Canadian Forest Fire Behavior Prediction (FBP) System: user's guide

K.G. Hirsch

Special Report 7

Natural Resources Canada / Ressources naturelles Canada
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Canada

The Canadian Forest Service's Northwest Region is responsible for fulfilling the federal role in forestry research, regional development, and technology transfer in Alberta, Saskatchewan, Manitoba, and the Northwest Territories. The main objectives are research and regional development in support of improved forest management for the economic, social, and environmental benefit of all Canadians. The Northwest Region also has responsibility for the implementation of federal–provincial forestry agreements within its three provinces and territory.

Regional activities are directed from the Northern Forestry Centre in Edmonton, Alberta, and there are district offices in Prince Albert, Saskatchewan, and Winnipeg, Manitoba. The Northwest Region is one of six regions and two national forestry institutes of the Canadian Forest Service, which has its headquarters in Ottawa, Ontario.

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Abstract

The Canadian Forest Fire Behavior Prediction (FBP) System provides a systematic method of assessing fire behavior. The FBP System has 14 primary inputs that can be divided into 5 general categories: fuels, weather, topography, foliar moisture content, and type and duration of prediction. In the FBP System these inputs are used to mathematically develop 4 primary and 11 secondary outputs. Primary outputs are generally based on a fire intensity equation, and secondary outputs are calculated using a simple elliptical fire growth model. This publication provides diagrams, examples, and exercises that explain the FBP System in a user-oriented manner. This guide delineates the interpretation of the FBP System's inputs and outputs and details how the predictions are derived.

Résumé

La méthode canadienne de prévision du comportement de incidies de forêt (PCI) est une méthode systématique d'évaluation du comportement des incendies. La méthode PCI comporte 14 entrées, en 5 catégories : les combustibles, la météorologie, la topographie, l'humidité des feuilles, et la sorte et la durée de la prévision. Ces 14 entrées servent à développer mathématiquement 4 sorties primaires et 11 sorties secondaires. Les sorties primaires sont basés sur une équation décrivant l'intensité de l'incendie, et les sorties secondaires sont calculés selon un model simple de croissance élliptique de l'incendie. Cette publication donne des diagrammes, des examples, et des exercises expliquant la méthode PCI de façon abordable. Ce guide indique l'interprétation des entrées et sorties de la méthode PCI, et explique la dérivation des prévisions.

Preface

The Canadian Forest Fire Behavior Prediction (FBP) System provides a systematic method for assessing fire behavior. It is a complex system that mathematically expresses and integrates many of the major factors that are known to influence fire behavior and can therefore assist to fire managers in a wide range of decision-making processes. The FBP System was developed over a period of 10–15 years; however, it is linked to concepts dating back to the beginnings of forest fire research in Canada in the 1920s. The FBP System was developed by a group of Canadian Forest Service (CFS) fire researchers, namely B.J. Stocks and T.J. Lynham (Great Lakes Forestry Centre), M.E. Alexander (Northern Forestry Centre), B.D. Lawson (Pacific Forestry Centre), and R.S. McAlpine (formerly of the Petawawa National Forestry Institute). C.E. Van Wagner (retired–Petawawa National Forestry Institute) also made major contributions to many of the mathematical and physical models in the system.

Traditionally the members of the CFS fire research community have emphasized and participated in a variety of technology transfer activities to assist in the dissemination and application of new research. Upon completion of the FBP System, four multi-day workshops were conducted in various regions of Canada to introduce the system to key operational fire management personnel and training officers. After these sessions, it became apparent that a broader technology transfer effort would be required.

This publication is meant to advance the technology transfer process by providing a user-oriented guide to the FBP System. Its primary purpose is to assist fire managers with the interpretation of the FBP System's inputs and outputs, and to foster a greater understanding of how the predictions are derived. This document provides numerous diagrams, examples, and exercises that explore, illustrate, and explain the scientific information presented in the FBP System technical report (Forestry Canada Fire Danger Group 1992). This user's guide was designed for use on an individual basis or in a classroom situation. It is based on and should be used in conjunction with other publications related to the FBP System and the Canadian Forest Fire Danger Rating System.

The prediction of fire behavior is often referred to as both an art and a science. It requires not only an understanding of the basic principles of fire behavior but also depends on an individual's experience and their ability to cope with distinct and unusual situations. Fire behavior is an extremely complex process that is affected by a large number of variables, and it is unlikely that any model could realistically account for all of these influential factors and their interactions. Therefore, the best possible fire behavior predictions will be those that consider the systematically calculated values of the FBP System in combination with the opinions and assessments of experienced fire management personnel.

To conclude, special thanks are extended to Bruce Lawson, Brad Hawkes, Steve Taylor, Rob Thorburn, Tim Lynham, and Rob McAlpine for their insightful review comments; to Bryan Lee and Dennis Dube for their support of this project; to Dennis Lee for his exceptional layout and graphics work; and to Brenda Laishley for her editorial advice. The technical assistance, support, and encouragement of all of the CFS fire researchers who developed the FBP System also is gratefully acknowledged.

Kelvin G. Hirsch

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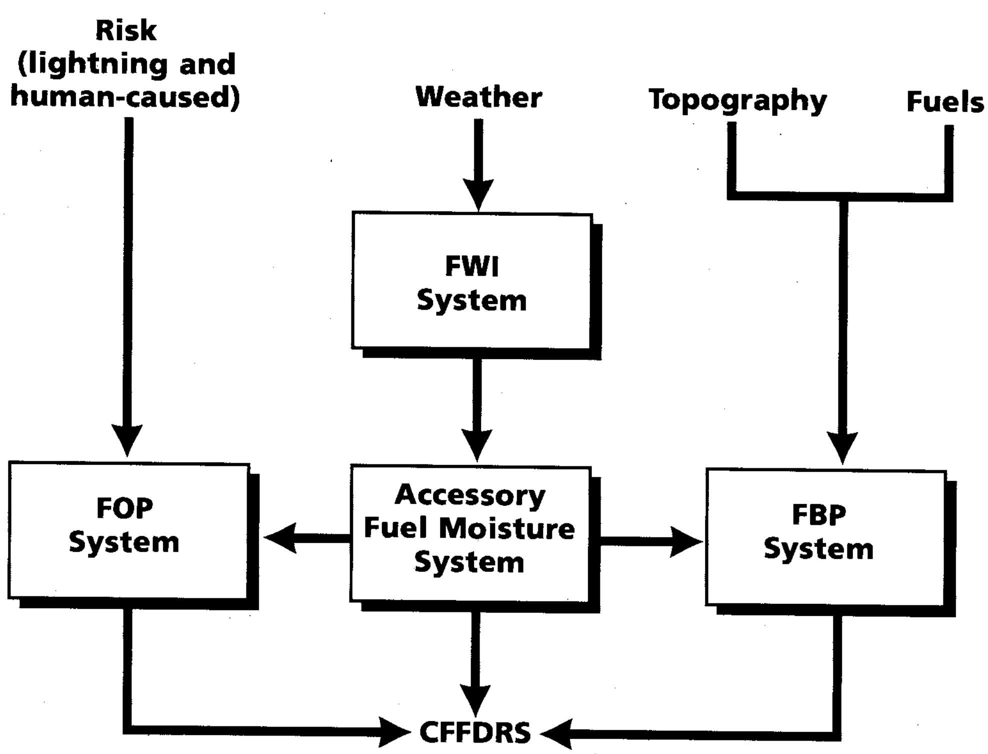
1.0 Background

1.1 Structure of the Canadian Forest Fire Danger Rating System

Development of the Canadian Forest Fire Danger Rating System (CFFDRS) began in 1968 when a modular approach to a national system for fire danger rating was conceived. The Canadian Forest Fire Weather Index (FWI) System was the first subsystem to be completed. It was implemented by operational fire management agencies in Canada in the early 1970s. The Canadian Forest Fire Behavior Prediction (FBP) System, which was released in an interim form in 1984, is the second subsystem to be completed. Currently the other two modules, the Canadian Forest Fire Occurrence Prediction (FOP) System and the Accessory Fuel Moisture System are incomplete; however, there are some regional occurrence prediction systems in use and research is continuing on various elements of the Accessory Fuel Moisture System (Fig. 1).



FWI = Canadian Forest Fire Weather Index System.
FBP = Canadian Forest Fire Behavior Prediction System.
FOP = Canadian Forest Fire Occurrence Prediction System.
CFFDRS = Canadian Forest Fire Danger Rating System.

Figure 1. Structure of the Canadian Forest Fire Danger Rating System.

1.2 Comparison of the FWI System and the FBP System

The FWI System and the FBP System provide fire management agencies in Canada with significantly different types of information. These differences are illustrated in the definitions for each system.

FWI System

This system provides numerical ratings of **relative** fire potential in a **standard** fuel type (i.e., a mature pine stand) on **level** terrain, based solely on consecutive observations of four fire-weather elements (temperature, relative humidity, wind speed, and precipitation) measured daily at **noon** local standard time (LST) or 1300 local daylight time (LDT).

FBP System

This system provides **quantitative** outputs of selected fire behavior characteristics for certain major Canadian **fuel types** and **topographic** situations. It is based partly on the FWI System and **hourly** fire weather observations.

Example:

Case	ISI[a]	ROS[b] (m/min)
1	8	10
2	15	22

[a] ISI = Initial Spread Index.
[b] ROS = Rate of spread in the Boreal Spruce (C-2) fuel type on level ground

Explanation: using the Initial Spread Index (ISI) component of the FWI System, and assuming that the fuel and topographic features are the same for both of the above cases, the rate of fire spread in Case 2 will be faster than in Case 1; however, it is not possible to state how much faster. If the same comparison is made using the rate of spread (ROS) component of the FBP System, it is clear that the fire in Case 2 is 12 m/min faster than the fire in Case 1. Thus, the FBP System provides information that is quantitative and specific while the FWI System produces relative and general information.

Familiarization with the FWI System is recommended prior to using the FBP System.

1.3 Structure of the FBP System

The FBP System has 14 primary inputs that can be divided into 5 general categories: fuels, weather, topography, foliar moisture content, and type and duration of prediction. In the FBP System these inputs are used to mathematically develop 4 primary and 11 secondary outputs (Fig. 2). Primary outputs are generally based on the fire intensity equation (see Section 4.1) developed by Byram (1959), and secondary outputs are calculated using a simple elliptical fire growth model.

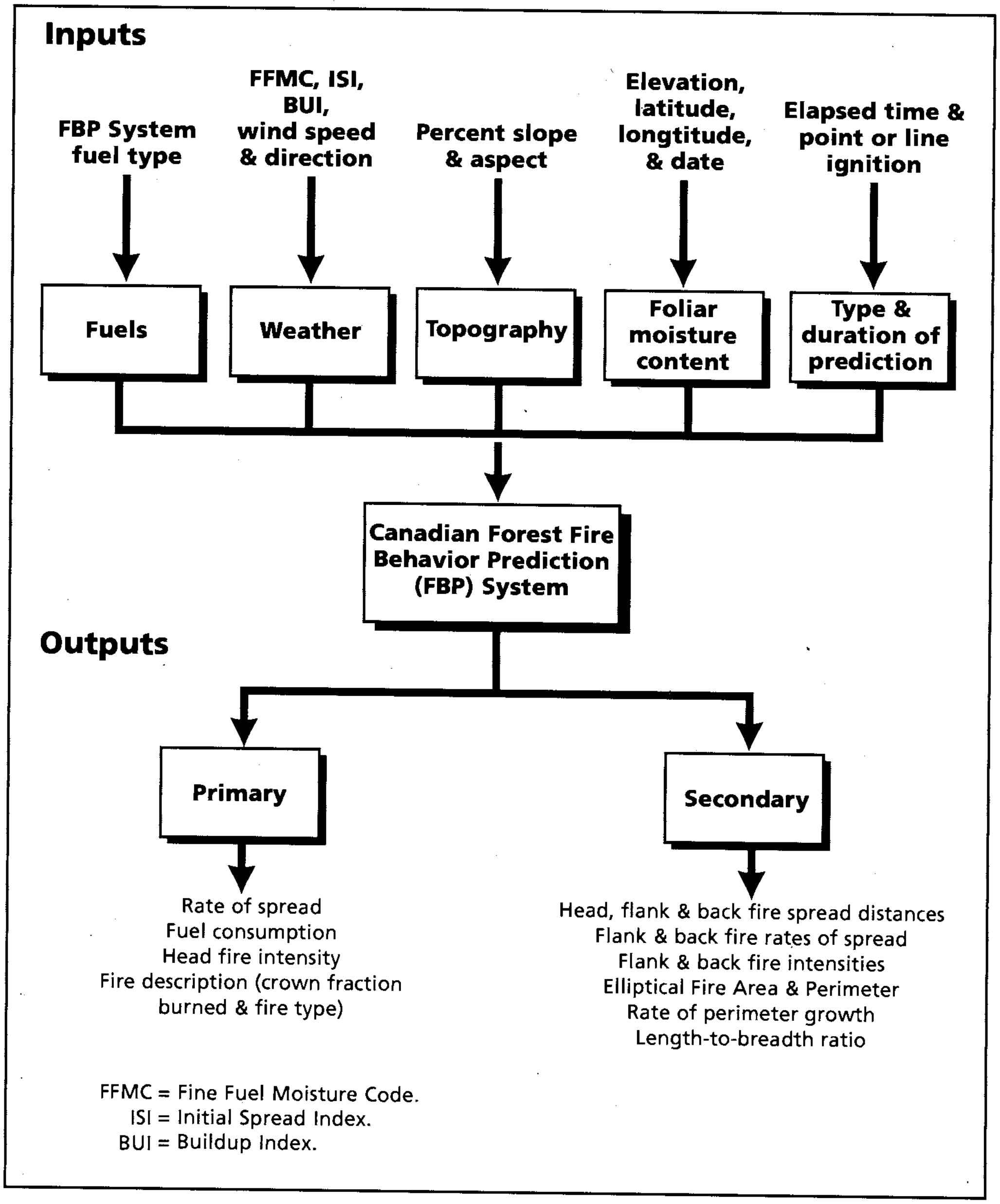


Figure 2. Structure of the Canadian Forest Fire Behavior Prediction (FBP) System.

1.4 Inputs and Outputs: General Characteristics

Inputs:

Fuel Type

The FBP System has 16 general fuel types (including 7 coniferous, 1 deciduous, 4 mixedwood, 3 slash, and 1 open or grass type), which represent many, but not all, of the major fuel types found in Canada.

Weather

The FBP System uses the Fine Fuel Moisture Code (FFMC), the Initial Spread Index (ISI), and the Buildup Index (BUI) from the FWI System. These indexes are considered weather inputs because they are calculated from observations of temperature, relative humidity (RH), wind speed, and precipitation. The FBP System can also use detailed (e.g., hourly) observations or forecasts of wind speed and wind direction.

Topography

Percent slope and aspect (i.e., slope direction) are necessary inputs when the influence of topography on fire behavior is to be considered.

Foliar Moisture Content

The percent foliar moisture content (FMC) is computed using the latitude (°N), longitude (°W), elevation (m) above mean sea level (MSL), and the date. The FMC influences calculations relating to crown fire involvement and is only computed for coniferous and mixedwood fuel types. It also influences the crown fire rate of spread model in the Conifer Plantation (C-6) fuel type.

Type and Duration of Prediction

The FBP System allows for two different types of fire behavior predictions depending on whether or not the fire has reached its equilibrium rate of spread. A point source prediction is used for a fire that is in its early stages of fire growth and is still accelerating. A prediction for a line ignition fire is used when a fire has already reached its steady-state rate of spread. For example, a point source prediction would be used for a fire started from a lightning strike, match, or campfire, while a line ignition prediction would be used when a wind shift occurs on a large fire causing the flank fire to become the head fire.

Duration of the prediction or the elapsed time (in minutes) determines the degree of impact the acceleration effect has on point ignition fires. It is also necessary for the calculation of many of the secondary outputs.

Outputs:

Primary

Three of the four primary outputs relate directly to Byram's fire intensity equation. They are rate of spread (m/min), fuel consumption (kg/m^2), and head fire intensity (kW/m). The fourth primary output, fire description, has three categories: surface fire, intermittent crown fire, and continuous crown fire. They are defined by the degree of crown involvement or crown fraction burned (CFB).

Secondary

The 11 secondary outputs follow the assumption that a fire will grow in an elliptical shape if conditions remain constant. The secondary outputs and their units are as follows:

- head, flank, and back fire spread distances (m),
- flank and back fire rates of spread (m/min),
- flank and back fire intensities (kW/m),
- elliptical fire area (ha),
- elliptical fire perimeter (m),
- rate of perimeter growth (m/min), and
- length-to-breadth ratio.

1.5 Major Calculation Procedures

To produce a fire behavior prediction, the FBP System uses a variety of theoretical and empirical modeling techniques. Understanding why and how a specific calculation is made is crucial to the effective use of the FBP System. A summary of the major calculation procedures is given below with more detail provided in subsequent sections.

Hourly FFMC and ISI

The hourly or adjusted FFMC and ISI can be calculated using three methods, each requiring different types and amounts of information.

Rate of Spread (ROS)

The ROS is based on the hourly ISI value and can be adjusted for the steepness of a slope, the interaction between slope direction and wind direction, and increasing fuel availability as accounted for through the BUI.

Fuel Consumption

The fuel consumption calculation includes both surface (i.e., down woody and forest floor) fuel consumption and crown fuel consumption. Surface fuel consumption is based on the BUI for most fuel types, and crown fuel consumption is dependent on the crown fuel load and the degree of crown involvement.

Crown Fire Initiation

The FBP System uses Van Wagner's crown fire theory to determine whether the crown fuel layer of a given coniferous or mixedwood stand will become involved in the fire. The theory states that there is a minimum or critical surface fire intensity value that must be exceeded for crowning to occur.

Fire Intensity

The FBP System predictions of fire intensity are modeled according to Byram's fire intensity equation.

Elliptical Fire Growth Model

A simple elliptical fire growth model is used to calculate most of the secondary components.

Acceleration of Point Source Fires

An acceleration period has been incorporated into fire growth projections for point source ignition fires to account for the time it takes point ignition fires to reach their equilibrium rate of spread. Note that the FBP System has separate approaches for open- and closed-canopy fuel types.

Back Fire Rate of Spread

Back fire ROS is calculated from the wind speed and the head fire ROS.

Grass Fuels Rate of Spread

The ROS in open, grass fuels is dependent on the degree of curing but not on fuel load. Fuel load does, however, influence the amount of fuel consumption and therefore the fire intensity.

Conifer Plantation Fuel Type

Certain fire behavior characteristics, especially rate of spread, are modeled differently for the Conifer Plantation (C-6) fuel type than other fuel types in the FBP System.

2.0 Data in the FBP System: Types, Collection Procedures, and Analytical Techniques

2.1 Characteristics of the FBP System

The FBP System is primarily empirical in nature; many of the relationships within the system are based on observations of actual fire behavior. A total of 495 fires are included in the FBP System data base, of which 409 are experimental fires and 86 are well-documented wildfires. Experimental fires are generally small (0.3–3.0 ha in size), intensively sampled by a team of fire researchers and are usually conducted under low-to-moderate fire danger conditions. On the other hand, wildfires in the FBP System data base are usually large, high intensity fires that have made major fire runs. Wildfires are never sampled as intensively as experimental fires; however, they do provide valuable information about many aspects of extreme fire behavior.

Table 1. Type and number of fires in the FBP System data base and the number of data points used in both the rate of spread and fuel consumption analysis

Fuel type	No. fires in data base			No. fires analyzed[a]	
	Experi-mental	Wild-fires[b]	Total	ROS[c]	FC[d]
(C–1) Spruce–Lichen Woodland	7	1	8	8	7
(C–2) Boreal Spruce	18	30	48	48	13
(C–3) Mature Jack or Lodgepole Pine	41	22	63	63	41
(C–4) Immature Jack or Lodgepole Pine	15	20	35	35	15
(C–5) Red and White Pine	19	1	20	20	10
(C–6) Conifer Plantation	12	0	12	12	11
(C–7) Ponderosa Pine/Douglas-fir	8	5	13	13	3
(D–1) Leafless Aspen	32	3	35	35	26
(M–1) Boreal Mixedwood—Leafless	—[e]	—	—	—	—
(M–2) Boreal Mixedwood—Green	—	—	—	—	—
(M–3) Dead Balsam Fir/ Mixedwood—Leafless	5	0	5	5	5
(M–4) Dead Balsam Fir/ Mixedwood—Green	1	0	1	1	1
(S–1) Jack or Lodgepole Pine Slash	48	11	59	53	56
(S–2) Spruce/Balsam Slash	49	21	70	52	68
(S–3) Coastal Cedar/Hemlock/ Douglas-fir Slash	28	5	33	16	33
(O–1a) Matted Grass[f]	52	6	58	58	—[g]
(O–1b) Standing Grass[f]	74	—[g]	74	74	—[g]
Total	409	125	534[h]	493	289

[a] In the standing fuel types, the number of fires analyzed for rate of spread is generally higher than the number analyzed for fuel consumption because fuel consumption data is very difficult to collect on wildfires.

[b] The wildfire category also includes a few well-documented operational prescribed burns conducted in the slash fuel types.

[c] ROS = rate of spread.

[d] FC = fuel consumption.

[e] The M-1 and M-2 fuel types are derived mathematically from the equations for C-2 and D-1.

[f] The O-1a and O-1b fuel types are based on Australian grass fire data that was analyzed by the Canadian Forest Service.

[g] No data available.

[h] A total of 39 wildfire observations were used in more than one fuel type (mostly in C-2, C-3, and C-4) because a combination of these fuel types were consumed during the major wildfire runs.

2.2 General Locations of the Fires Used in the FBP System Data Base

The FBP System data base consists of 345 fires from across Canada as well as 18 fires from 6 areas in the northern U.S.A. and 132 Australian grass fires. Figure 3 shows the general locations of the experimental burns and documented wildfires in Canada. To date, the data collection in some provinces has been minimal, however, the FBP System is still considered applicable on a national basis.

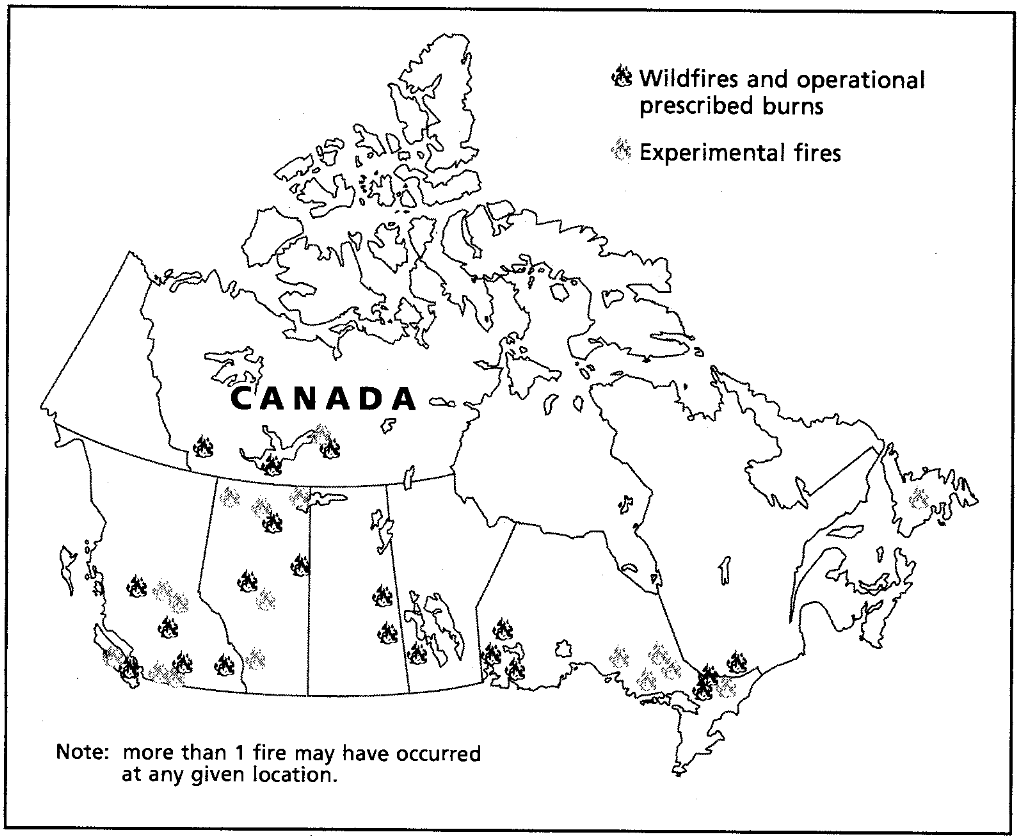


Figure 3. General location of fires in the Canadian Forest Fire Behavior Prediction (FBP) System data base.

2.3 Type of Data Collected on Experimental Fires

A large number of factors can influence fire behavior. Experimental fires are conducted to ensure as many of these factors as possible can be studied under natural conditions. Two types of experimental fires can be ignited, namely point and line ignition fires. A point ignition fire is started with a single match and simulates a wildfire that is accelerating towards its equilibrium rate of spread. A line ignition fire is ignited along an entire edge of the plot and represents a wildfire that has already reached its equilibrium rate of spread. Regardless of which type of experimental burn is conducted, detailed information about the fire environment and the fire behavior is collected, and a listing of this data is provided below.

