both sides of the fire at an equal pace. Therefore, the specified line construction rate is split into two equal parts starting at the point of attack, either at the head or the rear (see Fig. 4). Suppression forces are assumed to be 100% effective; the fire will never breach the control line.

Technology transfer, training and support

The BehavePlus program and supporting material is available at http://www.firemodels.org (accessed 8 July 2013). In addition to providing papers written specifically about BehavePlus, the website includes many of the publications referenced in this paper, some of which are government reports not easily found elsewhere. A set of self-study lessons address program operation and model understanding. Although aspects of BehavePlus are included in courses and some local efforts have resulted in BehavePlus workshops, there is not a formal BehavePlus course.

As the sponsor, the US Forest Service provides access to a Help desk for questions about program operation. The developers are available as second level support, providing program bug fixes. However, there is not a help desk for fire modelling or application questions.

Future needs

Although BehavePlus is an established tool for many fire and fuels management applications and is useful for a range of research analysis applications, it is time for major update. Although the fire modelling capabilities of BehavePlus should be improved and expanded, it is increasingly hard to add or change models in the current framework, which was put in place over 15 years ago (Andrews and Bevins 1998). The approach to an update is not merely a redesign of the current program, but a rebuild of the code from the bottom up to facilitate integration of fire behaviour, fire effects and fire danger rating systems, as well as point and spatial systems. Effective testing, evaluation, documentation and technology transfer are an integral part of an update.

Expanded fire modelling scope

Although BehavePlus provides a means of modelling many aspects of wildland fire (see Fig. 1, Table 1), deficiencies would be addressed by incorporating new or improved models. For example, it would be worthwhile to add the large fuel burnout model which is currently in FARSITE and FOFEM, to model post-frontal combustion for fuel consumption and smoke production and to characterise intensity of more than the flaming front for modelling scorch height and transition to crown fire (Albini and Reinhardt 1995; Finney *et al.* 2003).

A multitude of models have been developed to describe various aspects of wildland fire (Pastor *et al.* 2003). Ongoing research efforts worldwide are aimed at improvements. For example, the empirical tree mortality models may someday be replaced by physically based models (Butler and Dickinson 2010). Sullivan (2009*a*, 2009*b*) reviewed 39 models for surface fire spread developed from 1990 to 2007, and Alexander and Cruz (2012) list 20 fireline intensity–flame length relationships. Although research users may benefit from access to multiple models, fire managers will appreciate recommended models and methods. Replacing a mathematical model that is currently in BehavePlus is not just a matter of modifying computer code. Changes could have significant fire management implications. For example, approved land management plans and fire prescriptions that are based on acceptable or desired flame length would be affected by a changed model that gives different results for the same conditions. The effect of additions and changes on fire managers' workload is an important consideration in developing the next generation system.

Code block approach

Effective incorporation of new models and data into BehavePlus and improved integration of related systems requires a redesign of the coding structure. The approach will address inconsistencies in model implementation in existing systems (e.g. Scott and Reinhardt 2001; Andrews 2012) and will produce model code blocks that can be used by developers of collaborative systems such as BlueSky, which utilises a modular approach.

There will be several layers of code blocks, from the basic models (such as fine dead fuel moisture) to modules (such as crown fire behaviour) to comprehensive dynamic-link libraries (DLLs) (such as fire growth simulation). A code block library will include documentation and means of update.

Design and features

The model code blocks will be separate from the user interface, allowing for various platforms, from web to handheld.

A redesign will integrate what are now separate systems, resolving differences in the approach to user interface.

An update should retain positive aspects of the BehavePlus design, while addressing its limitations. BehavePlus' dynamic worksheets that are based on user selections provide modelling flexibility not possible with static worksheets (like the old BEHAVE). Context-sensitive help is a useful feature to be retained and improved upon. In addition to the current interactive input, a batch version would allow a multitude of calculations. Input data could come from other systems, such as fuel moisture calculated in FireFamilyPlus (Bradshaw and McCormick 2000).

It is valid to retain the focus of a point modelling system that produces tables, graphs and simple diagrams. A useful expansion would be a time component to allow modelling of hourly changes for a site (Beck and Trevitt 1989; Beck *et al.* 2002). The Nelson (2000) fuel moisture model could be used in modelling changes throughout the day in flame length, scorch height, safety zone size and transition to crown fire. The relationship between point and spatial systems should be strengthened. Data from a pixel could be accessed to examine the effect of values assigned to fuel model or fuel moisture on resulting fire behaviour.

A redesign would address the challenge of satisfying users who want a quick and easy way to model fire as well as those who want features that support advanced analysis, without developing a separate system for each user group. Care must be taken to avoid 'black box' modelling and to avoid use of default values. Reliance on educated users will continue to be a recognised part of the modelling process.

Documentation and technology transfer

An update to BehavePlus and related systems will include comprehensive documentation of the science and application, as well as operation. Scientific publications will address model development, model coupling and validation results (Alexander and Cruz 2013). Validation includes scientific testing of individual models and also evaluation of linked models in the context of the application. Evaluation standards for an application that uses model results for ranking is different from one that requires specific predictions (Andrews and Queen 2001).

Because models are simplifications of reality, there will always be limitations to modelling wildland fire. The key is for users to be fully aware of the limitations and assumptions of the models they are using. There is a need for widely accessible training material on model foundation and application. Technology transfer of updated systems will include explanation of model changes, comparison of results and reasons for the change.

Summary

The BehavePlus Fire Modeling System has evolved through redesign and expansion of the BEHAVE Fire Behavior Prediction and Fuel Modeling System. BehavePlus is a flexible system that can be used in a simple manner for quick calculations, or the many features can be used for advanced fire modelling tasks. BehavePlus is used for a range of research and fire management applications.

There is a continued need for a point-based system with improved linkages to spatial modelling systems. The gaps, overlaps and inconsistencies in fire modelling capabilities, as well as the different user interfaces among the many available fire modelling systems, must be addressed. An update to BehavePlus will be based on an improved method of coding the mathematical models at its foundation and will be done in conjunction with an update to related systems.

Fire modelling systems will play an increasingly important role in wildland fire management. It is appropriate to learn from and build on successful systems such as BehavePlus in moving to the next generation.

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