Fuels Data

- Tree height and diameter, stand density, and species composition
- Amount of dead and down woody material
- Depth, bulk density, and organic content of the duff layers
- Type and amount of surface vegetation (herbs and shrubs)
- Height to, amount, and density of the crown fuel layer
- Moisture content (immediately prior to ignition) of significant fire carrying fuels such as mosses, tree lichen, conifer needles, and selected surface fuels.

Weather Data

- Prior to the day of the fire

  Observations of temperature, relative humidity (RH), wind speed, wind direction, and precipitation are made daily at 1300 h (LDT) at a weather station located at the burn site.

- On the day of the fire

  Hourly readings of temperature, RH, wind speed, wind direction, and precipitation.

- Immediately prior to and after the fire

  Observations of temperature, RH, and cloud cover are taken.

- During the fire

  Wind speed and direction observations are made. Observations of the 10-m open wind are taken every 1 or 10 minutes while in-stand winds (measured at 1.2 m immediately adjacent to the burn plot) are taken every minute.

Topographic Data

- Slope (%) and aspect (degrees). Note that most experimental burning plots are usually established on level sites to eliminate any influence that slope might have on the fire behavior.

Fire Behavior Data

- Head fire rate of spread
- Flank and back fire spread rates (on point ignition fires)
- Fuel consumption, which is determined by measuring:
  - depth of burn of the litter and forest floor (duff),
  - crown scorch height, and
  - the decrease in the loading of dead and down woody material.
- Visual estimates and photographic documentation of fire behavior characteristics (e.g., flame length, flame height, and degree of crown involvement).

2.4 Types of Data Collected on Wildfires

Wildfire documentation provides the FBP System with important information about extreme fire behavior that cannot be obtained from experimental burning projects (because experimental fires are not usually ignited when extreme fire danger conditions exist). Invaluable observations of key fire behavior characteristics are often made on wildfires by operational fire suppression personnel. These observations are then provided to fire researchers who will collect the other necessary information (e.g., topography, weather, etc.) from available data sources. If information about wildfire behavior has been recorded, please contact the Canadian Forest Service office in your region. There is no standard approach for documenting wildfires; however, Table 2 does list the types of information that can be readily collected and some techniques for acquiring such data.

Table 2. Wildfire data and collection techniques

Type of information	Collection technique
Head fire rate of spread	Record the location of the fire's head on a map, or with a photograph, along with the time of the observation.
Fire shape (length-to-breadth ratio)	Record the position of the flank fire and back fire (in relation to the head fire, if possible) on a map, or with a photograph, along with the time of the observation.
Fire behavior characteristics	Make observations of various characteristics and when they occurred. For example: ■ type of fire (surface, intermittent crown, continuous crown), ■ percentage of crown involvement, ■ smoke column characteristics (height, angle, color, wind driven vs. convective), ■ spotting distances, ■ flame length and flame height, ■ fire whirl development, ■ suppression effectiveness, and ■ post-fire observations of depth of burn, fuel consumption, presence of "tree-crown streets".
Fire weather observations	Fire weather observations should be made as close to the fire site as possible (e.g., at a base camp weather station). If this is not possible, measurements from a nearby station (which is representative of the conditions at the fire site) can be used if supported by estimated observations made on-site. Observations of wind speed and wind direction are the most critical during major fire runs and should be made hourly or when major changes occur. If possible, hourly temperature, RH, and precipitation observations should also be made.
Fuel type and topography	Changes in fuel type and topography that significantly affect fire behavior should be noted. This information often can be obtained from maps and field inspections after the fire has occurred.

Note: observations often can be made using common landmarks such as roads, streams, lakes, or changes in fuel types. Recording the time of changes in fire behavior (e.g., a shift in spread direction, a significant increase or decrease in rate of spread, etc.) is extremely valuable.

2.5 Analysis and Modeling Techniques

The general analysis and modeling approach used in the FBP System consists of four steps.

(1) Data is collected on experimental fires and wildfires,

(2) Data analysis is conducted using simple mathematical models and correlation techniques,

(3) Laboratory-based fire research in moisture physics and heat transfer theory is used as a framework for explaining the results of the data analysis, and

(4) The physical theories of fire behavior are related to the actual data to ensure that the best and most logical predictions are provided by the FBP System.

> **The data analysis and resultant modeling is conducted jointly by a group of fire researchers allowing for a wide variety of inputs and opinions.**

3.0 Inputs

The FBP System has 14 primary inputs that can be placed into five general categories (Table 3). Each input can have a significant influence on the final accuracy and validity of the FBP System's outputs, therefore, a thorough understanding of the inputs and how they are derived is required.

Table 3. Inputs used in the FBP System

Category	Input
Fuels	One of 16 fuel types in the FBP System
Weather	Fine Fuel Moisture Code (FFMC) Initial Spread Index (ISI) Buildup Index (BUI) Wind speed (km/h) Wind direction (°)
Topography	Percent slope Aspect (°)
Foliar moisture content	Latitude (°N) Longitude (°W) Elevation (m) Date
Type and duration of prediction	Point or line ignition Elapsed time (min)

3.1 Fuel Types

The FBP System has 16 distinct fuel types that have been divided into five categories (Table 4). These fuel types represent most, but not all, of the major fuel complexes found in Canada. New fuel types will therefore be added to the system as data becomes available. The FBP System fuel types are general in nature and are described primarily in qualitative rather than quantitative terms. A summary of the major features of each fuel type is provided in Table 5, and representative photos are presented in a poster by De Groot (1993).

Table 4. Fuel types in the FBP System

General category	Fuel type	
Coniferous	C-1	Spruce—Lichen Woodland
	C-2	Boreal Spruce
	C-3	Mature Jack or Lodgepole Pine
	C-4	Immature Jack or Lodgepole Pine
	C-5	Red and White Pine
	C-6	Conifer Plantation
	C-7	Ponderosa Pine/Douglas-fir
Deciduous	D-1	Leafless Aspen
Mixedwood	M-1	Boreal Mixedwood—Leafless
	M-2	Boreal Mixedwood—Green
	M-3	Dead Balsam Fir/Mixedwood—Leafless
	M-4	Dead Balsam Fir/Mixedwood—Green
Slash	S-1	Jack or Lodgepole Pine Slash
	S-2	Spruce/Balsam Slash
	S-3	Coastal Cedar/Hemlock/Douglas-fir Slash
Open	O-1a	Matted Grass
	O-1b	Standing Grass

Table 5. Major features of the FBP System fuel types

Type	Stand structure and composition	Forest floor	Organic layer	Surface fuels: Herbs and shrubs	Surface fuels: Understory conifer	Surface fuels: Dead and down fuels	Ladder fuels
C-1	Open stands of black spruce in dense clumps on well-drained upland sites. Jack pine and white birch can be present in small amounts.	Continuous reindeer lichens (mainly *Cladonia*) 3–4 cm in depth.	Shallow (0–5 cm) or absent; uncompacted.	Very sparse.	Not present.	Light and scattered.	Live and dead black spruce branches extending to the forest floor. Layering is extensive.
C-2	Moderately well-stocked black spruce stands on upland and lowland sites (excluding sphagnum bogs).	Continuous feather moss and reindeer lichen (usually *Cladonia*).	Compact and deep (often exceeding 20–30 cm).	Continuous. Labrador tea is often dominant.	Scattered in open stands. Absent in denser stands.	Low to moderate.	Tree crowns extending to or near the ground. Tree bark is flaky and arboreal lichens may be present on branches.
C-3	Fully stocked (1000–2000 stems/ha) mature jack pine or lodgepole pine stands.	Continuous feather moss.	Compact and moderately deep (about 10 cm).	Sparse to moderate.	Absent or sparse.	Light and scattered.	Absent. Live crown base is well above the surface fuels.

Continued on next page

Table 5. Major features of the FBP System fuel types, *continued*

Type	Stand structure and composition	Forest floor	Organic layer	Surface fuels: Herbs and shrubs	Surface fuels: Understory conifer	Surface fuels: Dead and down fuels	Ladder fuels
C-4	Pure dense (10 000–30 000 stems/ha) stands of immature jack pine or lodgepole pine.	Continuous needle litter.	Shallow (0–5 cm) and moderately compact.	Moderate cover. A low shrub layer (e.g., *Vaccinium* spp.) is often present.	Large quantity of standing dead stems.	Heavy.	Continuous vertical and horizontal fuel continuity.
C-5	Moderately well-stocked stands of red and white pine. Small amounts of white spruce, white birch or aspen can be present.	Continuous needle litter.	Moderately shallow (5–10 cm).	Moderate (usually beaked hazel).	Moderately dense (usually red maple or balsam fir).	Very sparse.	Generally absent. Live crown are often very high above the ground.
C-6	Pure, fully stocked conifer plantations with full crown closure. Rate of spread and crown involvement vary with crown base height.	Continuous needle litter.	Moderately shallow (up to 10 cm).	Absent.	Absent.	Absent.	Dependent on crown base height (e.g., in younger plantations tree crowns may extend to near the ground).

Continued on next page

Table 5. Major features of the FBP System fuel types, *continued*

Type	Stand structure and composition	Forest floor	Organic layer	Surface fuels			Ladder fuels
				Herbs and shrubs	Understory conifer	Dead and down fuels	
C-7	Open, mature, uneven-aged stands of Ponderosa pine and Douglas-fir. Western larch or lodgepole pine can be present on some sites.	Perennial grasses except in Douglas-fir thickets where needle litter is dominant.	Very shallow (0–5 cm) or absent.	Scattered.	Clumpy thickets of multi-age Douglas-fir or larch.	Light and scattered.	Scattered conifer thickets.
M-1 and M-2	Moderately well-stocked stands of boreal coniferous (e.g., black or white spruce, balsam or subalpine fir) and deciduous (e.g., aspen, white birch) species. Variation in fuel type occurs by season (leafless = M-1 and green = M-2) and percent coniferous and deciduous composition.	Continuous leaf litter in deciduous portions of stands. Discontinuous feather moss and needle litter in coniferous portions.	Shallow (0–5 cm). Uncompacted to moderately compacted.	Moderate shrub and continuous herb layer.	Scattered to moderate.	Low to moderate.	Conifer crowns may extend to near the ground in some stands.

Continued on next page

Table 5. Major features of the FBP System fuel types, *continued*

Type	Stand structure and composition	Forest floor	Organic layer	Surface fuels: Herbs and shrubs	Surface fuels: Understory conifer	Surface fuels: Dead and down fuels	Ladder fuels
M-3 and M-4	Moderately well-stocked stands of black and white spruce, jack pine or white birch with dead balsam fir (often as an understory). Fuel type varies by season (leafless = M-3 and green = M-4). Note that this fuel type is in the Great Lakes and boreal forests and is not to be confused with the pure balsam fir stands typical of Nova Scotia and New Brunswick.	Continuous leaf litter in deciduous portions of stands. Discontinuous feather moss, needle litter and hardwood leaves in mixed portions.	Moderately compact and moderately deep (8–10 cm).	Dense, continuous herbaceous cover after green-up occurs.	Dead balsam fir.	Initially low, becoming heavy 5–8 years after balsam fir mortality occurs.	Dead balsam fir understory with arboreal lichen covered branches.
D-1	Pure, semi-mature, moderately well-stocked stands of trembling aspen.	Continuous leaf litter.	Shallow (0–5 cm) and uncompacted.	Well developed medium to tall shrub layer. Moderate herbaceous layer.	Absent.	Sparse.	Absent.

Continued on next page

Table 5. Major features of the FBP System fuel types, *continued*

Type	Stand structure and composition	Forest floor	Organic layer	Surface fuels: Herbs and shrubs	Surface fuels: Understory conifer	Surface fuels: Dead and down fuels	Ladder fuels
O-1	Occasional trees or shrub clumps.	Continuous dead grass litter.	Absent to shallow (0–5 cm) and moderately compact.	Continuous grass; matted (O-1a) or standing (O-1b). Percent cured must be estimated. Standard fuel load is 0.3 kg/m^2 but can vary.	Not applicable.	Very sparse or scattered.	Not applicable.
S-1	Clear-cut logging slash from mature jack pine or lodgepole pine stands.	Continuous feather moss and discontinuous needle litter.	Compact and moderately deep (5–10 cm).	Absent to sparse.	Not applicable.	Continuous slash of moderate loading and depth. Slash is typically 1–2 years old retaining up to 50% of its foliage. No post-logging treatment has been applied.	Not applicable.

Continued on next page

Table 5. Major features of the FBP System fuel types, *concluded*

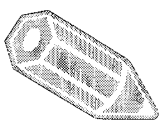
Type	Stand structure and composition	Forest floor	Organic layer	Surface fuels: Herbs and shrubs	Surface fuels: Understory conifer	Surface fuels: Dead and down fuels	Ladder fuels
S-2	Clear-cut logging slash from mature or over-mature stands of white and/or Engelmann spruce and subalpine fir.	Continuous feather moss with considerable needle litter.	Compact and moderately deep (5–10 cm).	Moderate.	Not applicable.	Continuous to discontinuous slash (caused by skid trails) of moderate depth and loading. Slash is 1–2 years old with 10–50% foliage retention. Shattered large and rotten fuels can be significant.	Not applicable.
S-3	Slash resulting from higher-lead logging of mature to over-mature western red cedar, western hemlock, and Douglas-fir.	Continuous feather moss of compact old needle litter under significant quantities of fresh litter from slash.	Compact and moderately deep to deep (10–25 cm).	Sparse to moderate.	Not applicable.	Continuous, deep slash usually one season old. Large broken and rotten nonmerchantable material can be present. Foliage retention on cedar is 100% and 50% on other species.	Not applicable.

Exercise 1.

Classifying fuel types

Classifying fuel types is an extremely important aspect of fire behavior prediction; however, it is not an easy task when dealing with non-standard vegetation types. In this exercise, evaluate each vegetative description and determine the FBP System fuel type that is most appropriate based on the information provided in Table 5. Fill in your answer on the dotted lines below. Note that this process is not only important for real-time fire behavior predictions but is a critical component of fuel type identification within preparedness planning systems and computerized fire management systems.

(1) Young jack or lodgepole pine plantation. A seven-year-old plantation is 80% stocked (about 2000 stems/ha) with jack or lodgepole pine trees averaging 2.0–2.5 m in height. Tree crowns extend to near the ground and surface fuels consist primarily of a heavy (3–4 t/ha) cured, standing grass layer.



FBP System fuel type ....

(2) Mixed conifer stand. A fully stocked mature stand of black spruce (50%) and jack or lodgepole pine (50%). Surface fuels consist of needles and scattered shrubs with a fairly shallow (5–10 cm) organic layer. Average height to the live tree crown is 1.0 m for black spruce and 7.0 m for the pine.

FBP System fuel type ....

(3) Red spruce stand. A fully stocked stand of mature (average height = 15 m) red spruce. Surface fuels consist of needles and scattered shrubs with a 10–15 cm organic layer. Average height to the live tree crown is 5.0–7.0 m.

FBP System fuel type ....

Suggested answers:

Classifying fuel types

The most important factor in fuel type classification is to identify the fuel characteristic(s) that will most significantly influence how a fire will spread and the type of fire (e.g., surface fire, intermittent crown fire, or continuous crown fire) that occurs. This process is highly subjective and therefore the following answers should be considered only as suggested solutions.

(1) O-1b (Standing Grass) within an increased fuel loading (e.g., 5 t/ha). Reasoning: fire spread in this type of fuel likely will be dominated by the characteristics of the grass fuel layer rather than the immature pine; however, the pine trees will increase the amount of available fuel thereby increasing the fire intensity.

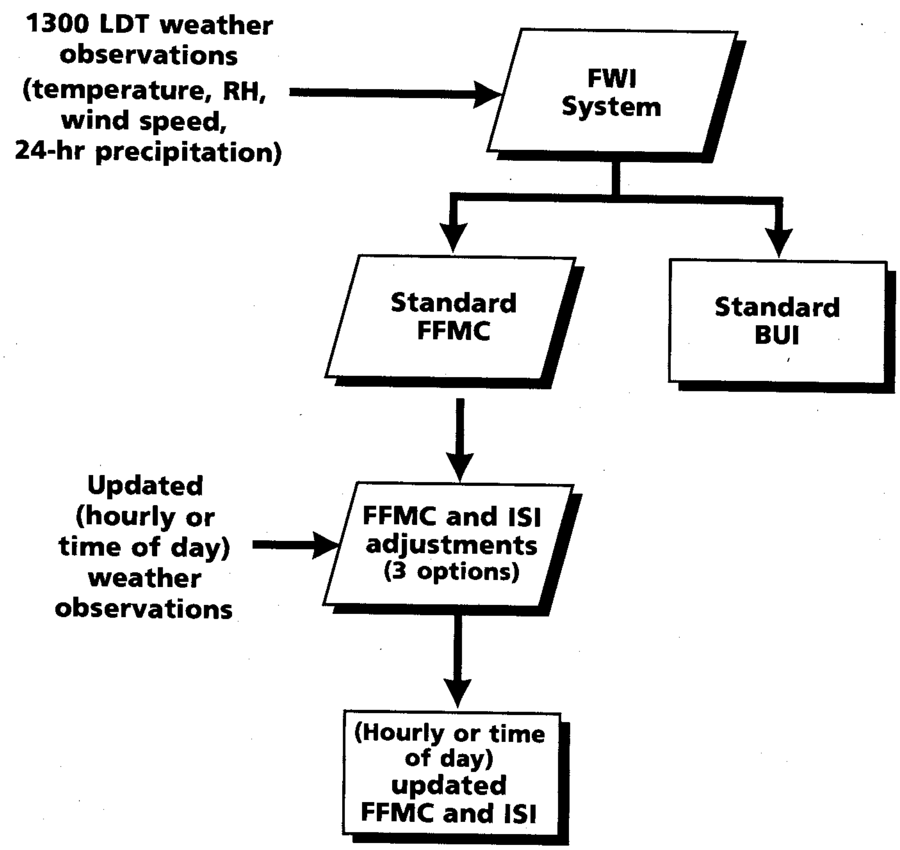
(2) C-2 (Boreal Spruce). Reasoning: even though this stand has a mixture of pine and spruce a fire is still likely to involve crown fuels at fairly low intensities due to the high percentage of black spruce trees, which have crowns extending to near the ground.

(3) C-3 (Mature Jack or Lodgepole Pine). Reasoning: even though the tree species is red spruce there is a significant gap between the surface fuels and the crown fuels. Thus, a very intense surface fire will be required before crown involvement will occur.

**Most vegetation types can be classified as an FBP System Fuel Type; however, in some instances this may not be possible.
For further information contact a member of the CFS Fire Research unit in your region.**

3.2 Weather

The weather inputs used in the FBP System include both basic weather observations (wind speed and wind direction) as well as the FFMC, ISI and BUI components of the FWI System. The FWI System indexes are considered weather inputs because they are calculated directly from four weather observations (temperature, RH, wind speed, and precipitation) taken daily at 1300 LDT (Fig. 4). To provide the most representative indexes possible, the FFMC and ISI can also be adjusted using updated (i.e., hourly or time of day) fire weather observations (see Section 3.2.1). Note also that wind direction is not an input required for the calculation of the FWI System components; however, it is used in conjunction with aspect (i.e., slope direction), if applicable, in the calculation of fire spread rate and direction (see Section 4.1.1.2).



RH = relative humidity.
FWI = Canadian Forest Fire Weather Index System.
FFMC = Fine Fuel Moisture Code.
BUI = Buildup Index.
ISI = Initial Spread Index.

Figure 4. Weather inputs used in the FBP System.

3.2.1 Computing Hourly or Adjusted FFMC and ISI Values

The standard components of the FWI System were designed to reflect the fire danger conditions during the peak burning period (i.e., about 1700 LDT), assuming a normal diurnal weather pattern occurs. It is often desirable, however, to make fire behavior predictions for other times of the day or when normal diurnal weather conditions do not exist, therefore three options exist for the calculation of an updated (i.e., hourly or time of day adjusted) FFMC and ISI (Fig. 5). Determining which method should be used is dependent upon the type of weather observations available and the desired accuracy of the indexes.

Option 1

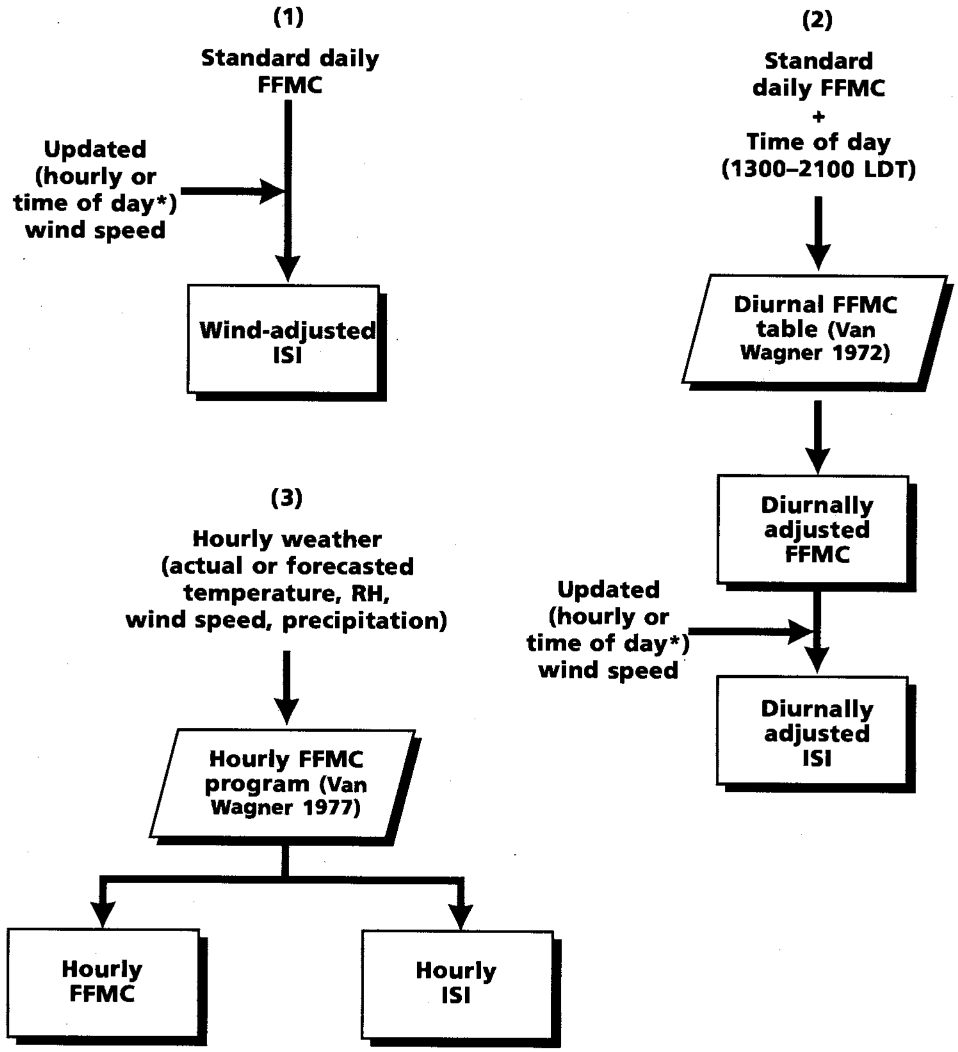
Option 1 calculates a wind-adjusted ISI value using the standard daily FFMC and an updated (actual or estimated) wind speed for the time of the desired fire behavior prediction. This option is generally considered the least accurate but is easily calculated using the FWI System equations or tables.

Option 2

Option 2 begins with the adjustment of the standard daily FFMC, based on the time of day (1300–2100 LDT), in accordance with the diurnal FFMC adjustment table developed by Van Wagner (1972). This FFMC adjustment does not require additional weather information but does assume that normal diurnal weather conditions exist. Once the diurnally adjusted FFMC is determined, it is combined with an updated wind speed measurement to produce a diurnally adjusted ISI. This option requires more information and is usually more accurate than option 1 if a normal diurnal weather pattern occurs. If, however, a normal diurnal pattern does not arise (e.g., the peak burning conditions do not occur around 1700 LDT) then this option would not be appropriate.

Option 3

Option 3 requires the greatest amount of input data; however, it also provides the most representative index values. Option 3 requires the use of a small computer program (Van Wagner 1977a) to calculate hourly FFMC and ISI values from an initial FFMC value and consecutive hourly readings of temperature, RH, wind speed, and precipitation.



FFMC = Fine Fuel Moisture Code.
ISI = Initial Spread Index.
RH = relative humidity.
LDT = local daylight time.

*Time of day refers to the desired time of the fire behavior prediction.

Figure 5. Options for computing adjusted FFMC and ISI values.

Exercise 2.

Options for calculating FFMC and ISI

Using the following information and Tables 6 and 7 (provided on pages 29 and 30), calculate the adjusted FFMC and ISI using options 1 and 2. Compare your results to the results in option 3 (below) and answer the following discussion questions on page 31.

Case no.	Time[a] (LDT)	Standard daily indexes[b] FFMC	ISI	Updated wind speed[c] (km/h)	Option 1 FFMC	ISI[d]	Option 2 FFMC[e]	ISI[f]	Option 3 FFMC	ISI
1	1900	88	4	15	88	____	____	____	*90.9*	*10.2*
2	1700	85	9	20	85	____	____	____	*86.0*	*7.1*
3	2000	92	7	20	92	____	____	____	*50.0*	*0.4*
4	1300	90	5	15	90	____	____	____	*90.1*	*9.3*
5	1400	90	4	15	90	____	____	____	*89.7*	*8.0*

[a] Time of the desired fire behavior pediction. LDT = local daylight time.

[b] Calculated using the 1300 LDT weather observations. FFMC = Fine Fuel Moisture Code; ISI = Initial Spread Index.

[c] Wind speed (observed or forecasted) for the desired time of the fire behavior prediction.

[d] Calculated from the ISI table given on page 29, using the standard daily FFMC and updated wind speed as inputs. This produces a wind-adjusted ISI.

[e] Calculate from the diurnal FFMC adjustment table given on page 30, using the standard daily FFMC and the time of day as inputs. This produces a diurnally adjusted FFMC.

[f] Calculate from the ISI table given on page 29 using the diurnally adjusted FFMC and the updated wind speed as inputs. This produces a diurnally adjusted ISI.

Table 6. Initial Spread Index table

Wind speed (km/h)	Fine Fuel Moisture Code														
	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
	Initial Spread Index														
0	2.0	2.5	3.0	3.0	4.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	13.0	15.0
1	2.0	2.5	3.0	3.0	4.0	5.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	14.0	16.0
2	2.5	2.5	3.0	4.0	4.0	5.0	5.0	6.0	7.0	8.0	10.0	11.0	13.0	14.0	16.0
3	2.5	3.0	3.0	4.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	12.0	13.0	15.0	17.0
4	2.5	3.0	3.0	4.0	5.0	5.0	6.0	7.0	8.0	9.0	11.0	12.0	14.0	16.0	18.0
5	2.5	3.0	4.0	4.0	5.0	6.0	6.0	7.0	8.0	10.0	11.0	13.0	15.0	17.0	18.0
6	3.0	3.0	4.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	12.0	13.0	15.0	18.0	20.0
7	3.0	3.0	4.0	5.0	5.0	6.0	7.0	8.0	9.0	11.0	12.0	14.0	16.0	18.0	21.0
8	3.0	4.0	4.0	5.0	6.0	6.0	7.0	9.0	10.0	11.0	13.0	15.0	17.0	19.0	22.0
9	3.0	4.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	12.0	14.0	16.0	18.0	20.0	23.0
10	3.0	4.0	5.0	5.0	6.0	7.0	8.0	9.0	11.0	12.0	14.0	16.0	19.0	21.0	24.0
11	4.0	4.0	5.0	6.0	6.0	7.0	9.0	10.0	11.0	13.0	15.0	17.0	20.0	23.0	26.0
12	4.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	12.0	14.0	16.0	18.0	21.0	24.0	27.0
13	4.0	5.0	5.0	6.0	7.0	8.0	10.0	11.0	13.0	15.0	17.0	19.0	22.0	25.0	28.0
14	4.0	5.0	6.0	7.0	8.0	9.0	10.0	12.0	13.0	15.0	18.0	20.0	23.0	26.0	30.0
15	4.0	5.0	6.0	7.0	8.0	9.0	11.0	12.0	14.0	16.0	18.0	21.0	24.0	28.0	31.0
16	5.0	5.0	6.0	7.0	8.0	10.0	11.0	13.0	15.0	17.0	19.0	22.0	25.0	29.0	33.0
17	5.0	6.0	7.0	8.0	9.0	10.0	12.0	13.0	15.0	18.0	20.0	23.0	27.0	31.0	35.0
18	5.0	6.0	7.0	8.0	9.0	11.0	12.0	14.0	16.0	19.0	21.0	25.0	28.0	32.0	37.0
19	5.0	6.0	7.0	8.0	10.0	11.0	13.0	15.0	17.0	20.0	23.0	26.0	30.0	34.0	38.0
20	6.0	7.0	8.0	9.0	10.0	12.0	14.0	16.0	18.0	21.0	24.0	27.0	31.0	36.0	40.0
21	6.0	7.0	8.0	9.0	11.0	12.0	14.0	16.0	19.0	22.0	25.0	29.0	33.0	37.0	43.0
22	6.0	7.0	8.0	10.0	11.0	13.0	15.0	17.0	20.0	23.0	26.0	30.0	34.0	39.0	45.0
23	7.0	8.0	9.0	10.0	12.0	14.0	16.0	18.0	21.0	24.0	28.0	32.0	36.0	41.0	47.0
24	7.0	8.0	9.0	11.0	12.0	14.0	17.0	19.0	22.0	25.0	29.0	33.0	38.0	43.0	50.0
25	7.0	9.0	10.0	11.0	13.0	15.0	17.0	20.0	23.0	27.0	31.0	35.0	40.0	46.0	52.0
26	8.0	9.0	10.0	12.0	14.0	16.0	18.0	21.0	24.0	28.0	32.0	37.0	42.0	48.0	55.0
27	8.0	9.0	11.0	13.0	14.0	17.0	19.0	22.0	26.0	29.0	34.0	39.0	44.0	51.0	58.0
28	8.0	10.0	11.0	13.0	15.0	18.0	20.0	23.0	27.0	31.0	35.0	41.0	47.0	53.0	61.0
29	9.0	10.0	12.0	14.0	16.0	18.0	21.0	25.0	28.0	33.0	37.0	43.0	49.0	56.0	64.0
30	10.0	11.0	13.0	15.0	17.0	19.0	22.0	26.0	30.0	34.0	39.0	45.0	51.0	59.0	67.0
31	10.0	12.0	13.0	15.0	18.0	20.0	24.0	27.0	31.0	36.0	41.0	47.0	54.0	62.0	70.0
32	11.0	12.0	14.0	16.0	19.0	22.0	25.0	29.0	33.0	38.0	43.0	50.0	57.0	65.0	74.0
33	11.0	13.0	15.0	17.0	20.0	23.0	26.0	30.0	35.0	40.0	46.0	52.0	60.0	68.0	78.0
34	12.0	13.0	15.0	18.0	21.0	24.0	27.0	32.0	36.0	42.0	48.0	55.0	63.0	72.0	82.0
35	12.0	14.0	16.0	19.0	22.0	25.0	29.0	33.0	38.0	44.0	51.0	58.0	66.0	76.0	86.0
36	13.0	15.0	17.0	20.0	23.0	26.0	30.0	35.0	40.0	46.0	53.0	61.0	70.0	80.0	91.0
37	14.0	16.0	18.0	21.0	24.0	28.0	32.0	37.0	42.0	49.0	56.0	64.0	73.0	84.0	95.0
38	14.0	16.0	19.0	22.0	25.0	29.0	34.0	39.0	45.0	51.0	59.0	67.0	77.0	88.0	100.0
39	15.0	17.0	20.0	23.0	27.0	31.0	35.0	41.0	47.0	54.0	62.0	71.0	81.0	92.0	105.0
40	16.0	18.0	21.0	24.0	28.0	32.0	37.0	43.0	49.0	57.0	65.0	74.0	85.0	97.0	111.0
41	17.0	19.0	22.0	25.0	29.0	34.0	39.0	45.0	52.0	60.0	68.0	78.0	90.0	102.0	117.0
42	17.0	20.0	23.0	27.0	31.0	36.0	41.0	47.0	54.0	63.0	72.0	82.0	94.0	108.0	123.0
43	18.0	21.0	24.0	28.0	32.0	37.0	43.0	50.0	57.0	66.0	76.0	87.0	99.0	113.0	129.0
44	19.0	22.0	26.0	30.0	34.0	39.0	45.0	52.0	60.0	69.0	79.0	91.0	104.0	119.0	136.0
45	20.0	23.0	27.0	31.0	36.0	41.0	48.0	55.0	63.0	73.0	84.0	96.0	110.0	125.0	143.0
46	21.0	25.0	28.0	33.0	38.0	44.0	50.0	58.0	67.0	77.0	88.0	101.0	115.0	132.0	150.0
47	23.0	26.0	30.0	34.0	40.0	46.0	53.0	61.0	70.0	81.0	92.0	106.0	121.0	138.0	158.0
48	24.0	27.0	31.0	36.0	42.0	48.0	56.0	64.0	74.0	85.0	97.0	111.0	127.0	146.0	166.0
49	25.0	29.0	33.0	38.0	44.0	51.0	58.0	67.0	78.0	89.0	102.0	117.0	134.0	153.0	175.0
50	26.0	30.0	35.0	40.0	46.0	53.0	61.0	71.0	82.0	94.0	108.0	123.0	141.0	161.0	184.0

Note: see Canadian Forestry Service (1984) for complete set of Canadian Forest Fire Weather Index System tables.

Table 7. Diurnal-adjustment table for the Fine Fuel Moisture Code (FFMC)[a]

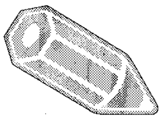
Time (LDT)[b]	Standard daily FFMC																			
	80	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**
1300	69	70	72	74	76	79	81	83	85	87	88	89	90	91	92	93	94	95	96	97
1500	76	77	79	81	82	83	84	85	86	88	89	90	91	92	93	94	95	96	97	98
1700	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
1900	80	81	82	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
2100	78	79	80	81	82	82	83	84	85	86	87	88	89	90	91	92	92	93	94	95

[a] From Van Wagner (1972).

[b] LDT = local daylight time. Local daylight time is in effect from the first Sunday in April to the last Sunday in October (except in Saskatchewan where standard time is used year-round). Subtract one hour to obtain local standard time (LST).

Example: if the standard daily FFMC is determined to be 94, and the desired time is 1500 LDT, then the FFMC determined from the table equals 93. This is the diurnally adjusted FFMC.

Questions:



(1) Explain why the standard FFMC and the option 1 FFMC are the same but the ISI values are different.

(2) When will the diurnally adjusted FFMC (option 2) be higher, lower, and the same as the standard FFMC?

(3) Give two possible reasons why the option 3 values are, in some cases, significantly different than the option 2 values.

Suggested answers:

Options for calculating FFMC and ISI

Case No.	Time (LDT)	Standard indexes[a]		Updated wind speed (km/h)	Option 1		Option 2		Option 3	
		FFMC	ISI		FFMC	ISI	FFMC	ISI	FFMC	ISI
1	1900	88	4	15	88	7	87	6	90.9	10.2
2	1700	85	9	20	85	6	85.5	6	86.0	7.1
3	2000	92	7	20	92	16	90	12	50.0	0.4
4	1300	90	5	15	90	9	88	7	90.1	9.3
5	1400	90	4	15	90	9	88.5	7.5	89.7	8.0

[a] FFMC = Fine Fuel Moisture Code; ISI = Initial Spread Index.

(1) In option 1 the standard daily FFMC is used in conjunction with a time of day (or updated) wind speed observation to calculate a wind-adjusted ISI. Thus, the FFMC values are equal but the ISI values will differ if the updated wind speed does not equal the 1300 LDT wind speed that was used to calculate the standard ISI.

(2) Indexes calculated by the FWI System are representative of conditions during the peak burning period (which is assumed to be 1700 LDT) if a standard diurnal weather pattern occurs. Calculation of the diurnally adjusted FFMC also assumes a standard diurnal weather pattern exists and therefore will be equal to the standard FFMC at 1700 LDT. The diurnally adjusted FFMC will be lower than the standard daily FFMC both before and after 1700 LDT, but it will never be higher than the standard FFMC value.

(3) One possible reason why the values in option 3 are significantly different than the option 2 values is that the hourly weather may not have followed the standard diurnal pattern. A common reason for this is a sudden change in weather conditions such as temperature changes, showers at the weather station, or increased afternoon winds. A second reason for the variation could be that the diurnal pattern used for option 2 is not appropriate for a particular location. For example, the diurnal pattern used in option 2 assumes that the peak burning period occurs at 1700 LDT; however, at higher latitudes the peak burning conditions may actually take place later in the day and last longer due to the amount of summer time daylight at higher latitudes.

3.3 Topography

The FBP System has two topographic inputs: percent slope and aspect[1]. Percent slope has a direct impact on a fire's rate of spread because the steeper the slope the faster the fire will spread (assuming there is no wind). Percent slope can be determined from topographic maps using Equation 1 or from on-site measurements using Equation 2 (see Section 4.1.1.2 for an example).

$$\textbf{Percent slope} = \frac{\textbf{elevation rise}}{\textbf{horizontal ground distance}} \times 100 \qquad \textbf{(1)}$$

$$\textbf{Percent slope} = 100 \times \tan \Theta \qquad \textbf{(2)}$$

where Θ = number of degrees the line of slope is above horizontal.

Aspect, or the direction the slope faces, is expressed in degrees and is used in combination with wind direction to determine the interactive effect of slope and wind on rate of spread and spread direction.

[1] Please note that in the FBP System technical document (Forestry Canada Fire Danger Group 1992) upslope direction is used rather than aspect. Upslope direction is simply the opposite of aspect (i.e., upslope direction (°) = aspect ± 180°). Aspect is used in this user's guide and most FBP System software programs because it is a term commonly used to describe slope direction.

3.4 Foliar Moisture Content

Foliar Moisture Content (FMC) is technically a fuel characteristic, but it is identified as a separate FBP System input because it varies with location and time of year. The moisture content of conifer needles that are at least one-year old varies during the fire season between about 120 and 85%. This trend includes a spring dip in FMC, that generally occurs between mid-May and late June, during which crown fire initiation is theoretically easier (Fig. 6). Note that in the C-6 fuel type the FMC also influences the predicted rate of spread of crown fires.

In the FBP System the FMC is calculated from the latitude (°N), longitude (°W), elevation (m), and date. The FMC model is based on data that has been collected at 9 study sites across Canada (Fig. 7) and on the general northwest to southeast climatic patterns that occur in Canada. The model also assumes that the date of minimum FMC will occur later in the fire season as the elevation increases (Fig. 8).

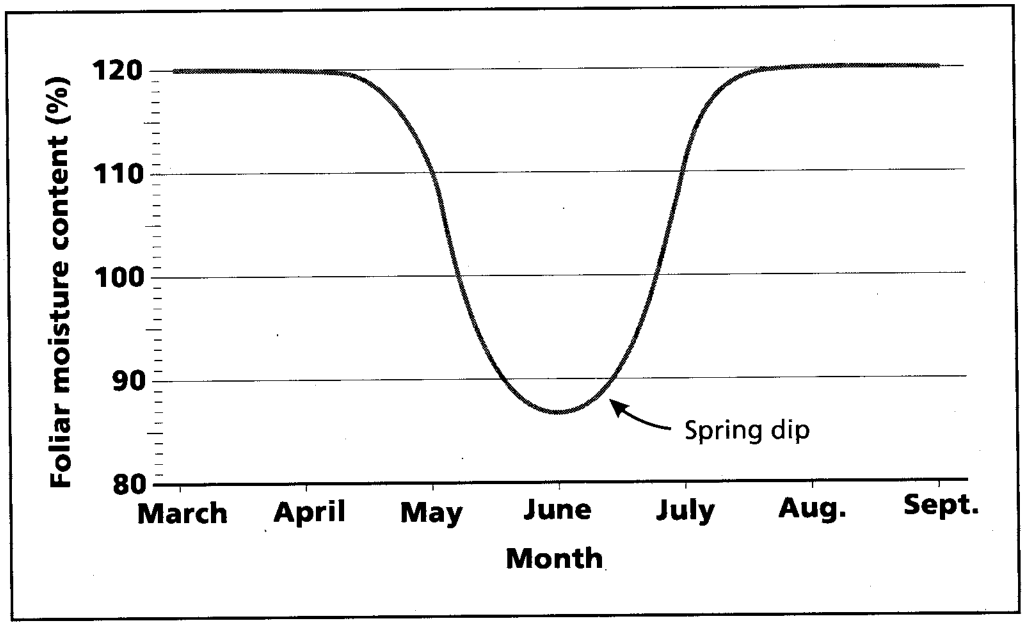


Figure 6. **Conceptual example of the seasonal trend in the foliar moisture content of conifer foliage.**

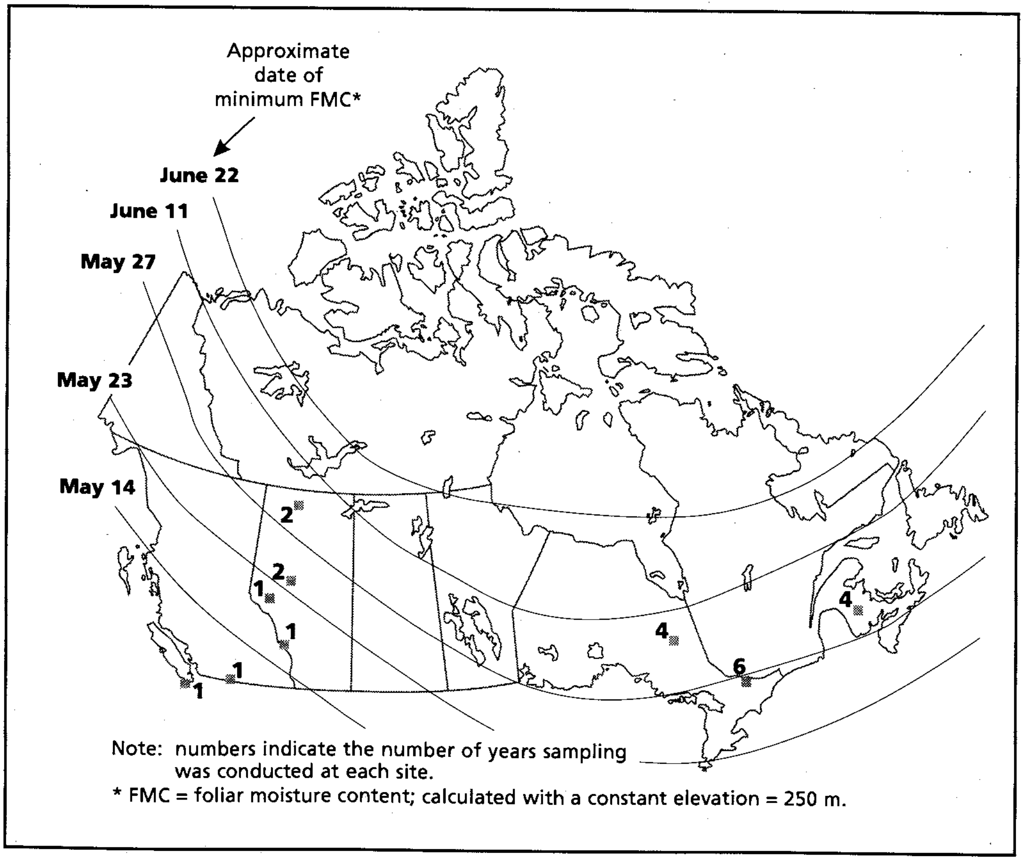


Figure 7. **Foliar moisture content data collection sites and approximate dates of minimum foliar moisture content as calculated by the FBP System.**

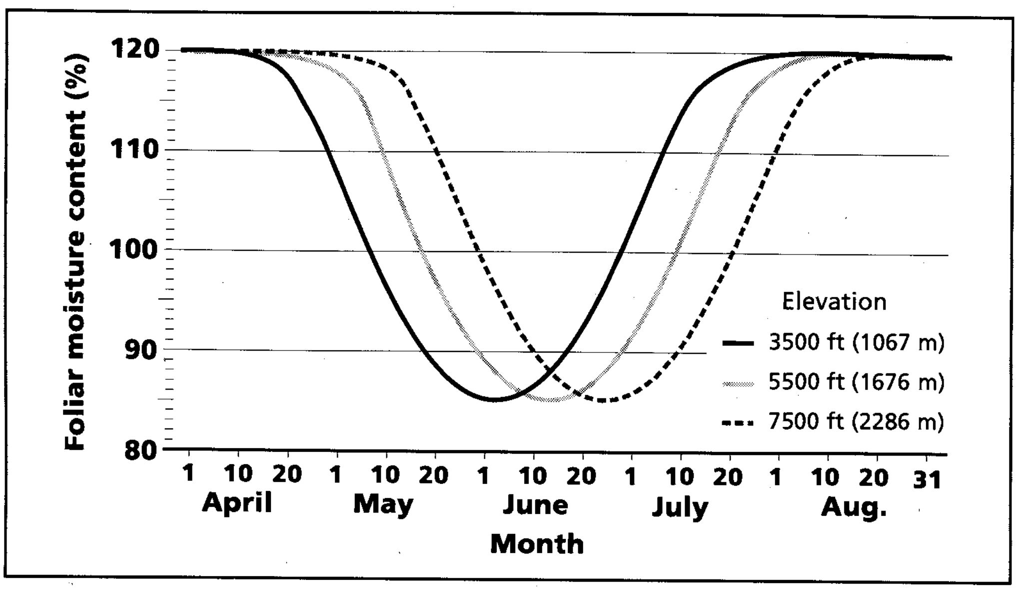


Figure 8. **Example of the variation in foliar moisture content due to elevation as calculated by the FBP System for Jasper, Alberta (latitude 52°53′; longitude 118°04′).**

3.5 Type and Duration of Prediction

The FBP System permits two types of predictions: point source and line source. A point source prediction is used when a fire is in its early stages of fire growth and is accelerating towards its equilbrium rate of spread. Point source predictions would be used for fires that are started by a match or lightning strike and are detected at a relatively small size (e.g., 0.1 ha). A line source prediction assumes that a fire has reached its steady state or equilibrium ROS. It would be used to predict the behavior of a fire that already has a well-established fire front (e.g., a fire detected at a fairly large size or a campaign fire that experiences a major wind shift). Choosing the type of prediction is quite important because it significantly influences fire behavior predictions in the early stages of fire growth. Table 8 shows the type of variation that could exist between line and point source predictions.

Duration of prediction or the elapsed time (in minutes) determines the degree of impact that acceleration will have on point ignition fires. That is, the longer the elapsed time from ignition, the closer the rate of spread will be to its equilibrium value. Also, elapsed time is necessary to calculate many of the secondary outputs such as spread distance, area, perimeter, and rate of perimeter growth.

Table 8. Simplified examples of variation in fire behavior predictions between point source and line ignition fires[a]

	Point Source				Line Source			
Elapsed time (min)	ROS[b] (m/min)	Spread distance (m)	Area (ha)	Perimeter (m)	ROS (m/min)	Spread distance (m)	Area[c] (ha)	Perimeter[c] (m)
10	5.0	29	0.1	092	8.1	41	0.3	218
15	6.2	58	0.2	172	8.1	122	0.7	327
20	7.0	91	0.5	263	8.1	163	1.3	436
30	7.7	165	1.4	463	8.1	244	2.9	654
45	8.0	283	4.1	781	8.1	365	6.4	981
60	8.1	404	8.2	1106	8.1	488	11.4	1308

[a] Calculations are based on the Boreal Spruce (C-2) fuel type, Initial Spread Index = 10, Buildup Index = 60, foliar moisture content = 97%, and slope = 0%.

[b] ROS = rate of spread at elapsed time in the first column.

[c] Technically speaking, line source predictions should not be used to calculate area and perimeter. These parameters have been included here only for the purposes of illustration.

4.0 Outputs

The FBP System has 4 primary and 11 secondary outputs (Table 9). The primary outputs are generally based on Byram's (1959) fire intensity equation (Equation 3), and the secondary outputs are derived primarily from a simple elliptical fire growth model.

Table 9. Outputs produced by the FBP System

Category	Input
Primary	Rate of spread (m/min)
	Fuel consumption (kg/m^2)
	Head fire intensity (kW/m)
	Fire description (crown fraction burned and fire type)
Secondary	Head, flank, and back fire spread distance (m)
	Flank and back fire rates of spread (m/min)
	Flank and back fire intensities (kW/m)
	Elliptical fire area (ha)
	Elliptical fire perimeter (m)
	Rate of perimeter growth (m/min)
	Length-to-breadth ratio

4.1 Primary Outputs

The FBP System uses an adaptation of Byram's (1959) fire intensity equation (Equation 3) to obtain three of the four primary outputs (Fig. 9).

$$I = Hwr \tag{3}$$

where I = fire intensity (kW/m),
H = fuel low heat of combustion (kJ/kg),
w = weight of fuel consumed per unit area in the active fire front (kg/m^2), and
r = rate of forward spread (m/sec).

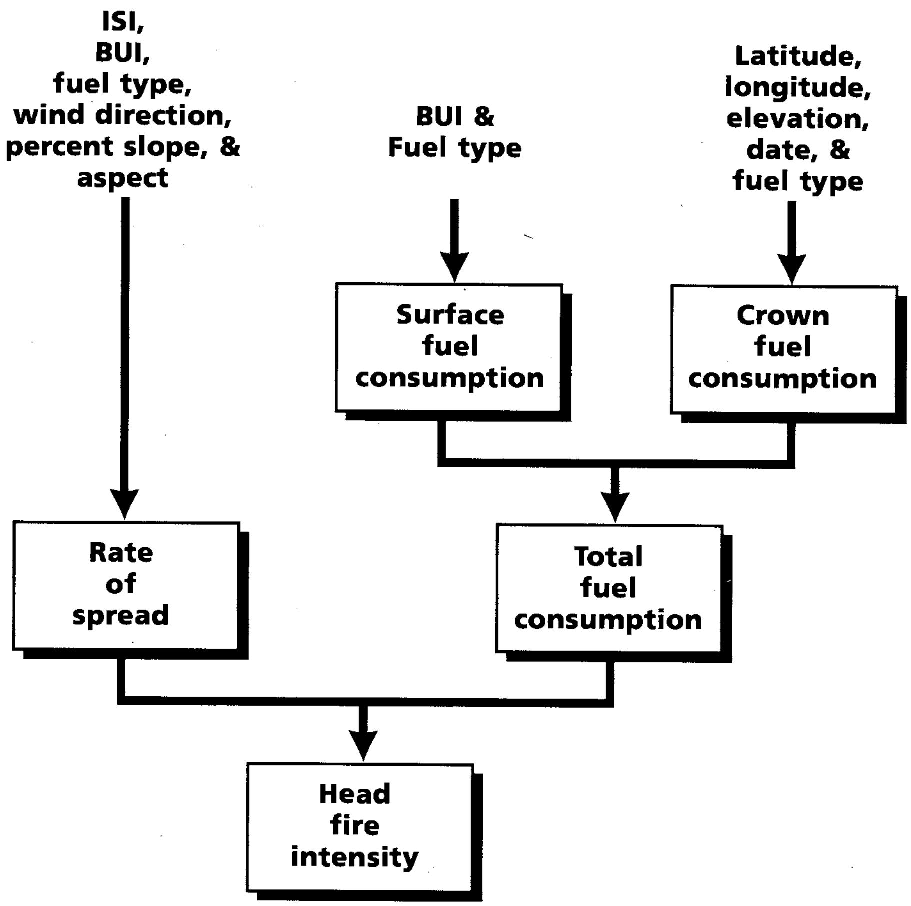
The major differences between Byram's equation and the FBP System approach are:

(1) the FBP System uses predicted rate of spread and fuel consumption values to calculate head fire intensity rather than observed values,

(2) the fuel low heat of combustion (H) is assumed to be a constant value in the FBP System (i.e., 18 000 kJ/kg) rather than a variable quantity as in Byram's equation, and

(3) the FBP System assumes all fuel consumption occurs within the fire front while Byram assumed the consumption of large fuels occurred after the fire front had passed.

The fourth primary output, fire description, is determined, in part, from the predicted head fire intensity. It is expressed in terms of fire type (i.e., surface fire, intermittent crown fire, or continuous crown fire) and/or crown fraction burned (i.e., degree of crown fuel involvement in the fire).



ISI = Initial Spread Index.
BUI = Buildup Index.

Figure 9. Flow chart showing the procedure used in the FBP System to calculate head fire intensity.

4.1.1 Rate of Spread

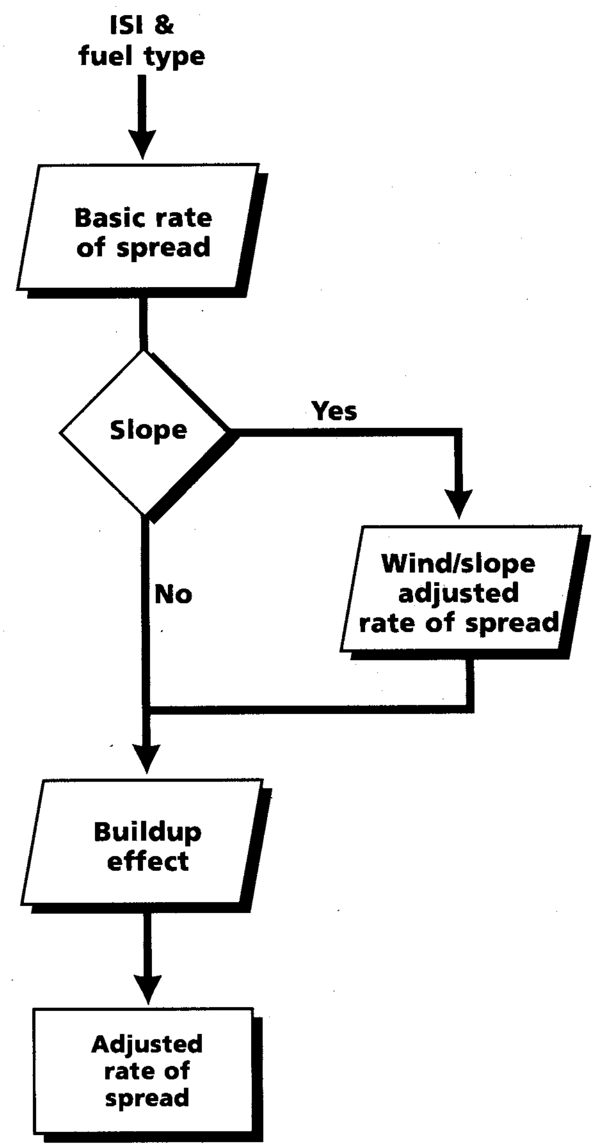
The process used in the FBP System for predicting the equilibrium head fire rate of spread involves three steps (Fig. 10):

(1) calculation of the basic rate of spread using ISI and fuel type,

(2) modification of the rate of spread to account for slope, if present, and

(3) adjustment of the rate of spread according to the buildup effect.

Each of these steps is discussed in detail in subsequent sections.



ISI = Initial Spread Index.

Figure 10. Process for calculating head fire rate of spread.

4.1.1.1 Basic ISI/Rate of Spread Relationship

The first step in calculating the predicted head fire rate of spread involves determining the basic rate of spread. For each fuel type, a best-fit curve was developed relating the ISI to the rate of spread. An example of this type of relationship is shown in Figure 11 and Table 10. Curves and equations for all of the FBP System fuel types are presented in Forestry Canada Fire Danger Group (1992).

The following are the assumptions and general features regarding the basic ISI/rate of spread relationships:

(a) It is assumed that the predicted head fire rate of spread occurs on level terrain under constant weather and fuel type conditions.

(b) Acceleration is not included in this relationship. That is, it is assumed that the basic rate of spread is at equilibrium or steady state (see Section 4.2.1 for more information on acceleration).

(c) The effects of crowning and spotting on rate of spread are automatically accounted for in the empirical data base.

(d) For most fuel types the ISI/rate of spread relationship is empirically based. Data for the lower rate of spread values are from experimental fires, and data for higher rates of spread were obtained from well-documented wildfires.

(e) An S-shaped curve is used for all fuel types to ensure that the curve passes through the origin (i.e., so the rate of spread will be zero when the ISI is zero) and levels off at higher ISI values.

(f) In some fuel types (primarily Boreal Spruce, C-2; Mature Pine, C-3; and Immature Pine, C-4) data points from wildfires that exhibited extreme fire behavior were used in more than one fuel type because these fires were known to have burned through a mosaic of forest fuels. This approach results in very little variation in rates of spread between these fuel types at extreme ISI values (Fig. 12).

(g) The rate of spread predictions for the Boreal Mixedwood—Leafless (M-1) and Boreal Mixedwood—Green (M-2) fuel types were developed by combining the values for the Leafless Aspen (D-1) and Boreal Spruce (C-2) fuel types according to the percentage of deciduous and coniferous species in the stand (Figs. 13 and 14). No empirical data set currently exists for these fuel types.

(h) For the Dead Balsam Fir/Mixedwood—Leafless (M-3) and Dead Balsam Fir/Mixedwood—Green (M-4) the rate of spread will vary with the percentage of dead balsam fir (i.e., as the proportion of dead balsam fir decreases the rate of spread decreases).

(i) Rate of spread in the Open (O-1) and the Conifer Plantation (C-6) fuel types is modeled differently than the other fuel types and is therefore explained separately in Sections 4.1.1.4 and 4.1.1.5, respectively.

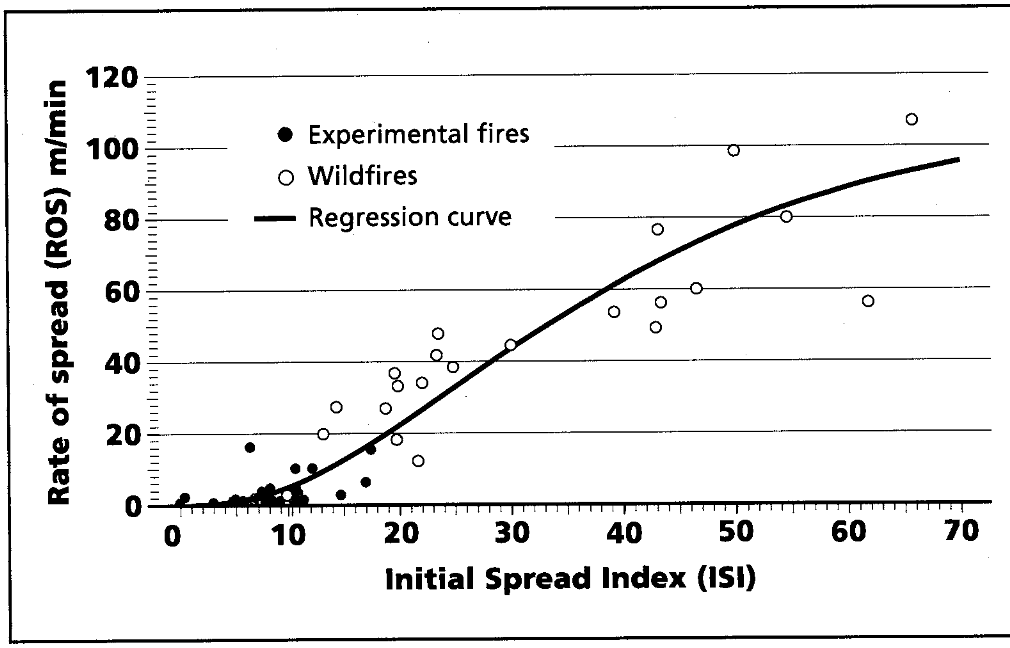


Figure 11. Basic rate of spread curve for the Mature Jack or Lodgepole Pine (C-3) fuel type.

Table 10. Basic rate of spread values for the Mature Jack or Lodgepole Pine (C-3) fuel type (m/min)

ISI[a]	0	1	2	3	4	5	6	7	8	9
0	0	0	0.1	0.2	0.5	0.9	1.4	2.1	2.9	3.9
10	5.0	6.3	7.8	9.3	10.9	12.6	14.5	16.4	18.3	20.4
20	22.4	24.5	26.7	28.8	31.0	33.1	35.3	37.5	39.6	41.8
30	43.9	45.9	48.0	50.0	52.0	53.9	55.9	57.7	59.5	61.3
40	63.1	64.7	66.4	68.0	69.5	71.0	72.5	73.9	75.3	76.6
50	77.9	79.2	80.4	81.5	82.6	83.7	84.8	85.8	86.7	87.7

[a] ISI = Initial Spread Index.

Example: for an ISI of 22 (20 and 2) the basic rate of spread is 26.7 m/min.

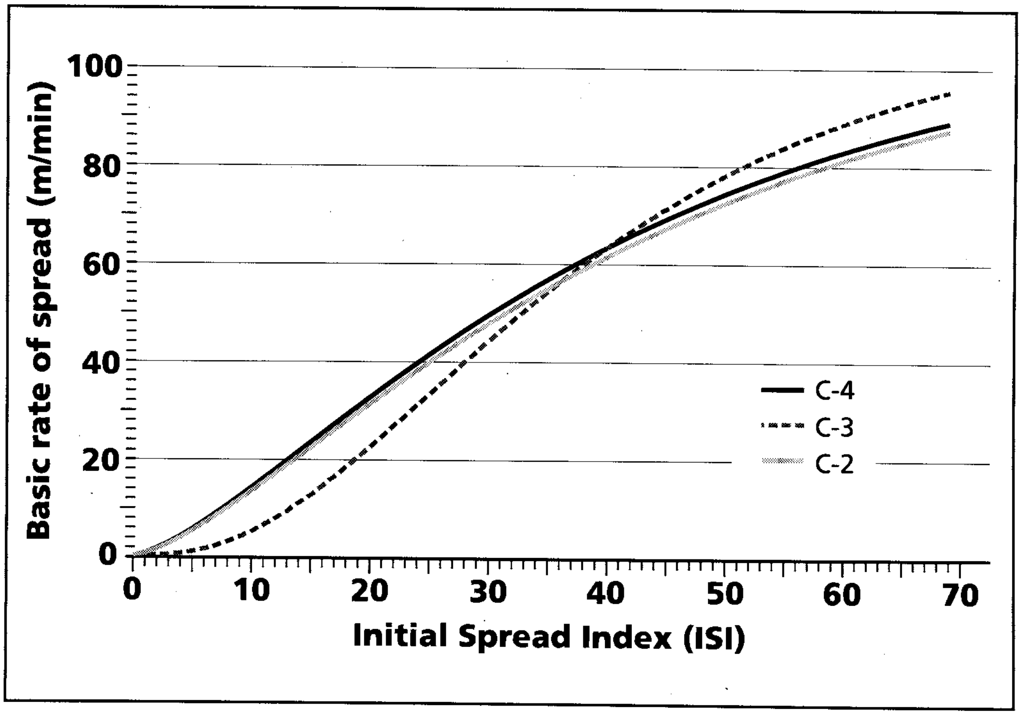


Figure 12. Basic rate of spread curves for the Boreal Spruce (C-2), Mature Jack or Lodgepole Pine (C-3), and Immature Jack or Lodgepole Pine (C-4) fuel types.

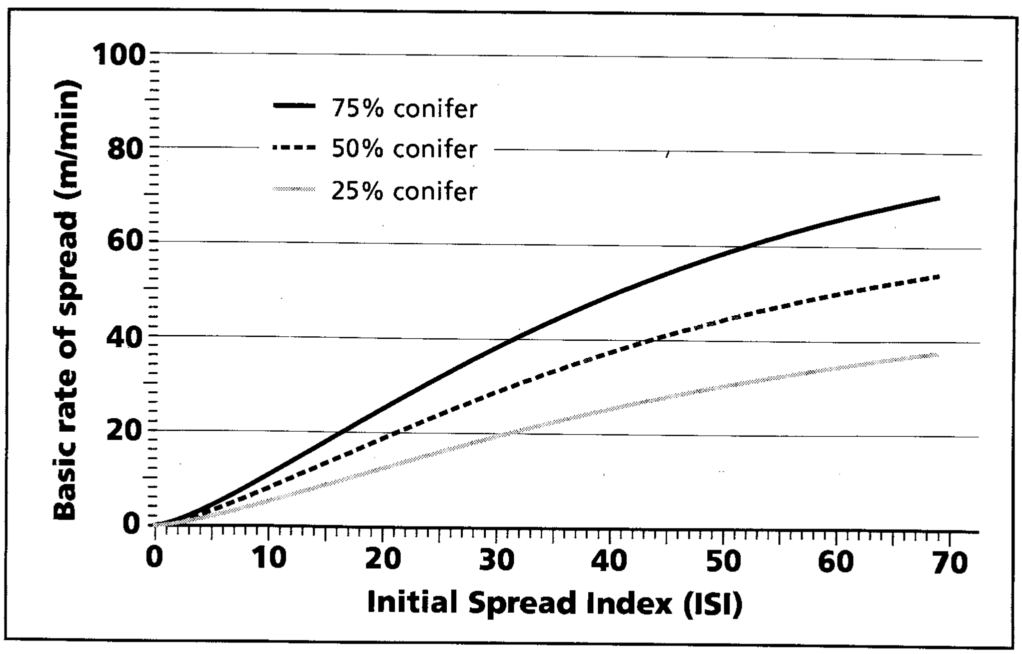


Figure 13. Basic rate of spread curves for the Boreal Mixedwood—Leafless (M-1) fuel type.

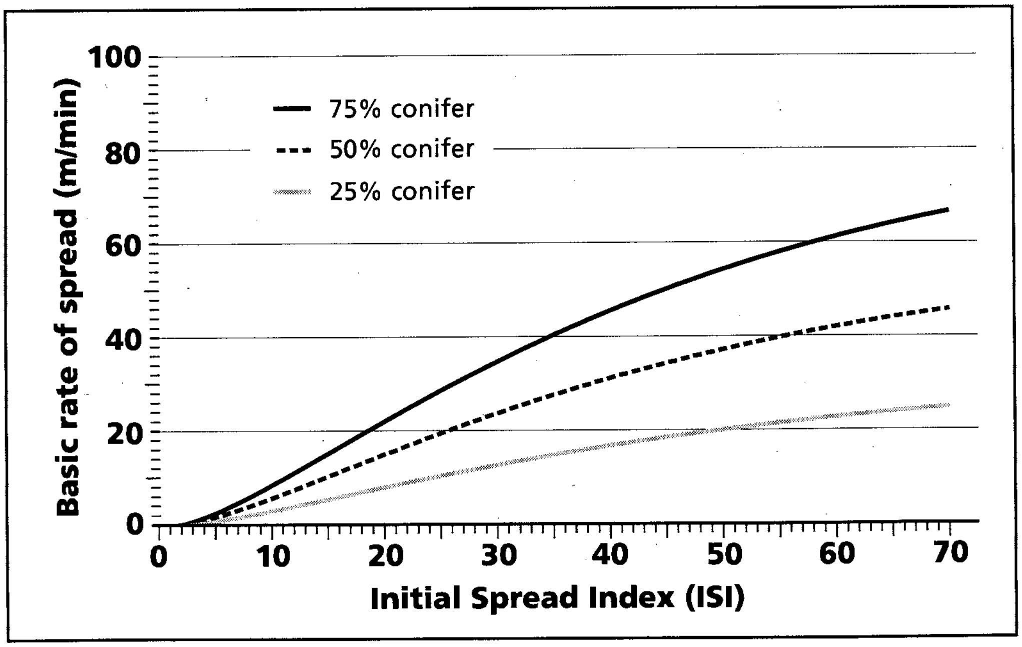


Figure 14. Basic rate of spread curves for the Boreal Mixedwood—Green (M-2) fuel type.

4.1.1.2. Slope Effect on Rate of Spread

The second step used in the FBP System to calculate rate of spread, is to account for the interactive effect that both slope (direction and steepness) and wind have on the rate and direction of fire spread. If applicable, the FBP System first determines the independent impacts of wind and slope on the fire, converts the two forces into common units, and combines the two effects using vector[2] mathematics. The entire procedure requires seven steps, which are listed below and illustrated using an example.

Step 1. Calculate the percent slope.

Step 2. Determine the slope spread factor (SF).

Step 3. Determine the slope-adjusted zero-wind rate of spread (RSF), which is the rate of spread on a slope independent of the wind conditions.

Step 4. Convert the slope-adjusted zero-wind rate of spread into an equivalent wind speed value (WSE).

Step 5. Add the equivalent wind speed vector and the observed wind speed vector to determine the net effective wind vector (WSV).

Step 6. Use the net effective wind speed in conjunction with the FFMC to calculate a wind/slope-adjusted (or final) ISI.

Step 7. Use the wind/slope-adjusted (or final) ISI and fuel type to calculate a wind/slope-adjusted rate of spread according to the basic ISI/rate of spread equations.

---

[2] A vector includes both magnitude (e.g., speed) and direction.

Example: **Calculating the effect of slope on fire spread.**

Input Data

Fuel type = Mature Lodgepole Pine (C-3)
FFMC = 92
Wind speed = 20 km/h
Wind direction = 315°
Aspect = 60°

Step 1. Calculate the percent slope.

Percent slope is simply the rise in elevation that occurs over a given horizontal ground distance (see Equation 4 and Section 3.3)[3]. Figure 15 shows that the elevation change between point "a" and point "b" is 2400 feet and the horizontal ground distance between the two points is 1300 m[4].

$$\textbf{Percent slope} = \frac{\textbf{elevation rise (m)}}{\textbf{horizontal ground distance (m)}} \times \mathbf{100} \qquad \textbf{(4)}$$

$$= \frac{\textbf{(7600–5200 ft)} \times \textbf{0.3048 m/ft}}{\textbf{1300 m}} \times \mathbf{100}$$

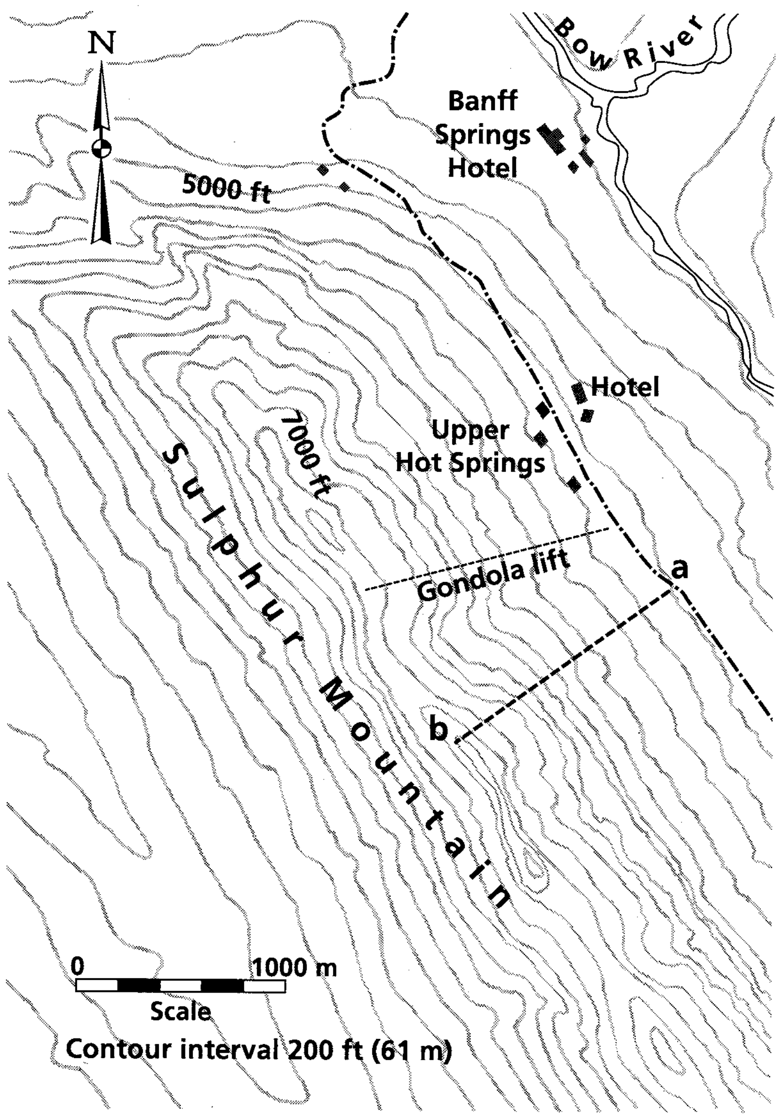
$$= \mathbf{56.3}$$

[3] If a map is not available, percent slope can be determined from an on-site measurement of slope angle with the equation:

$$\text{Percent slope} = 100 \times \tan(a)$$

where a is the number of degrees the line of slope is above the horizontal. Example: If a = 29.4°, then percent slope = 100 × tan (29.4) = 56.3%

[4] In this example it is necessary to convert the elevation from feet to metres using a conversion factor of 1 ft = 0.3048 m.



Note: the elevation change between point "a" and point "b" is 2400 ft and the horizontal ground distance between the two points is 1300 m.

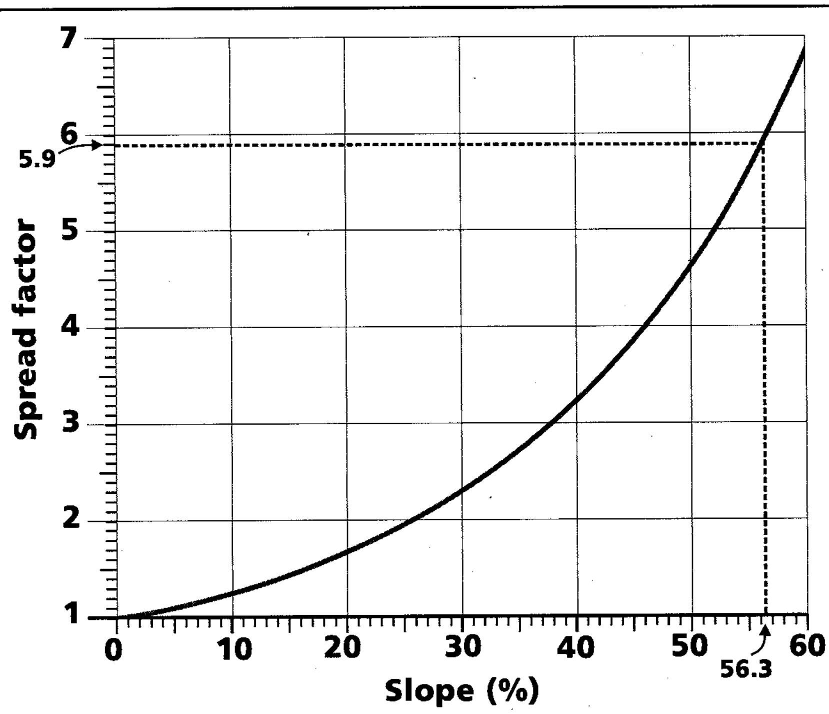
Figure 15. Topographic map of the Sulphur Mountain area in Banff National Park.

Step 2. Determine the slope spread factor.

The slope spread factor (SF) is a semi-theoretical adjustment factor developed by Van Wagner (1977c) in order to modify rates of spread on slopes up to 60%, assuming the wind speed is zero. It can be determined using Equation 5 or Figure 16.

$$\text{Spread factor (SF)} = {}_e3.533 \times (GS/100)^{1.2} \quad (5)$$
$$= {}_e3.533 \times (56.3/100)^{1.2}$$
$$= 5.9$$

where SF = spread factor, and
GS = percent ground slope



Note: when the slope is 25% the spread factor is 2.0.

Figure 16. Van Wagner's (1977c) slope spread factor.

Interpretation: this means the rate of spread of a fire spreading on a 56.3% slope (with no wind present) will be 5.9 times faster than the rate of spread of a fire on level ground under the identical fuel conditions.

Step 3. Determine the slope-adjusted zero-wind rate of spread (RSF), which is the rate of spread on a slope independent of the wind conditions.

The slope-adjusted zero-wind rate of spread (RSF) is the predicted rate of spread of a fire on a slope if the winds were calm. This value is determined using the following procedure (see Forestry Canada Fire Danger Group 1992 for equations).

(a) The FFMC and a wind speed of zero are used to obtain a zero-wind ISI (ISZ) according to the ISI equations in the FWI System.

If FFMC = 92 and
wind speed = 0, then
ISZ = 5.7

(b) The zero-wind ISI (ISZ) and fuel type are used to calculate the zero-wind rate of spread on level ground (RSZ) using the rate of spread equations for the specified fuel type.

If ISZ = 5.7 and
fuel type = C-3, then
RSZ = 1.22 m/min

(c) The slope-adjusted zero-wind rate of spread (RSF) is then calculated (Equation 6) by multiplying the zero-wind rate of spread on level ground (RSZ) by the spread factor (SF).

$$\mathbf{RSF = RSZ \times SF} \qquad \mathbf{(6)}$$

if RSF = 1.22 m/min, and
SF = 5.9, then
RSF = 1.22 m/min × 5.9 = 7.2 m/min.

Interpretation: if a fire was burning in a Mature Lodgepole Pine (C-3) fuel type on a hillside with a slope of 56.3% and there was no wind, the fire would spread uphill at a rate 7.2 m/min.

Step 4. Convert the slope-adjusted zero-wind rate of spread (RSF) into an equivalent wind speed value (WSE).

In order to allow the effects of slope and wind on the fire to be combined, it is necessary to convert the slope-adjusted zero-wind rate of spread (RSF) into a wind speed equivalent value (WSE). This is done by working backwards through the appropriate rate of spread equations and the ISI equation (see Forestry Canada Fire Danger Group 1992 for these equations). Figure 17 depicts the wind speed equivalent values for a number of fuel types under various slope conditions and an assumed FFMC of 92.

If RSF = 7.2 m/min, and
fuel type = C-3, then
WSE = 14.2 km/h.

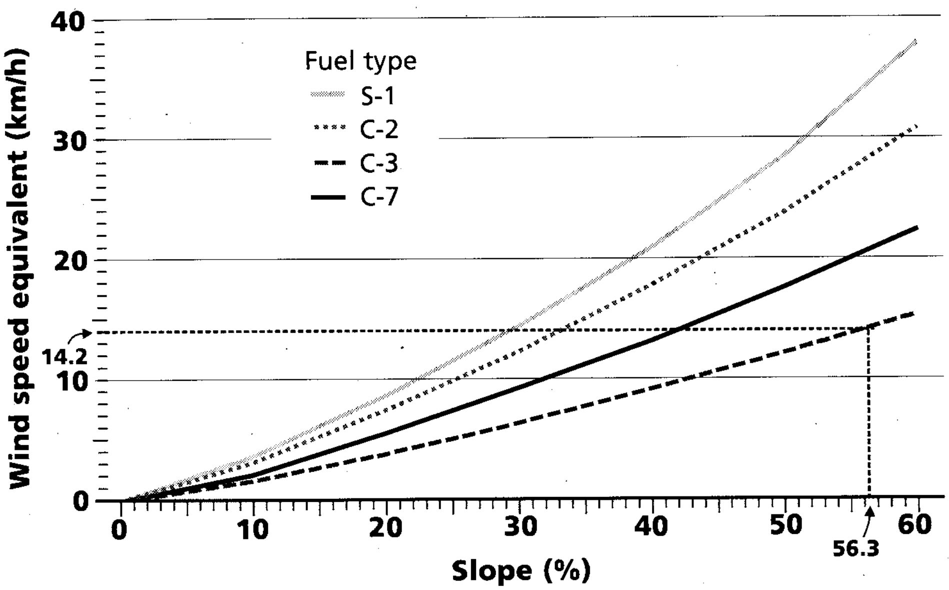


Figure 17. Wind speed equivalent values for various slopes, selected fuel types, and an FFMC of 92.

Interpretation: a slope of 56.3% would have the same impact on a fire burning in a Mature Lodgepole Pine (C-3) fuel type as a wind speed of 14.2 km/h.

Step 5. Add the equivalent wind speed vector (WSE) and the observed wind speed vector to determine the net effective wind vector (WSV)[5].

Adding the observed wind vector and the wind speed equivalent vector (WSE), which is based on the slope, produces the net effective wind vector (WSV). Vector mathematics involves some relatively complex equations but it can also be done quite easily using graph paper, a protractor, and a ruler. This is illustrated in Figure 18, which was created using the following procedures.

(a) It was assumed that 3 mm equals 1 km/h.

(b) At point "x", a line 42.6 mm (i.e., 14.2 km/h × 3 mm/km/h) in length was drawn at an angle of 240° (i.e., 60°+180° because the fire will burn upslope, which is the exact opposite direction of the aspect). This line is the wind speed equivalent vector (WSE), which represents a slope of 56.3% and an aspect of 60°.

(c) At point "x", another line 60 mm (i.e., 20 km/h × 3 mm/km/h) in length was drawn at an angle of 135° (i.e., 315°-180° because the vector represents the direction the wind is blowing to, not where the wind is coming from). This represents the observed wind speed of 20 km/h and a wind direction of 315°.

(d) At this point it is possible to see that there are two forces acting on the fire, the slope and the wind. The combined impact of these forces was determined by completing a parallelogram (dashed lines) and drawing a line from point "x" to the adjacent corner of the parallelogram (point "y"). By measuring the length of this new line (i.e., 64 mm) the net effective wind speed was computed to be 21.3 km/h (i.e., 64 mm/3 mm/km/h).

(e) The predicted direction of fire spread is determined by measuring the azimuth of the new line, which in this case is 175°.

Interpretation: the combined forces of slope (steepness = 56.3%; aspect = 60°) and wind (speed = 20 km/h; direction = 315°) on a fire burning in a Mature Lodgepole Pine (C-3) fuel type are equivalent to a level ground situation in which the wind would be 21.3 km/h from a direction of 355° (i.e., 175°+180° to convert from azimuth to wind direction).

[5] Vectors include both a speed and direction (e.g., 12 km/h at 270°).

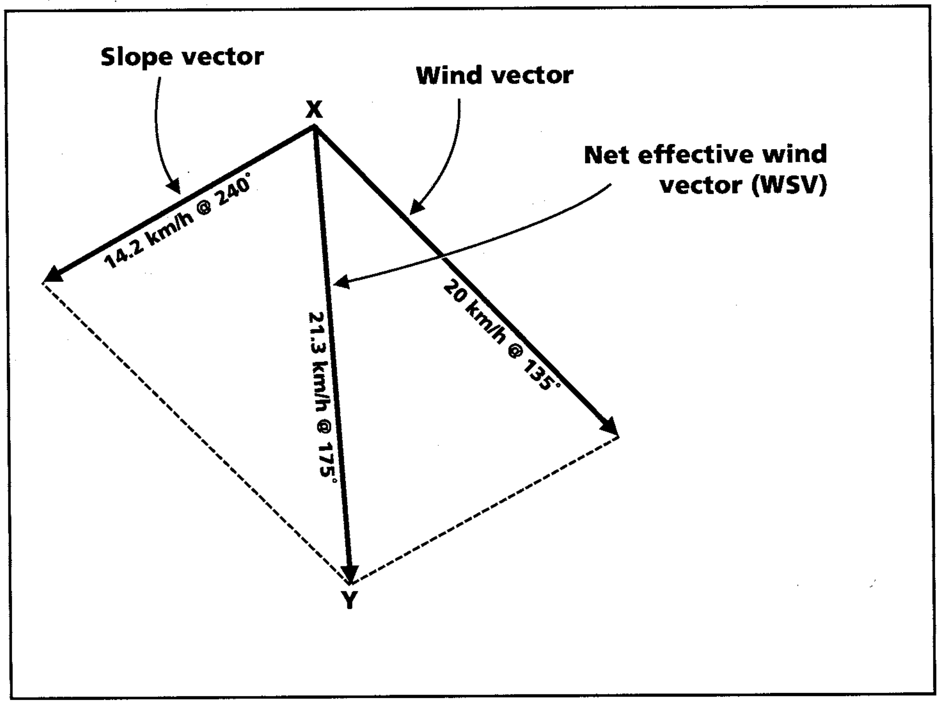


Figure 18. Schematic diagram illustrating vector addition.

Step 6. Use the net effective wind speed (WSV) in conjunction with the FFMC to calculate a wind/slope-adjusted (or final) ISI.

This is calculated from the FWI System using the standard ISI equation.

If FFMC = 92, and
WSV = 21.3 km/h, then
final ISI = 16.7

Step 7. Use the wind/slope-adjusted (or final) ISI to calculate a wind/slope-adjusted rate of spread (RSI) using the basic ISI/rate of spread curves.

If fuel type	**= C-3, and**
ISI	**= 16.7, then**
RSI	**= 15.8 m/min.**

Interpretation: the combined forces of slope (steepness = 56.3%; aspect = 60°) and wind (speed = 20 km/h; direction = 315°) on a fire burning in a Mature Lodgepole Pine (C-3) fuel type with an FFMC = 92, will result in a predicted rate of spread of 15.8 m/min at a direction of 175°.

4.1.1.3 Buildup Effect on Rate of Spread

The final step used in the FBP System to predict rate of spread modifies the basic rate of spread (or wind/slope-adjusted rate of spread, if applicable) to account for the amount of fuel that is available for combustion within the entire fuel complex. This modification is based on the Buildup Index (BUI) of the FWI System, which is a relative measure of the amount of fuel that becomes available for combustion as drying occurs.

The buildup effect influences rate of spread in the form of a multipler:

Basic (or slope adjusted) rate of spread × **Buildup effect** = **Adjusted rate of spread**

Theoretically, as the amount of available fuel increases (i.e., the higher the BUI becomes) the greater the fire intensity will be. This will result in the production of more heat, which will cause preheating of the fuels to occur more readily, and will produce a faster spreading fire (Fig. 19). Unfortunately statistical evidence of this

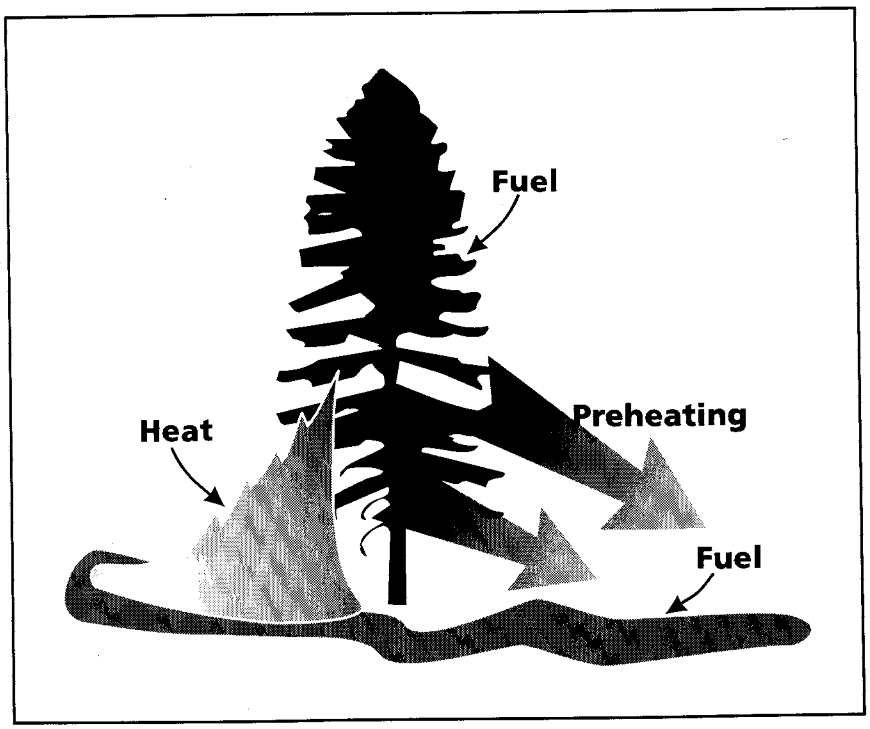


Figure 19. **Conceptual diagram illustrating the theoretical effect of large amounts of fuel availability on rate of spread.**

effect could not be found in the FBP System data base, which was judged to be a shortcoming of the empirical data. The buildup effect function was designed so that:

(1) the rate of spread would equal zero when the BUI is at zero, and

(2) the rate of spread curve would rise quickly with increasing BUI and level off at a finite BUI value (Fig. 20).

In some fuel types the buildup effect can have a significant impact on the rate of spread predictions, especially at higher ISI levels (Figs. 21 and 22).

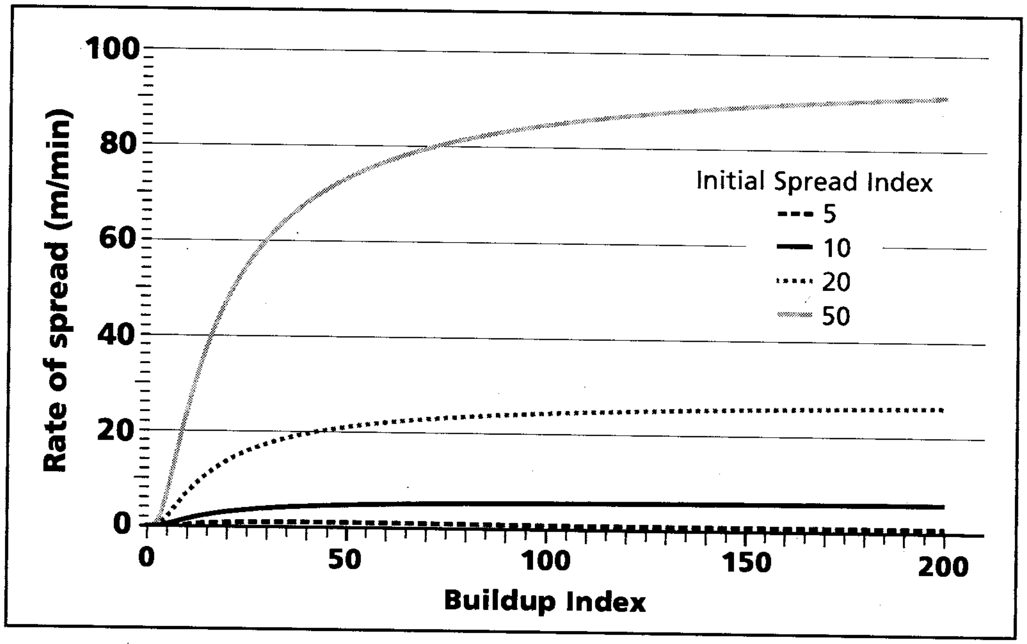


Figure 20. Rate of spread for the Mature Jack or Lodgepole Pine (C-3) fuel type for selected Initial Spread Index (ISI) and Buildup Index (BUI) values.

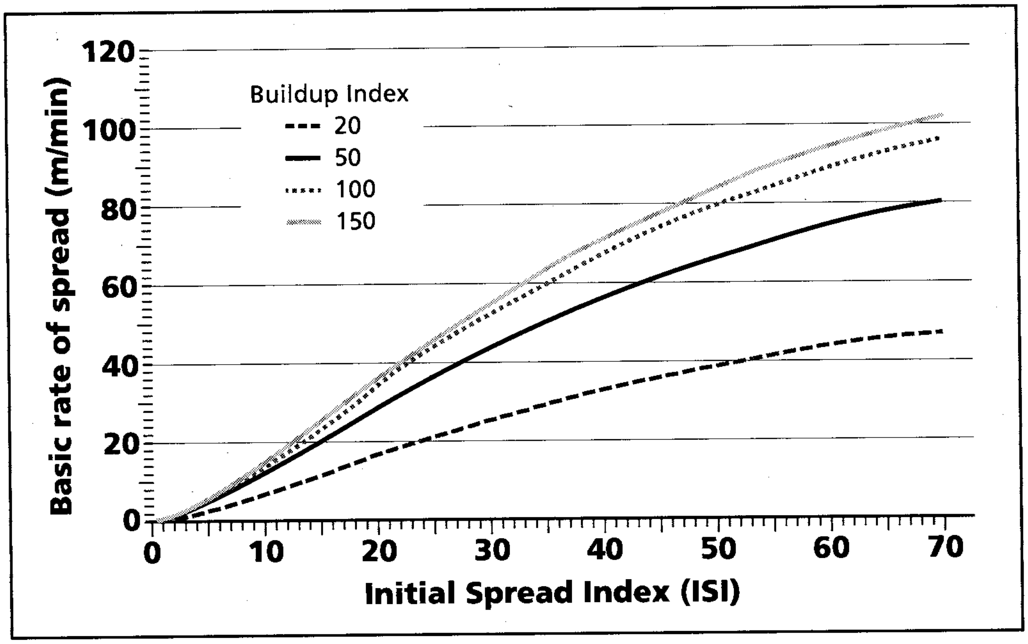


Figure 21. Rate of spread for the Boreal Spruce (C-2) fuel type for selected Initial Spread Index (ISI) and Buildup Index (BUI) values.

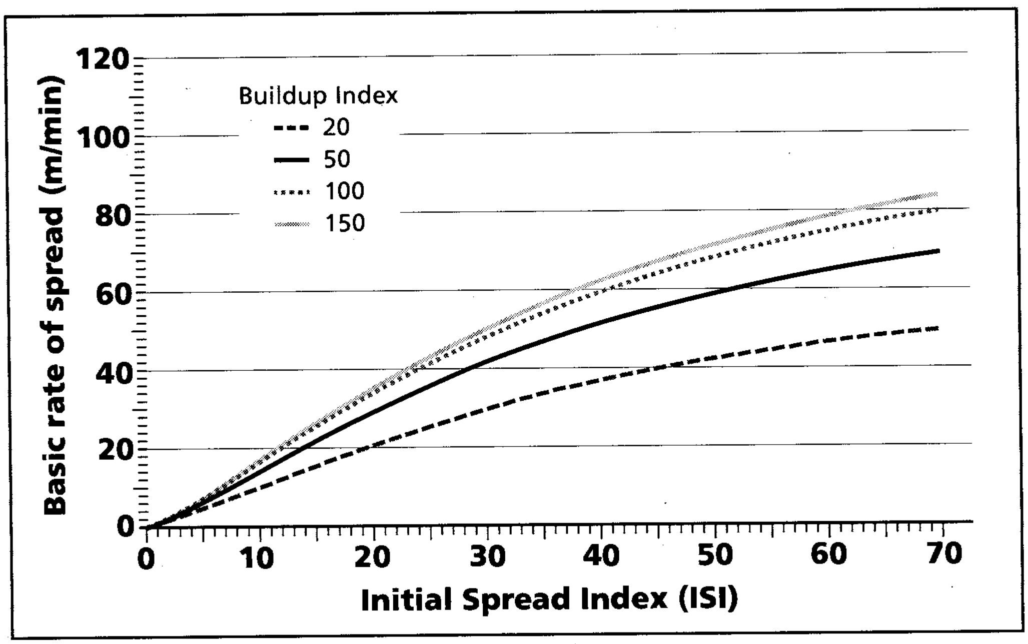


Figure 22. Rate of spread for the Jack or Lodgepole Pine (S-1) fuel type for selected Initial Spread Index (ISI) and Buildup Index (BUI) values.

Exercise 3.

Calculating the basic and adjusted head fire rate of spread

Using the information presented in Sections 4.1.1.1 and 4.1.1.3, calculate the basic and adjusted head fire rates of spread for each case below.

Case no.	Fuel type	Initial Spread Index	Basic rate of spread (m/min)[a]	Buildup Index	Buildup effect[b]	Adjusted rate of spread (m/min)[c]
1	C-2	5	________	*20*	*0.54*	________
2	C-2	5	________	*50*	*0.93*	________
3	C-2	5	________	*150*	*1.17*	________
4	C-2	10	________	*100*	*1.11*	________
5	C-2	20	________	*100*	*1.11*	________
6	C-2	40	________	*100*	*1.11*	________
7	C-3	5	________	*20*	*0.62*	________
8	C-3	5	________	*50*	*0.95*	________
9	C-3	20	________	*100*	*1.09*	________

[a] Estimate using Figure 12 (page 43) or for C-3 use Table 10 (page 42).

[b] Given for this exercise. See pages 33–34 in Forestry Canada Fire Danger Group (1992) for the actual formulas.

[c] Estimate using Figures 20 (page 55) and 21 (page 56) or multiply the basic rate of spread by the buildup effect.

Suggested answers:

Calculating the basic and adjusted head fire rate of spread

Case no.	Fuel type	Initial Spread Index	Basic rate of spread (m/min)[a]	Buildup Index	Buildup effect[b]	Adjusted rate of spread (m/min)[c]
1	C-2	5	5.2	*20*	*0.54*	2.8
2	C-2	5	5.2	*50*	*0.93*	4.8
3	C-2	5	5.2	*150*	*1.17*	6.1
4	C-2	10	13.4	*100*	*1.11*	14.9
5	C-2	20	31.1	*100*	*1.11*	34.5
6	C-2	40	61.2	*100*	*1.11*	67.9
7	C-3	5	0.9	*20*	*0.62*	0.6
8	C-3	5	0.9	*50*	*0.95*	0.9
9	C-3	20	22.4	*100*	*1.09*	24.4

[a] Estimate using Figure 12 (page 43) or for C-3 use Table 10 (page 42).

[b] Given for this exercise. See pages 33–34 in Forestry Canada Fire Danger Group (1992) for the actual formulas.

[c] Estimate using Figures 20 (page 55) and 21 (page 56) or multiply the basic rate of spread by the buildup effect.

4.1.1.4 Rate of Spread in the Grass (O-1) Fuel Type

The FBP System provides two sub-groups of the O-1 fuel type, namely, matted grass (O-1a) and standing grass (O-1b). Matted grass refers to those areas where the early spring fuel has been compacted by heavy amounts of snow. Standing grass represents midsummer fields of dry grass or sites that received very little overwinter snowfall.

Head fire rate of spread in the two O-1 fuel type sub-groups is modeled in a slightly different format than the other FBP System fuel types. First, the data on which the curves are based was obtained exclusively from experimental fires and wildfires in tall and cut grass fuels in Australia. Second, though the general shape of the rate of spread curve remains s-shaped, the final rate of spread will also depend on the percentage of cured grass[6] that is present on a site. The FBP System accounts for curing by assuming that the rate of spread will:

(a) be zero if the proportion of cured material is less than or equal 50%, and

(b) increase in a linear fashion between a percentage cured of 50% and 100%.

Figures 23 and 24 present the basic rate of spread curves for matted grass and standing grass for various amounts of curing. Once the basic rate of spread has been determined it is possible to make adjustments for slope and the buildup effect in the same manner as for any other fuel type.

[6] The percentage of cured material on a site refers to the proportional number of grass stems that have dried out and are no longer green.

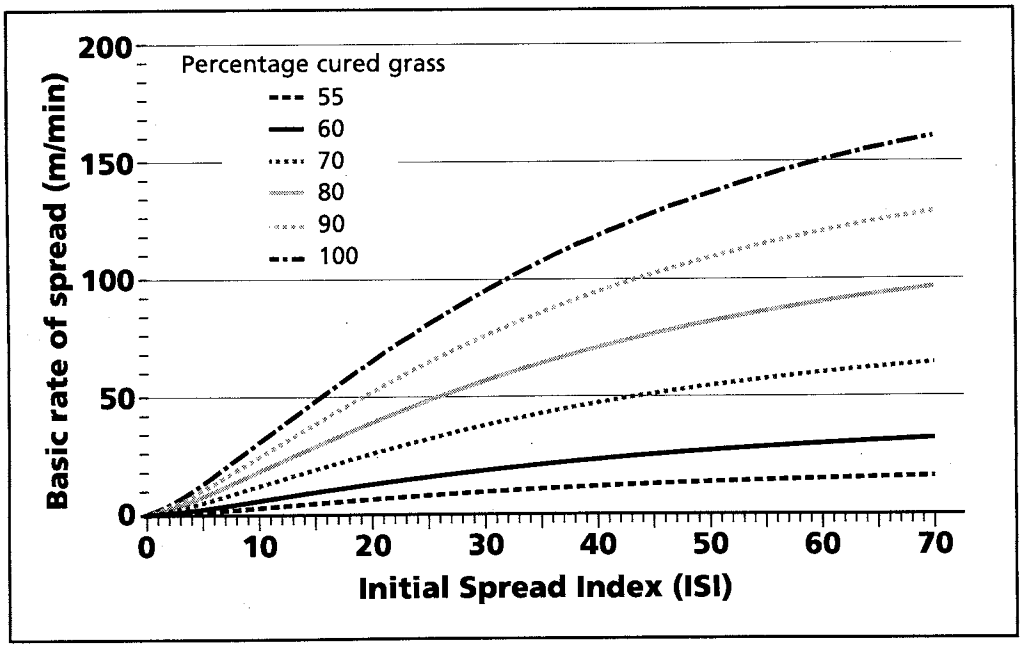


Figure 23. Rate of spread curves for the Matted Grass (O-1a) fuel type for selected percentages of cured grass.

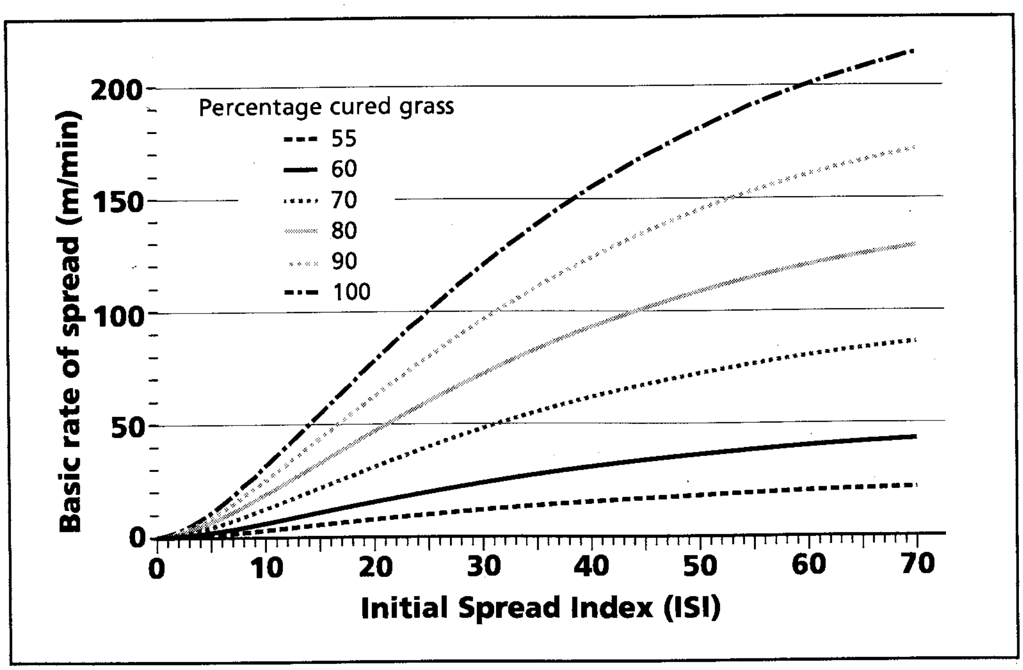


Figure 24. Rate of spread curves for the Standing Grass (O-1b) fuel type for selected percentages of cured grass.

4.1.1.5 Rate of Spread in the Conifer Plantation (C-6) Fuel Type

The FBP System uses an alternative, dual-equation model to predict rate of spread in the Conifer Plantation (C-6) fuel type. This is due, in part, to the fact that plantations tend to be more uniform in structure than natural forest stands. For the C-6 fuel type, the potential rate of spread is bounded by two rate of spread curves (Fig. 25). The lower curve represents possible rates of spread for surface fires and the upper curve defines the rate of spread for crown fires. Intermittent crown fires would exist between the two curves above the critical rate of spread line (RSO). Determination of the exact rate of spread depends upon:

(a) the final surface fire rate of spread (i.e., the basic surface fire rate of spread adjusted for slope and the buildup effect) (Fig. 26),

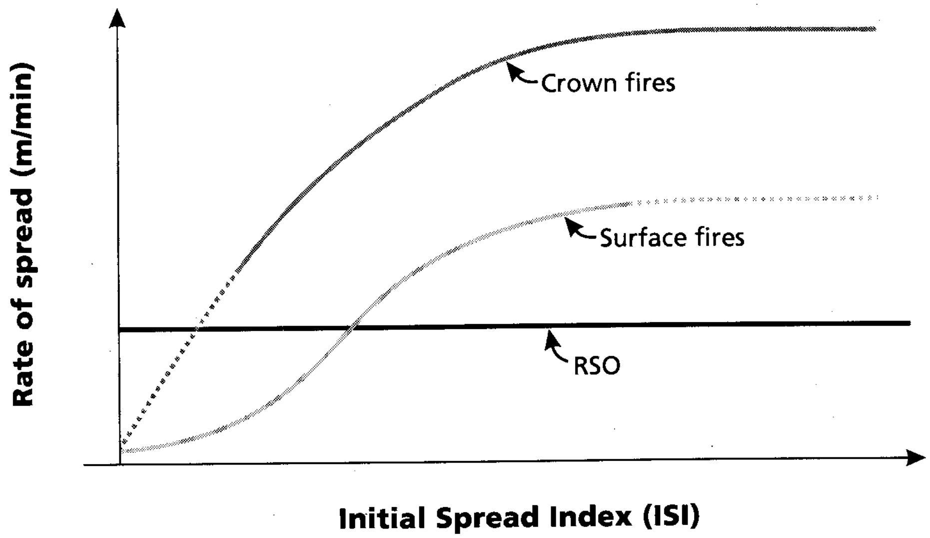
(b) the final crown fire rate of spread (which, for the C-6 fuel type, varies according to the foliar moisture content) (Fig. 27), and

(c) the degree of crown involvement, expressed as the crown fraction burned (see Section 4.1.2.3).

The relationship of these items is presented in Equation 7 and is explained in further detail in the FBP System technical report (see Forestry Canada Fire Danger Group 1992).

$$ROS = RSS + [CFB \times (RSC - RSS)] \qquad (7)$$

where ROS = final head fire rate of spread (m/min),
RSS = final surface fire rate of spread for C-6 fuel type (m/min),
RSC = final crown fire rate of spread for C-6 fuel type (m/min), and
CFB = crown fraction burned.



Note: the dashed lines indicate portions of the curves that are unlikely to be used because surface fires will not occur under extreme conditions and continuous crown fires will be unlikely at low ISI values.

RSO = Critical surface fire rate of spread. This line will move upwards or downwards depending on the plantations live crown base height, the foliar moisture content and the amount of surface fuel consumption.

Figure 25. Conceptual diagram illustrating the dual equation rate of spread model for the Conifer Plantation (C-6) fuel type.

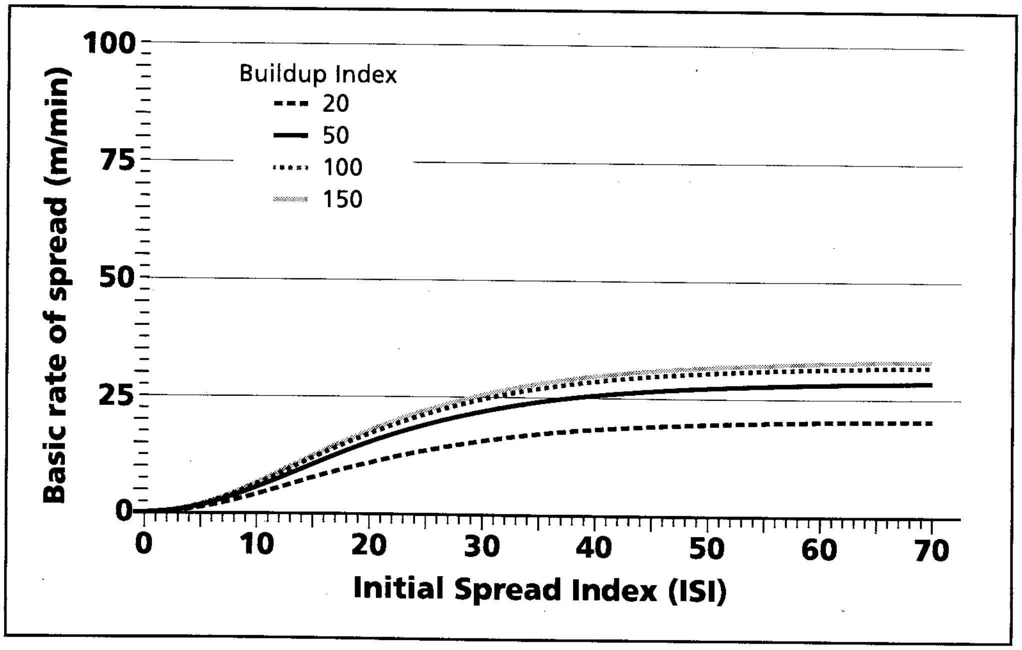


Figure 26. Surface fire rate of spread curves for selected Buildup Index (BUI) values for the Conifer Plantation (C-6) fuel type.

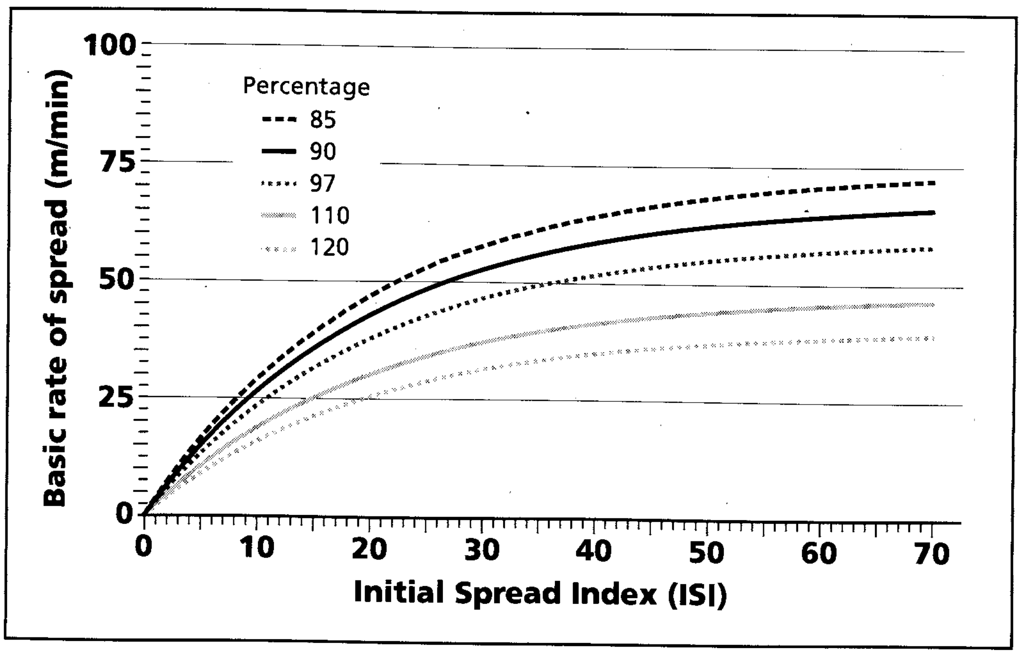
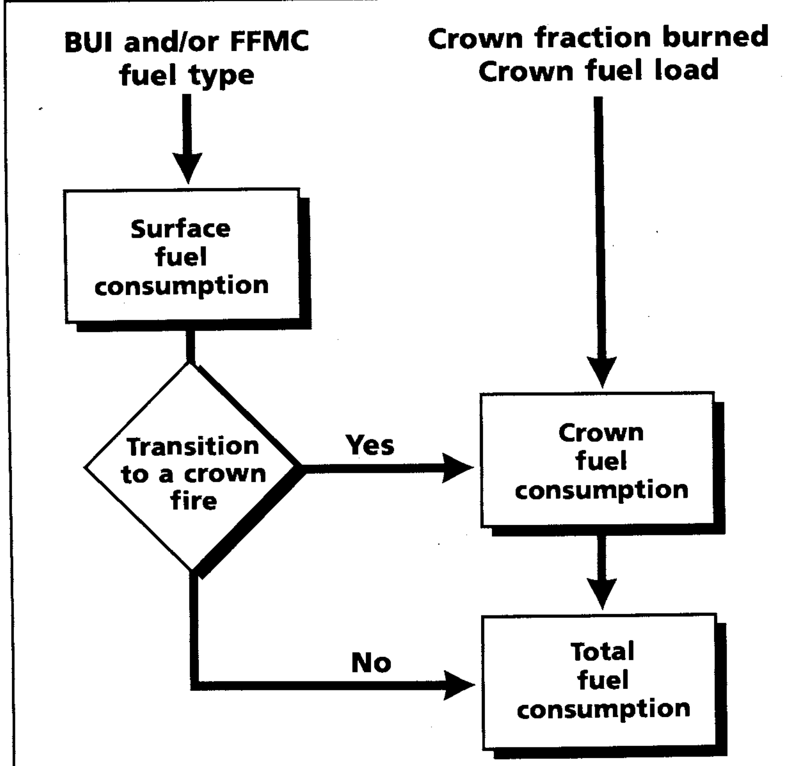


Figure 27. Crown fire rate of spread curves for selected foliar moisture content (FMC) values for the Conifer Plantation (C-6) fuel type.

4.1.2 Fuel Consumption

The prediction of total fuel consumption (TFC) requires the estimation of the surface fuel consumption (SFC) and, if applicable, the crown fuel consumption (CFC). Surface fuel consumption is based primarily on the BUI or FFMC and varies for each fuel type. Crown fuel consumption is dependent upon the degree of crown involvement, represented by the crown fraction burned (CFB), and the crown fuel load assigned to each fuel type (Fig. 28).



BUI = Buildup Index.
FFMC = Fine Fuel Moisture Code.

Figure 28. Flow chart depicting the inputs and processes used to predict total fuel consumption.

4.1.2.1 Surface Fuel Consumption

Surface fuel consumption (SFC) refers to the consumption of both woody (i.e., dead and down) and forest floor (i.e., organic layer, including litter and duff) fuels. It is a fuel type specific value based on the Buildup Index (BUI) and/or the Fine Fuel Moisture Code (FFMC) of the FWI System (Table 11). The relationship was derived from an empirical data set, obtained primarily from experimental fires and well-documented prescribed fires, using non-linear regression techniques similar to those used in calculating the basic head fire rate of spread values.

The assumptions and general features of the fuel consumption relationships are given below and an example is shown in Figure 29. The surface fuel consumption curves and equations for all of the fuel types can be found on pages 22–23 in the FBP technical report (Forestry Canada Fire Danger Group 1992).

Table 11. Indexes and range of data used in the FBP System fuel consumption functions

Fuel type	FWI system index	Number of data points	Index range		Total fuel consumption (kg/m^2) range[a]	
			Minimum	Maximum	Minimum	Maximum
C-1	FFMC	7	82	92.8	0.23	2.15
C-2	BUI	13	13	65.0	1.10	3.49
C-3	BUI	41	24	95.0	0.23	03.92
C-4	BUI	15	27	70.0	0.95	3.44
C-5	BUI	10	43	107.0	0.40	3.07
C-6	BUI	11	38	109.0	0.55	3.70
C-7	FFMC	3	89	94.0	4.30	5.33
—[b]	BUI	—	96	139.0	—	—
D-1	BUI	26	14	57.0	0.12	3.20
M-1	BUI	n/a[d]	n/a	n/a	n/a	n/a
M-2[c]	BUI	n/a	n/a	n/a	n/a	n/a
M-3	BUI	6	25	59.0	2.65	4.48
M-4	BUI	6	25	59.0	2.65	4.48
O-1[e]	n/a	n/a	n/a	n/a	n/a	n/a
S-1	BUI	56	7	87.0	1.51	27.40
S-2	BUI	65	15	114.0	3.69	17.50
S-3	BUI	32	15	63.0	3.39	25.72

[a] The minimum and maximum fuel consumption values do not necessarily correspond with the minimum and maximum index values.

[b] Fuel type C-7 uses both BUI and FFMC to calculate fuel consumption. This table shows 3 data points with an FFMC range of 89 to 94 and a BUI range of 96 to 139, which produces a fuel consumption range of 4.3 to 5.33.

[c] Surface fuel consumption values are based on the C-2 and D-1 values, weighted according to the percentage of coniferous and deciduous species in the stand.

[d] n/a = not applicable.

[e] Fuel consumption in the grass fuel type is equal to the grass fuel load.

Assumptions and General Features

(a) The surface fuel consumption relationships do not account for the consumption of live fuels such as shrubs.

(b) It is assumed that all fuel is consumed during the passing of the fire front. There is no attempt to distinguish between the fuel consumed in the flaming and smouldering phases of combustion.

(c) Due to the difficulty of collecting fuel consumption data, especially on wildfires, the data for some fuel types has been combined. This includes C-2 with M-3/M-4, C-3 with C-4, and C-5 with C-6. The upper range of the data in most fuel types is also limited because experimental fires are rarely conducted when extreme BUI values exist (Table 11).

(d) The s-shaped fuel consumption curves, similar in form to those used to predict head fire rate of spread, ensures that for all fuel types the surface fuel consumption will equal zero when the BUI is zero and that the surface fuel consumption will level of at extreme BUI values.

(e) For the C-1 fuel type, the surface fuel consumption is based on the FFMC (Fig. 30) because the majority of the fuel available for consumption in this fuel type is reindeer lichen and some fine woody fuels.

(f) For the C-7 fuel type, which has a shallow forest floor, surface fuel consumption is determined by adding the predicted woody fuel consumption (based on the BUI) to the predicted forest floor consumption (based on the FFMC).

(g) It is assumed that for the O-1 fuel type, all of the cured grass fuel on a site will be consumed by the fire. Therefore, fuel consumption will equal the amount of fuel on the site. The standard fuel load used in the FBP System is 0.3 kg/m^2; however, this value can be altered if site-specific estimates or measurements are made.

(h) Surface fuel consumption for the slash fuel types is predicted by summing predictions of the woody fuel consumption and the forest floor consumption. Both predictions are based on the BUI (Fig. 31).

Surface fuel consumption is based primarily on the BUI

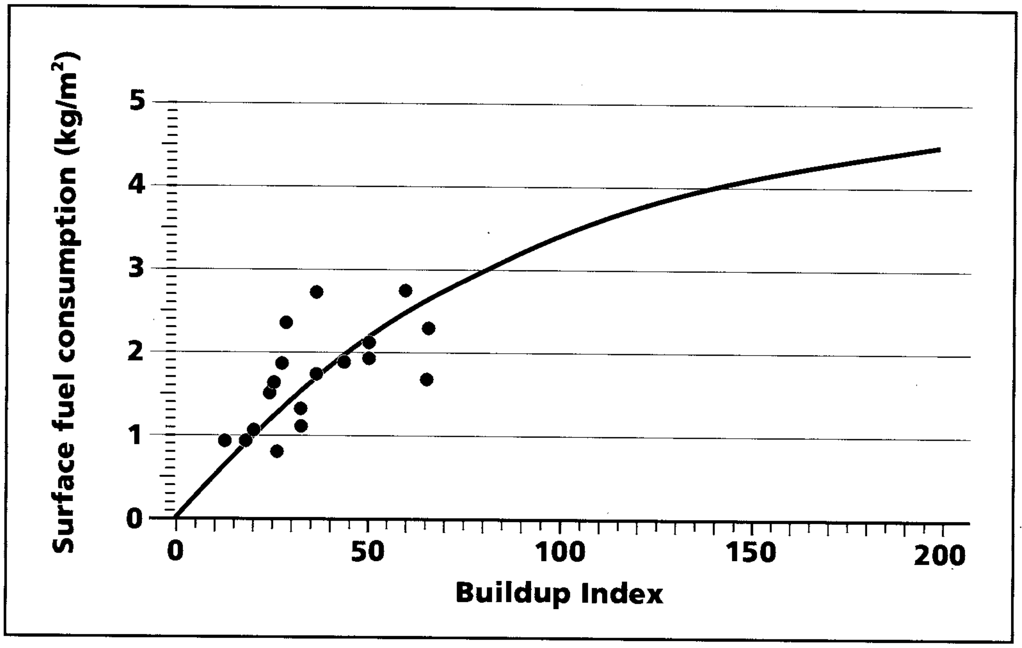


Figure 29. Surface fuel consumption curve and data points for the Boreal Spruce (C-2), Dead Balsam Fir/Mixedwood (M-3/M-4) fuel types.

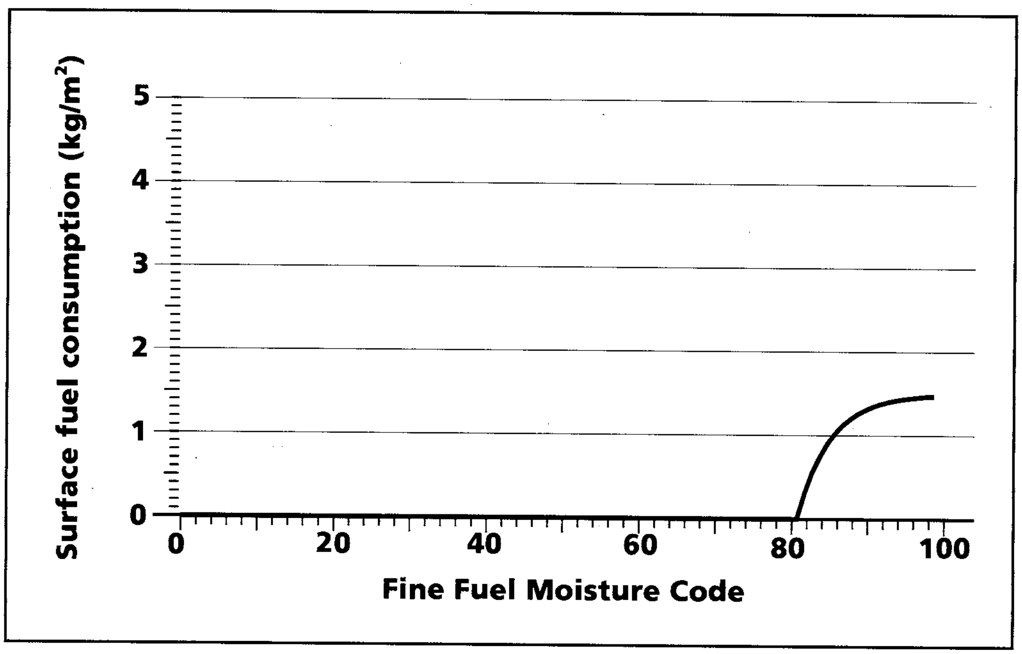


Figure 30. Surface fuel consumption curve for the Spruce–Lichen Woodland (C-1) fuel type.

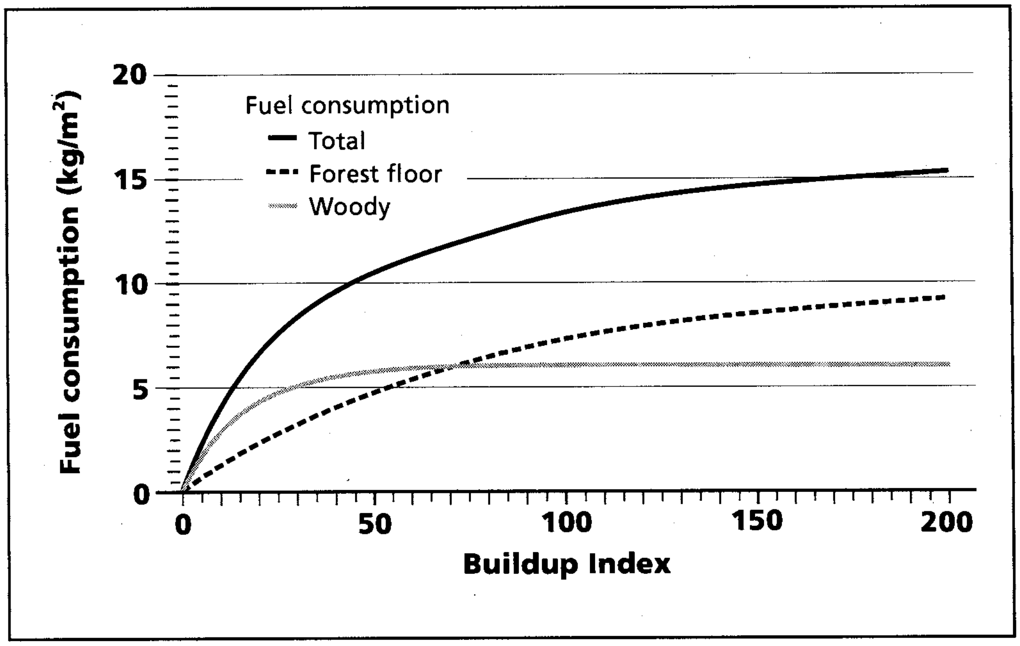


Figure 31. Surface fuel consumption curves for the Spruce/Balsam Slash (S-2) fuel type.

4.1.2.2 Transition from Surface Fire to Crown Fire

In order to determine total fuel consumption, and subsequently head fire intensity, it is first necessary to predict whether a given fire will be strictly a surface fire or have some degree of crown involvement. This is dependent upon the predicted surface fire intensity, the foliar moisture content, and the height to the live crown base (Fig. 32).

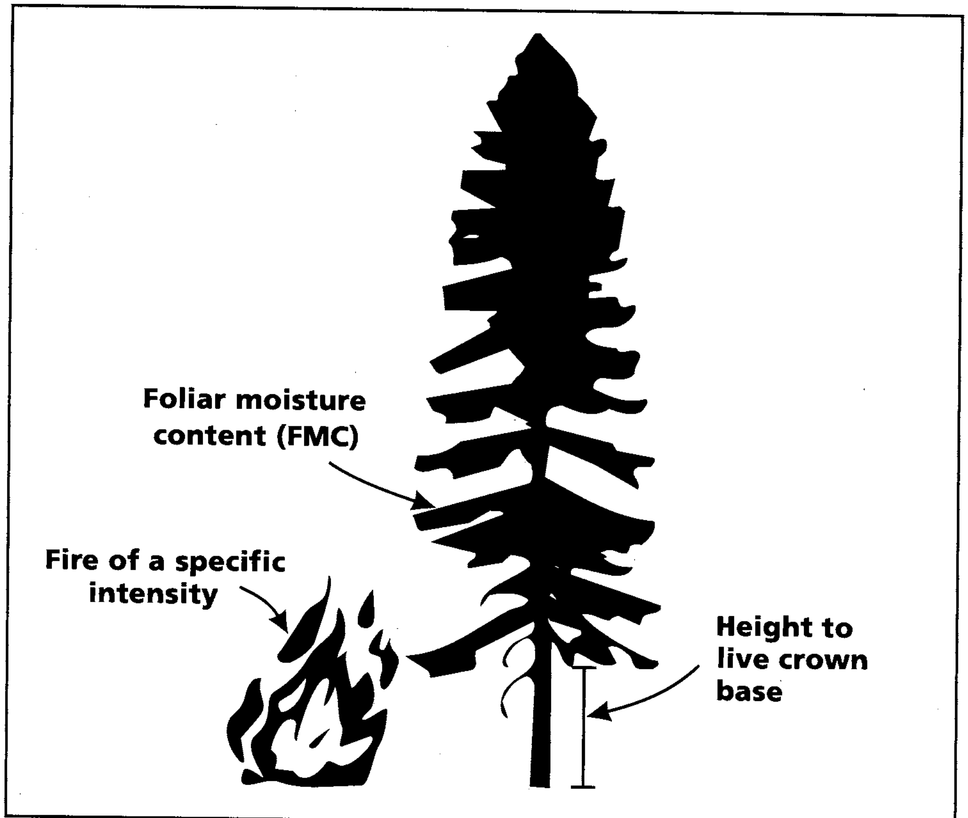


Figure 32. Illustration of the parameters that influence the prediction of crown fire involvement.

Van Wagner's Crown Fire Theory

The approach used in the FBP System to predict crown fire initiation is based on Van Wagner's (1977b) crown fire theory. This theory compares the surface fire intensity (SFI) to a **critical** surface fire intensity (CSI) value, which is derived from the height of the live crown base (CBH) and foliar moisture content (FMC). If the intensity of a surface fire exceeds the critical surface fire intensity, then the live tree crowns will ignite. For example, if SFI > CSI then there will be crown involvement, and if SFI ≤ CSI then there will be a surface fire (i.e., no crown involvement).

Critical Surface Fire Intensity

The critical surface fire intensity (Equation 8) is calculated from a fuel type specific crown base height (CBH) value (Table 12) and the foliar moisture content (FMC), which varies according to date, location (latitude and longitude), and elevation (see Section 3.4). Figure 33 shows that crown base height has a greater relative impact on CSI than the foliar moisture content.

$$CSI = 0.001 \times CBH^{1.5} \times (460 + 25.9 \times FMC)^{1.5} \quad (8)$$

where CSI = critical surface fire intensity required for crowning (kW/m),
CBH = height to the live crown base (m), and
FMC = foliar moisture content (%).

Table 12. Crown base height values for coniferous and mixedwood fuel types[a]

Fuel type		Crown base height (m)
(C–1)	Spruce–Lichen Woodland	2
(C–2)	Boreal Spruce	3
(C–3)	Mature Jack or Lodgepole Pine	8
(C–4)	Immature Jack or Lodgepole Pine	4
(C–5)	Red and White Pine	18
(C–6)	Conifer Plantation	variable[b]
(C–7)	Ponderosa Pine/Douglas-fir	10
(M–1)	Boreal Mixedwood—Leafless	6
(M–2)	Boreal Mixedwood—Green	6
(M–3)	Dead Balsam Fir/Mixedwood—Leafless	6
(M–4)	Dead Balsam Fir/Mixedwood—Green	6

[a]The crown fire theory was based on empirical data for its final quantitative form, therefore the height values assigned to each fuel type required some trial and error to ensure representative fire behavior predictions were produced.

[b]Crown base height for the conifer plantation fuel type is variable with tree height.

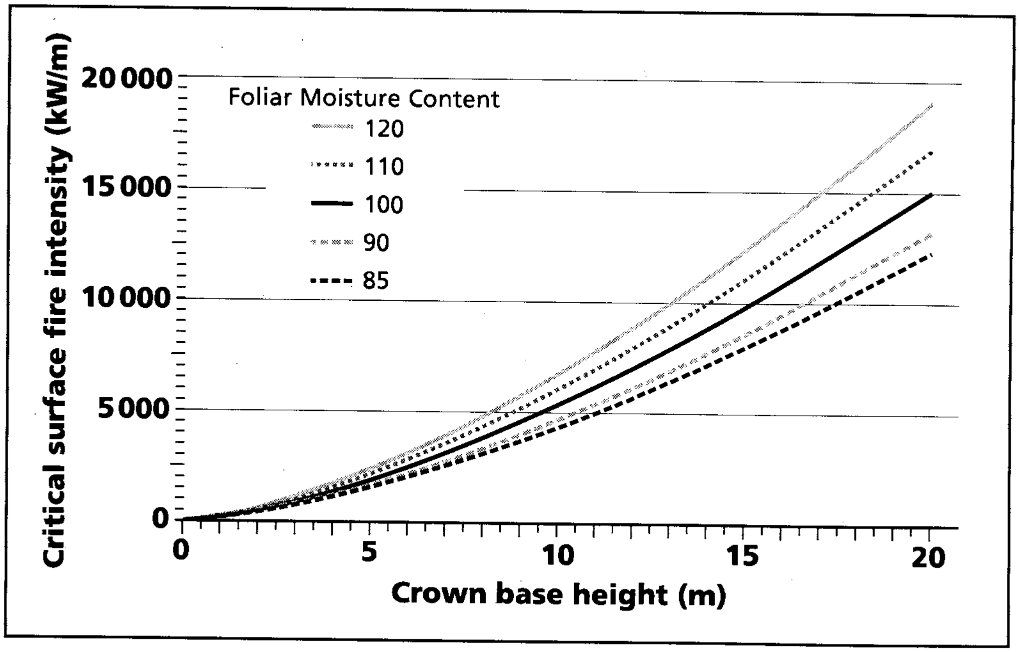


Figure 33. Selected critical surface fire intensity (CSI) values based on crown base height (CBH) and foliar moisture content (FMC).

Critical Surface Fire Rate of Spread

In the FBP System the critical surface fire intensity (CSI) value is mathematically converted to a critical surface fire rate of spread (RSO) value (Equation 9). This allows crown fire initiation to be determined by comparing the predicted rate of spread (ROS) for a particular fuel type to the critical rate of spread (Fig. 34). For example, if ROS > RSO then there will be crown involvement, and if ROS ≤ RSO then there will be a surface fire (i.e., no crown involvement).

$$\mathrm{RSO} = \frac{\mathrm{CSI}}{300 \times \mathrm{SFC}} \qquad (9)$$

where RSO = critical rate of spread required for crowning (m/min),
CSI = critical surface fire intensity required for crowning (kW/m), and
SFC = surface fuel consumption (kg/m²).

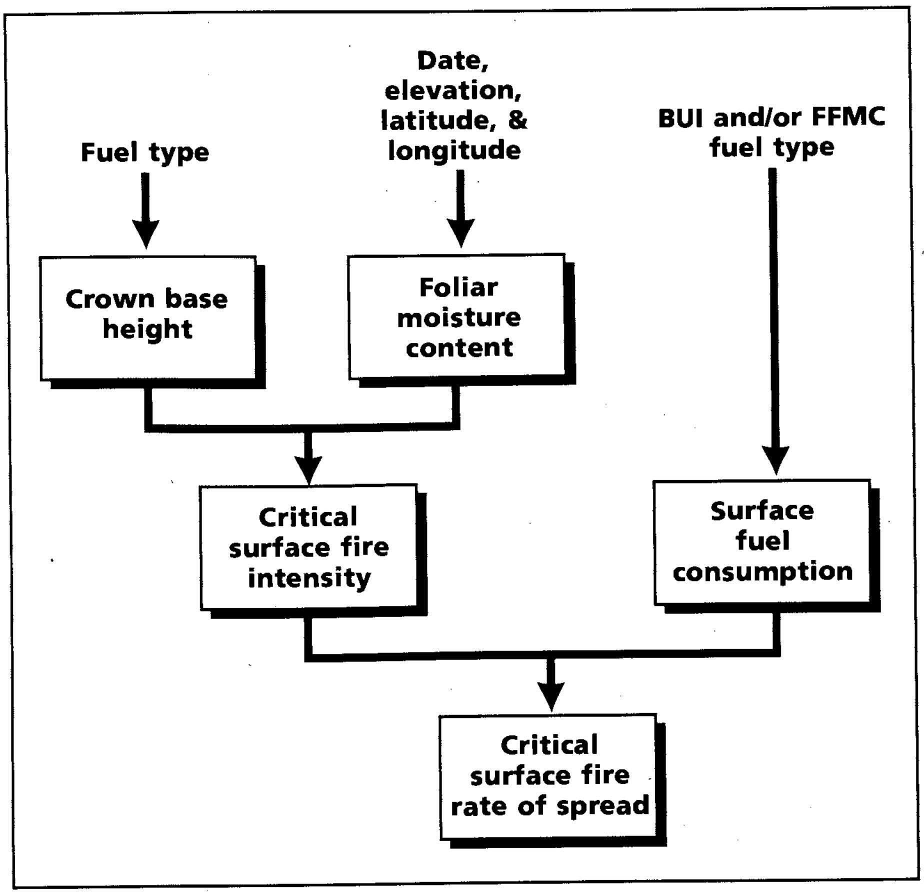


Figure 34. Inputs and process used to predict the critical surface fire rate of spread.

4.1.2.3 Crown Fraction Burned

The FBP System states that if the **predicted** surface fire rate of spread (ROS) exceeds the **critical** surface fire rate of spread (RSO) that the tree crowns will ignite, but what degree of crown involvement will there be in the fire?

To answer this question the FBP System relies on the following theory and assumptions.

(1) Fires undergo a gradual transition from being a surface fire to a complete crown fire.

(2) The degree of crown involvement depends on the amount by which the predicted rate of spread (ROS) exceeds the critical surface fire rate of spread for crowing (RSO). It was assumed that crown involvement will be 90% complete when the ROS exceeds the RSO by 10 m/min.

The transition function which indicates the degree of crown involvement is called the crown fraction burned (CFB). It is presented in Equation 10 and illustrated in Figure 35.

Crown fraction burned (CFB) is dependent on the predicted rate of spread (ROS) and the critical surface fire rate of spread (RSO) which, in turn, is based on the crown base height (CBH) and foliar moisture content (FMC). This means that the CFB will vary according to location, elevation, and date as well as by fuel type. Crown fraction burned refers to the percentage of a given area where the crown fuel has been consumed. This conveys on a spatial basis, the idea that fires may involve the crown fuel layer for a period of time, drop down to be a surface fire for a few moments, and then return to the tree crowns. A crown fraction burned of 50% does not, therefore, imply that the bottom half of every tree crown in an entire area was consumed by the fire.

The crown fraction burned will be 90% when ROS exceeds RSO by 10 m/min.

$$CFB = 1 - e^{-0.23 \times (ROS-RSO)} \qquad (10)$$

where CFB = crown fraction burned,
ROS*= predicted rate of spread (m/min), and
RSO = critical surface fire rate of spread required for crowning (m/min).

*ROS is replaced by RSS for the C-6 fuel type.

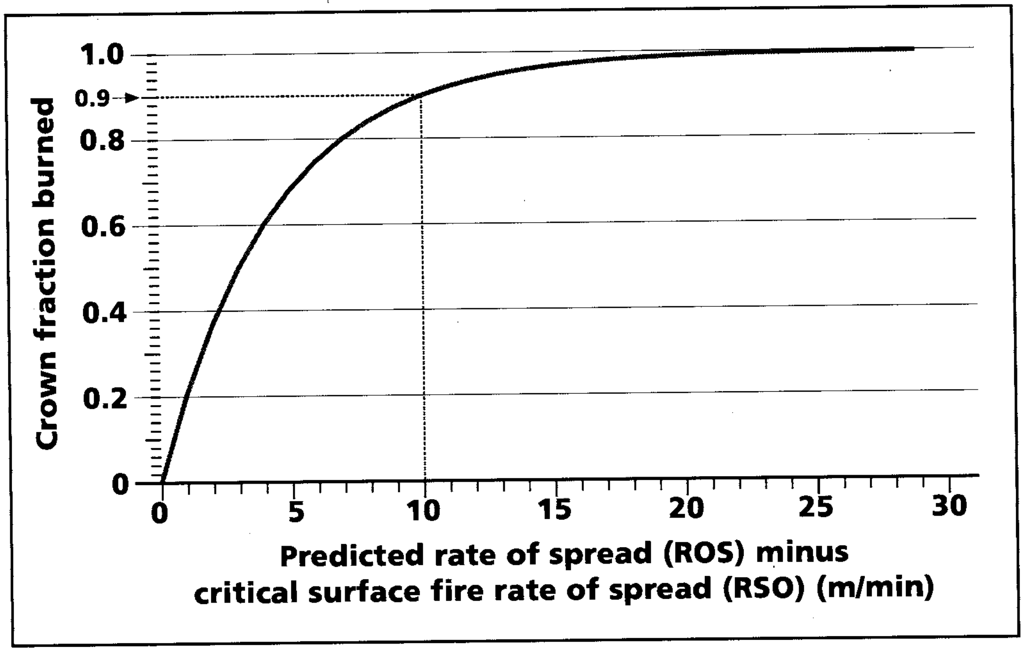


Figure 35. Crown fraction burned curve.

4.1.2.4 Crown Fuel Consumption

Crown fuel consumption (CFC) is calculated from the total amount of crown fuel available for consumption, termed the crown fuel load (CFL), and the degree of crown involvement as indicated by the crown fraction burned (CFB) (Equation 11). The calculation of crown fuel consumption assumes that only the foliage (i.e., needles) and twigs less than 0.5 cm in diameter will be consumed by the fire. Crown fuel load values for FBP System fuel types that are prone to crowning are given in Table 13.

$$\mathbf{CFC = CFL \times CFB} \qquad \mathbf{(11)}$$

where CFC = crown fuel consumption (kg/m²),
CFL = crown fuel load (kg/m²), and
CFB = crown fraction burned.

Table 13. Crown fuel load values for coniferous and mixedwood fuel types in the FBP System

Fuel type	Crown fuel load (kg/m²)
(C–1) Spruce–Lichen Woodland	0.75
(C–2) Boreal Spruce	0.80
(C–3) Mature Jack or Lodgepole Pine	1.15
(C–4) Immature Jack or Lodgepole Pine	1.20
(C–5) Red and White Pine	1.20
(C–6) Conifer Plantation	1.80
(C–7) Ponderosa Pine/Douglas-fir	0.50
(M–1) Boreal Mixedwood—Leafless	0.80
(M–2) Boreal Mixedwood—Green	0.80
(M–3) Dead Balsam Fir/ Mixedwood—Leafless	0.80
(M–4) Dead Balsam Fir/Mixedwood—Green	0.80

4.1.2.5 Total Fuel Consumption

The calculation of total fuel consumption (TFC) simply requires the addition of the surface fuel consumption (SFC) and the crown fuel consumption (CFC), if applicable (Equation 12). Figure 36 provides a graph showing total fuel consumption based on surface fuel consumption and selected crown fuel consumption values.

$$\mathbf{TFC = SFC + CFC} \qquad (12)$$

where TFC = predicted total fuel consumption (kg/m^2),
SFC = predicted surface fuel consumption (kg/m^2), and
CFC = predicted crown fuel consumption (kg/m^2).

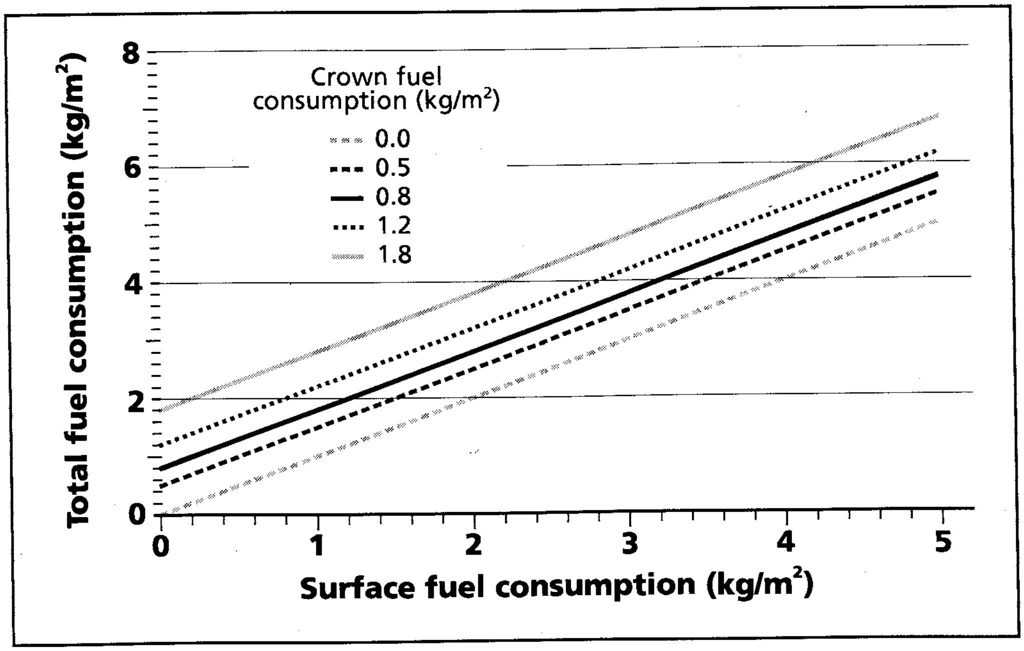


Figure 36. Total fuel consumption (TFC) based on surface fuel consumption (SFC) and selected crown fuel consumption (CFC) values.

4.1.3 Head Fire Intensity

The approach used in the FBP System to determine the predicted head fire intensity (HFI) is an adaptation of Byram's (1959) fire intensity equation (which is described briefly in Section 4.1). The FBP System uses the predicted head fire rate of spread (ROS) and the predicted total fuel consumption (TFC) to calculate the predicted head fire intensity (HFI) (Equation 13).

$$\text{HFI} = 300 \times \text{TFC} \times \text{ROS} \qquad (13)$$

where HFI = predicted head fire intensity (kW/m),
TFC = predicted total fuel consumption (kg/m^2), and
ROS = predicted head fire rate of spread (m/min).

The value of 300 in Equation 4.1.3 is calculated by dividing an assumed constant value for the low heat of combustion (i.e., 18 000 kJ/kg) by 60 so that the rate of spread can be expressed in m/min rather than m/sec. Note also that the predicted fuel consumption value will reflect whether a particular fire is a surface fire or a fire that involves some degree of crowning.

Fire intensity is a unique measurement because different combinations of rate of spread and fuel consumption values can produce the same HFI values (Equation 13 and Fig. 37). This means that two fires that have the same HFI value could display somewhat different types of behavior. For example, a fire with a ROS of 13.3 m/min and a fuel consumption value of 1.0 kg/m^2 would have a HFI of 4000 kW/m. This would likely be a fast moving, shallow burning fire that would not consume the deeper duff or medium to larger fuels. On the other hand, a fire with a ROS of 3 m/min and a fuel consumption value of 4.5 kg/m^2 would also have an intensity of 4000 kW/m; however, it would be a slow moving, deep burning fire that would consume a high percentage of the medium and heavy fuels on a site. Thus, even though these two fires have the same intensity their behavior will be different and could require different fire suppression strategies to ensure containment or have significantly different impacts on the forest ecosystem.

In Canada, fire intensity is technically defined as "the rate of heat energy release per unit time per unit length of fire front" and is synonymous with other terms such as frontal fire intensity and fire line intensity. Through research, fire intensity has been related to the visual characteristics of laboratory fires such as flame length and height. General descriptions of fire behavior, based on fire intensity, also have been developed for specific fuel types (e.g., Alexander and De Groot 1988 for the Mature Jack or Lodgepole Pine (C-3) fuel type and Alexander and Lanoville (1989) for the Spruce–Lichen Woodland (C-1) fuel type). An adaptation of these descriptions is presented in Table 14 for selected FBP System fuel types. It should be noted that these descriptions are meant to serve as general indicators of fire behavior once the fire has become established, and that site-specific fuel, weather, and topographic conditions may result in variation from what has been presented here.

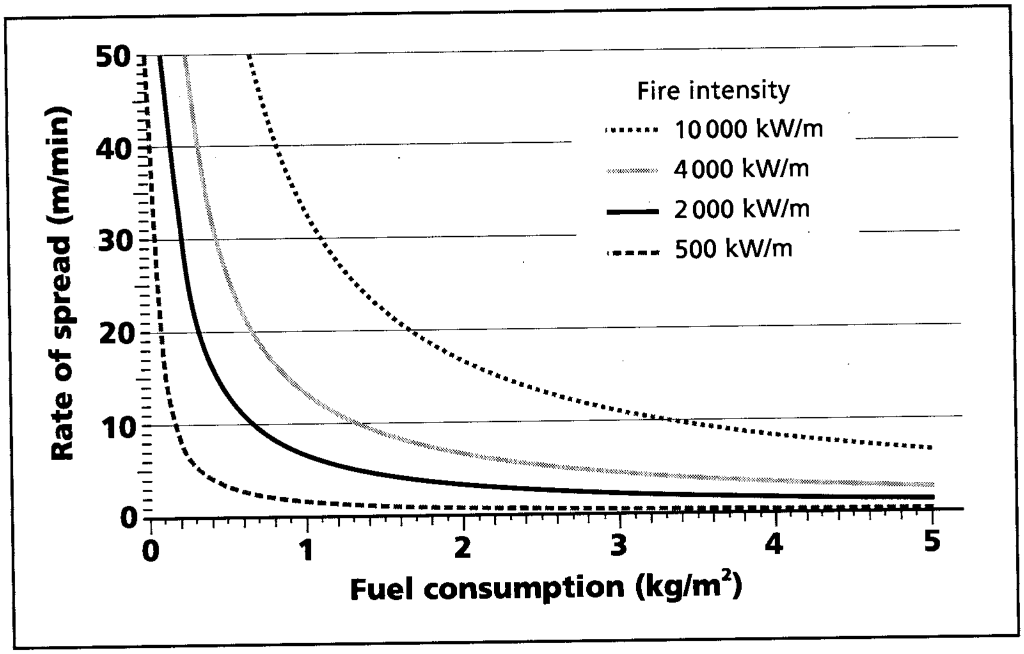


Figure 37. Selected fire intensity values based on the rate of spread and fuel consumption.

Table 14. General fire behavior descriptions based on head fire intensity for selected FBP System fuel types[a]

HFI category[b] (kW/m)	General fire behavior description[c]: Fuel types with ladder fuels present[d]	General fire behavior description[c]: Fuel types with ladder fuels absent[e]
<10	Fires, if they are able to sustain themselves, do not usually spread much beyond their point of origin and are often of the smouldering or subsurface variety with very little visible flame.	Fires, if they are able to sustain themselves, do not usually spread much beyond their point of origin and are often of the smouldering or subsurface variety with very little visible flame.
10–500	Generally slow moving surface fires with relatively low flames. In stands with very low crown base heights, a small portion of the foliage of individual tree crowns may be ignited.	Generally slow moving surface fires with relatively low flames.
500–2 000	Moderately fast spreading fires at times displaying both low and high flames. Ignition of individual tree crowns (i.e., isolated torching) will occur.	Moderately slow spreading surface fires displaying primarily low flames and occasionally high flames. Ladder fuels such as tree lichen and bark flakes may be consumed.
2 000–4 000	Fast spreading fires exhibiting mostly high flames. Intermittent crown fires with isolated to abundant torching may develop. Short range spotting may occur.	Moderately fast spreading fires exhibiting both low and high flames. Individual tree crowns may ignite (i.e., isolated torching).
4 000–10 000	Very fast spreading fires with abundant torching and possibly continuous crowning in dense stands. Flames will extend from the forest floor to above the forest canopy. Short to medium range spotting is likely.	Fast to very fast spreading fires with abundant torching and possibly continuous crowning. Flames may extend from the forest floor to above the forest canopy. Short to medium range spotting is possible.
>10 000	Fires may display extremely rapid spread rates, continuous crowning, great walls of flames, towering convection columns, medium to long range spotting, and firewhirls.	Fires may display extremely rapid spread rates, continuous crowning, great walls of flames, towering convection columns, medium to long range spotting, and firewhirls.

[a] Adapted, in part, from Alexander and De Groot (1988), Alexander and Lanoville (1989), and Alexander and Cole (1995). This table is not intended for use with the D-1, O-1, S-1, S-2, and S-3 fuel types.

[b] Head fire intensity is a continuum and therefore the intensity categories provided here should be considered as fuzzy benchmarks rather than discrete break points between the types of fire behavior.

[c] These descriptions are meant to serve as general indicators of fire behavior for the specified fuel types once the fire has become established. Site specific fuel, weather, and topographic conditions could result in variation from what has been presented here.

[d] Generally refers to the C-1, C-2, and C-4 fuel types; however, C-6, M-1, M-2, M-3, and M-4 stands with low coniferous crown base heights or considerable ladder fuels can also be placed in this category.

[e] Generally refers to the C-3, C-5, and C-7 fuel types. Older or pruned C-6 stands in which the ladder fuels have been removed can also be considered in this category.

4.1.4 Fire Description

To further assist fire managers in describing the behavior of a fire, three qualitative categories have been developed based on the predicted crown fraction burned (Table 15). The surface fire category refers to fires that have little or no crown involvement. For example, a fire in which a single tree crown is periodically consumed would be considered a surface fire. At the opposite end of the scale, a continuous crown fire would be a fire with flames that would consistently extend from the ground to above the tree crowns. Intermittent crown fires lie between surface fires and continuous crown fires. In this large category it is possible to have fires that exhibit only isolated torching as well as fires that are actively torching but have not reached the continuous crowning stage. Use of these descriptive terms, especially the intermittent crowning category, should therefore be used in conjunction with other quantitative outputs of the FBP System such as crown fraction burned, fire intensity, fuel consumption, and rate of spread in order to provide the most accurate possible description of a fire.

Table 15. Type of fire categories used in the FBP System

Type of fire	Crown fraction burned
Surface fire	< 0.1
Intermittent crown fire	0.1–0.89
Continuous crown fire	≥ 0.9

Exercise 4.

Calculating selected primary outputs

Using the information provided in Section 4, and on page 82, complete the table below and answer the questions on pages 84 and 85.

Case	Fuel type	ROS[a] (m/min)	BUI[b]	SFC[c] (kg/m^2)	CBH[d] (m)	FMC[e] (%)	CSI[f] (kW/m)	RSO[g] (m/min)	ROS–RSO[h] (m/min)	CFB[i]	Type of fire[j]	Fuel consumption (kg/m^2) CFL[k]	CFC[l]	TFC[m]	HFI[n] (kW/m)
1	C-2	3.9	40	*1.85*	*3*	115	*1 048*	*1.9*	*2.0*	*0.37*	*Intermittent crown fire*	*0.80*	*0.30*	*2.15*	*2 516*
2	C-2	8.4	40			90									
3	C-3	8.4	40			90									
4	C-3	5.4	80			90									
5	C-3	16.1	80			115									

[a]ROS = rate of spread.
[b]BUI = Build Up Index.
[c]SFC = surface fuel consumption. Refer to Figure 38.
[d]CBH = crown base height. Refer to Table 12.
[e]FMC = foliar moisture content.
[f]CSI = critical surface intensity. Refer to Table 16.
[g]RSO = official surface fire rate of spread. Use RSO = CSI/(300 × SFC);see Equation 9.
[h]ROS = head fire rate of spread. Subtract RSO from ROS. If less than zero, enter zero.
[i]CFB = crown fraction burned. Refer to Figure 35 or Equation 10.
[j]Surface fire = CFB < 0.1; intermittent crown fire = CFB 0.1–0.89; continuous crown fire = CFB ≥ 0.9. See Table 15.
[k]CFL = crown fuel load. Refer to Table 13.
[l]CFC = crown fuel consumption. CFC = CFL × CFB. See Equation 11.
[m]TFC = total fuel consumption. TFC = SFC + CFC. See Equation 12.
[n]HFI = head fire intensity. HFI = 300 × TFC × ROS. See Equation 13.

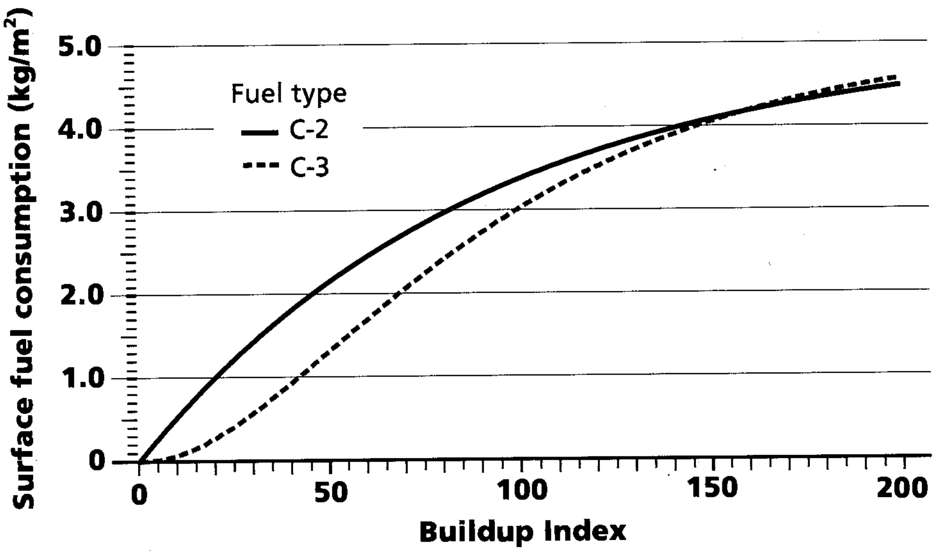


Figure 38. Surface fuel consumption (SFC) for the Boreal Spruce (C-2) and Mature Jack or Lodgepole Pine (C-3) fuel types.

Table 16. Critical surface fire intensity (kW/m) values for selected foliar moisture content and crown base height values[a]

Crown base height (m)	Foliar moisture content (%)							
	85	90	95	100	105	110	115	120
0	0	0	0	0	0	0	0	0
1	137	147	158	168	179	190	202	213
2	388	417	446	476	507	538	570	603
3	713	766	820	875	932	989	1 048	1 107
4	1 098	1 180	1 263	1 348	1 434	1 523	1 613	1 705
5	1 535	1 649	1 765	1 883	2 004	2 128	2 254	2 383
6	2 018	2 167	2 320	2 476	2 635	2 798	2 963	3 132
7	2 543	2 731	2 923	3 120	3 320	3 525	3 734	3 947
8	3 107	3 336	3 571	3 811	4 057	4 307	4 562	4 823
9	3 707	3 981	4 261	4 548	4 841	5 139	5 444	5 754
10	4 342	4 663	4 991	5 327	5 669	6 019	6 376	6 740
11	5 009	5 379	5 758	6 145	6 541	6 944	7 356	7 775
12	5 708	6 129	6 561	7 002	7 453	7 913	8 382	8 859
13	6 436	6 911	7 398	7 895	8 403	8 922	9 451	9 990
14	7 193	7 724	8 268	8 824	9 391	9 971	10 562	11 164
15	7 977	8 566	9 169	9 786	10 415	11 058	11 714	12 382
16	8 788	9 437	10 101	10 780	11 474	12 182	12 904	13 640
17	9 624	10 335	11 063	11 807	12 566	13 342	14 133	14 939
18	10 486	11 260	12 053	12 863	13 691	14 536	15 398	16 276
19	11 372	12 212	13 071	13 950	14 848	15 764	16 699	17 651
20	12 281	13 188	14 117	15 066	16 036	17 025	18 034	19 063

[a] Adapted from Alexander (1988).

Example: for a crown base height of 3 m and a foliar moisture content of 90% the critical surface fire intensity is 766 kW/m.

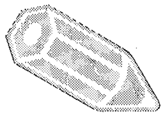
Suggested answers:

Calculating selected primary outputs

Case	Fuel type	ROS[a] (m/min)	BUI[b]	SFC[c] (kg/m^2)	CBH[d] (m)	FMC[e] (%)	CSI[f] (kW/m)	RSO[g] (m/min)	ROS–RSO[h] (m/min)	CFB[i]	Type of fire[j]	Fuel consumption (kg/m^2) CFL[k]	CFC[l]	TFC[m]	HFI[n] (kW/m)
1	C-2	3.9	40	*1.85*	*3*	115	*1 048*	*1.9*	*12.0*	*0.37*	*Intermittent crown fire*	*0.80*	*0.30*	*2.15*	*2 516*
2	C-2	8.4	40	*1.85*	*3*	90	*766*	*11.4*	*7.0*	*0.80*	*Intermittent crown fire*	*0.80*	*0.64*	*2.49*	*6 275*
3	C-3	8.4	40	*1.00*	*8*	90	*3 336*	*11.1*	*0.0*	*0.00*	*Surface fire*	*1.15*	*0.00*	*1.00*	*2 520*
4	C-3	5.4	80	*2.50*	*8*	90	*3 336*	*4.4*	*11.0*	*0.21*	*Intermittent crown fire*	*1.15*	*0.24*	*2.74*	*4 939*
5	C-3	16.1	80	*2.50*	*8*	115	*4 562*	*6.1*	*10.0*	*0.90*	*Continuous crown fire*	*1.15*	*1.04*	*3.54*	*17 098*

[a] ROS = rate of spread.
[b] BUI = Build Up Index.
[c] SFC = surface fuel consumption. Refer to Figure 38.
[d] CBH = crown base height. Refer to Table 12.
[e] FMC = foliar moisture content.
[f] CSI = critical surface intensity. Refer to Table 16.
[g] RSO = official surface fire rate of spread. Use RSO = CSI/(300 × SFC);see Equation 9.
[h] ROS = head fire rate of spread. Subtract RSO from ROS. If less than zero, enter zero.
[i] CFB = crown fraction burned. Refer to Figure 35 or Equation 10.
[j] Surface fire = CFB < 0.1; intermittent crown fire = CFB 0.1–0.89; continuous crown fire = CFB ≥ 0.9. See Table 15.
[k] CFL = crown fuel load. Refer to Table 13.
[l] CFC = crown fuel consumption. CFC = CFL × CFB. See Equation 11.
[m] TFC = total fuel consumption. TFC = SFC + CFC. See Equation 12.
[n] HFI = head fire intensity. HFI = 300 × TFC × ROS. See Equation 13.

Questions:



(1) Rank the following fuel types in terms of their expected surface fuel consumption given a BUI = 120.

Fuel type	Rank
C-1	
C-2	
C-3	
C-4	
S-2	
M-3	
M-4	

(2) Could the FBP System be used by itself to predict forest floor consumption from prescribed burns? Why?

(3) Why was the fire in case #4 an intermittent crown fire even though it had a lower rate of spread than the fire in case #3?

(4) Which fuel type (C-2, C-3, or C-6) is most susceptible to crowning? Why?

(5) What type of fire would you classify the following situation as:

(a) periodic torching

....

(b) steady wall of flame

....

(c) single tree occasionally candles

....

(6) Compare the fire in case #1 to the following fire. Given that the fire intensity is the same, would you expect the fire behavior to be significantly different? Why?

Fire information		
HFI	=	2520 kW/m
ROS	=	12 m/min
TFC	=	0.70 kg/m^2

....
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Suggested answers:

(1)

Fuel type	Rank
C-1	*not applicable*
C-2	*2*
C-3	*3 (least)*
C-4	*3 (least)*
S-2	*1 (most)*
M-3	*2*
M-4	*2*

Note: C-2, M-3, and M-4 use the same curve as do C-3 and C-4. C-1 is not dependent upon the BUI. See Figures 29, 30, 31, and 38.

(2) No. Ignition patterns used in prescribed burning can have a major impact on the rate of spread and fuel consumption and this is not accounted for in the FBP System. Also, the amount of pre-burn slash on a site can influence the forest floor consumption, but fuel load is not allowed to vary in the FBP System. Therefore, other prescribed fire guides should be used for the prediction of forest floor consumption by a prescribed fire.

(3) The surface fuel consumption was higher in Case 4 than in Case 3; therefore, the critical surface fire rate of spread (i.e., RSO) was lower. Thus the intensity needed for crowning could be obtained at a lower head fire rate of spread.

(4) C-2, because the live crown base height is low, indicating the branches are closer to the ground, and they serve as excellent ladder fuels. Note that C-6 could also have a low crown base height if it were a young, unpruned stand, and therefore could also be very susceptible to crowning.

(5) (a) Intermittent crown fire (CFB 0.1–0.89)

(b) Continuous crown fire (CFB ≥0.9)

(c) Surface fire (CFB <0.1)

(6) Yes, the fire behavior could be significantly different. The fire in Case 1 would be a slower moving, deeper burning fire (i.e., it has a slower rate of spread and a higher amount of fuel consumption) whereas the fire given in the question would be a very fast moving fire that would only consume a minimal amount of fuel.

4.2 Secondary Outputs

The secondary outputs calculated by the FBP System are derived primarily from a simple elliptical growth concept that assumes:

(1) fuels and topography are uniform and continuous,

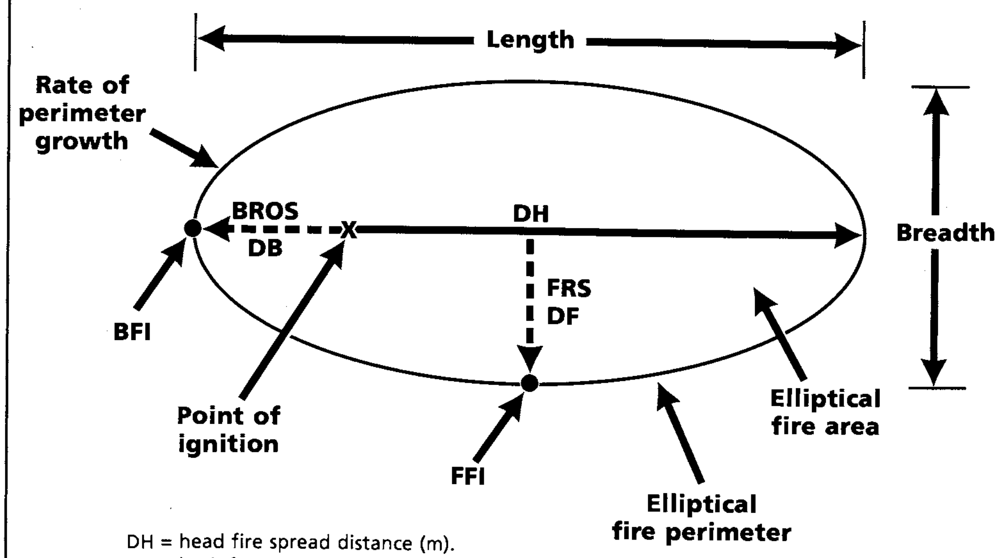
(2) wind is relatively constant and unidirectional,

(3) the fire is free burning and originates from a single point source ignition, and

(4) the fire is unaffected by suppression activities.

The secondary outputs take into account the role acceleration has on the behavior of a fire and, in general, describe the fire's spatial characteristics, such as its size and shape. In total, eleven secondary outputs are predicted (Fig. 39), namely:

- flank fire rate of spread,
- back fire rate of spread,
- head fire spread distance,
- flank fire spread distance,
- back fire spread distance,
- flank fire intensity,
- back fire intensity,
- length-to-breadth ratio,
- elliptical fire area,
- elliptical fire perimeter, and
- rate of perimeter growth.



DH = head fire spread distance (m).
DB = back fire spread distance (m).
DF = flank fire spread distance (m).
BROS = back fire rate of spread (m/min).
FRS = flank fire rate of spread (m/min).
BFI = back fire intensity (kW/m).
FFI = flank fire intensity (kW/m).

Figure 39. Conceptual diagram illustrating the secondary outputs produced by the FBP System.

4.2.1 Acceleration

In the primary outputs section, the FBP System predicts the equilibrium or steady state rate of spread for the head fire under a particular set of fuel, weather, and topographic conditions. However, a fire initiating from a single point source ignition, such as a match, campfire, or lightning strike will take some time to reach its equilibrium rate of spread. This is an important consideration because in the early stages of fire growth the FBP System can significantly over predict the rate of spread, leading to over predictions of the fire's size and perimeter (see Table 8). To account for the influence that acceleration has on rate of spread, the FBP System applies an "acceleration effect" to all point ignition fires.

Line source ignition fires, on the other hand, do not consider the influence of acceleration because it is assumed that the equilibrium rate of spread has already been reached. Line source predictions would be made, for example, when a fire is detected after it has reached a relatively large size (e.g., 1–2 ha) or when a distinct wind shifts occurs on a campaign fire causing the flank of the fire to become the head of the fire.

The FBP System has two different acceleration effects depending on whether the fuel type has an open or closed canopy (Table 17). In both instances it is assumed that the fuel type and topography are continuous and that weather conditions are relatively constant during the acceleration phase.

Table 17. Open and closed canopy fuel types in the FBP System

Category	Fuel type	
Open canopy	C-1	Spruce–Lichen Woodland
	S-1	Jack or Lodgepole Pine Slash
	S-2	White Spruce Balsam Slash
	S-3	Coastal Cedar/Hemlock/Douglas-fir Slash
	O-1	Grass
Closed canopy	C-2	Boreal Spruce
	C-3	Mature Jack or Lodgepole PIne
	C-4	Immature Jack or Lodgepole Pine
	C-5	Red and White Pine
	C-6	Conifer Plantation
	C-7	Ponderosa Pine/Douglas-fir
	D-1	Leafless Aspen
	M-1	Boreal Mixedwood—Leafless
	M-2	Boreal Mixedwood—Green
	M-3	Dead Balsam Fir/Mixedwood—Leafless
	M-4	Dead Balsam Fir/Mixedwood—Green

4.2.1.1 Acceleration in Open Canopy Fuels

The acceleration approach used in the FBP System for open canopy fuel types assumes that a fire will

(a) accelerate in a smooth, negative exponential manner (Fig. 40), and

(b) reach 90% of its equilibrium rate of spread 20 minutes after ignition.

This approach, which is based on laboratory and field evidence, assumes that fires in open canopy fuel types will be fully exposed to the ambient wind field and that the effect will be constant regardless of the severity of the weather conditions. For example, in Table 18 though the equilibrium rate of spread and the rate of spread after "t" minutes (where "t" is the elapsed time since ignition, in minutes) can vary significantly, the proportion of these values obtained by a particular fire is consistent for any given elapsed time.

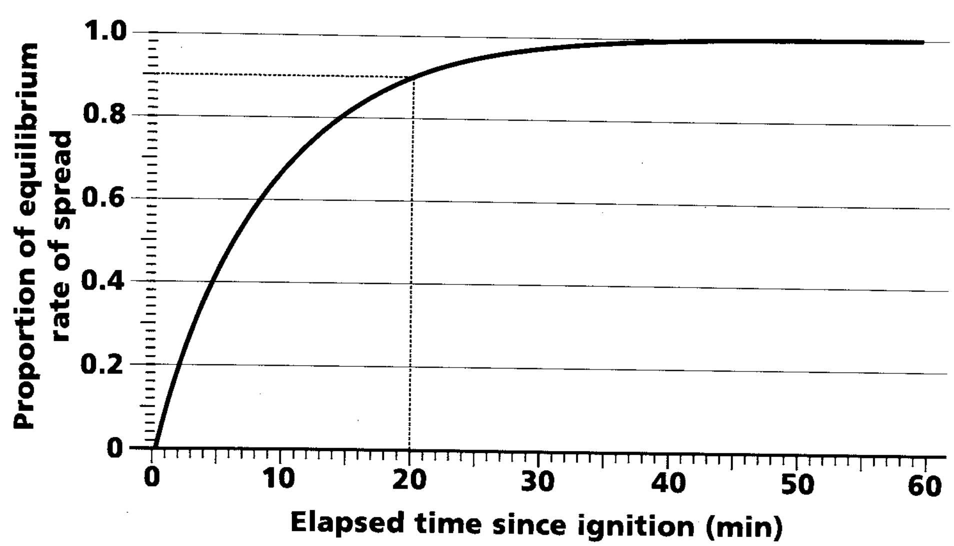


Figure 40. Acceleration curve for open canopy fuel types showing the proportion of equilibrium rate of spread as a function of elapsed time since ignition.

Table 18. Examples of the impact of acceleration on rate of spread in open canopy fuel types

Equilibrium ROS[a] (m/min)	Elapsed time ("t") since ignition (min)	Rate of spread at "t" minutes (m/min)	Proportion of equilibrium ROS (%)
5	10	3.4	68
10	10	6.8	68
15	10	10.3	68
15	20	13.5	90
25	20	22.5	90

[a]ROS = rate of spread.

4.2.1.2 Acceleration in Closed Canopy Fuels

For closed canopy fuel types[7], the FBP System attempts to account for the varying influence that the ambient wind field has on the head fire rate of spread. In some fuel types, two fires burning under exactly the same fuel, topographic, and ambient weather conditions can exhibit significantly different equilibrium rates of spread because the wind speed affecting the fire will vary vertically through the stand (e.g., the wind speed above a forest canopy may be 20 km/h while the wind speed within the stand may be only 5 km/h). This is referred to as a dual equilibrium rate of spread situation (Fig. 41) and has been observed on several experimental fires especially in dense stands (e.g., immature jack pine). It has also been noted that a slow burning surface fire under a dense forest canopy can quickly become a fast-moving crown fire when the surface fire reaches an appropriate sized opening in the overstory, allowing it to be influenced by the ambient wind.

Within the FBP System no attempt is made to rigorously model the dual-equilibrium rate of spread phenomenon; however, this phenomenon is incorporated indirectly by linking the acceleration effect in closed canopy fuel types to the crown fraction burned (CFB). Figure 42 shows that the elapsed time to 90% of equilibrium rate of spread ranges from 20 minutes to about 75 minutes, based on the degree of crown involvement. It indicates that fires with a low CFB will reach their near equilibrium rate of spread quite quickly. Likewise it is assumed that fires with a high CFB will achieve near equilibrium rates of spread in just over 20 minutes because they will move quickly into the tree crowns and be under the influence of the ambient wind field. Intermittent crown fires are allocated the longest time to reach 90% of equilibrium rate of spread because the fire will be influenced on a fluctuating basis by both the in-stand and ambient wind fields.

[7] For individual stands within some FBP System fuel types (e.g., C-2 and C-7) that have a very open canopy it may be more appropriate to use the acceleration model for open canopy fuels.

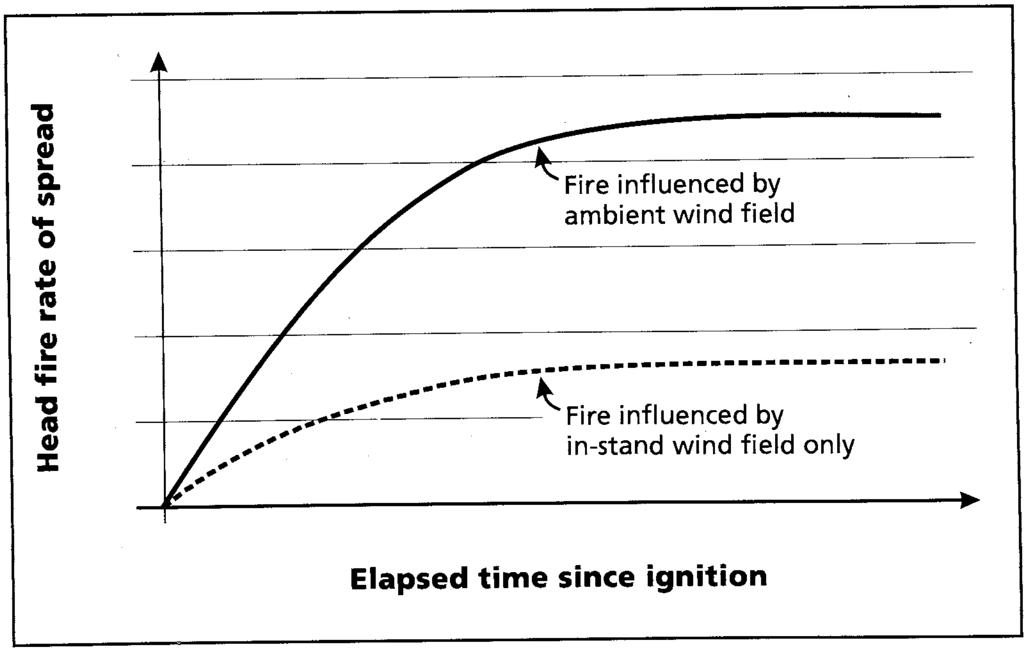


Figure 41. Conceptual diagram of the dual-equilibrium rate of spread situation.

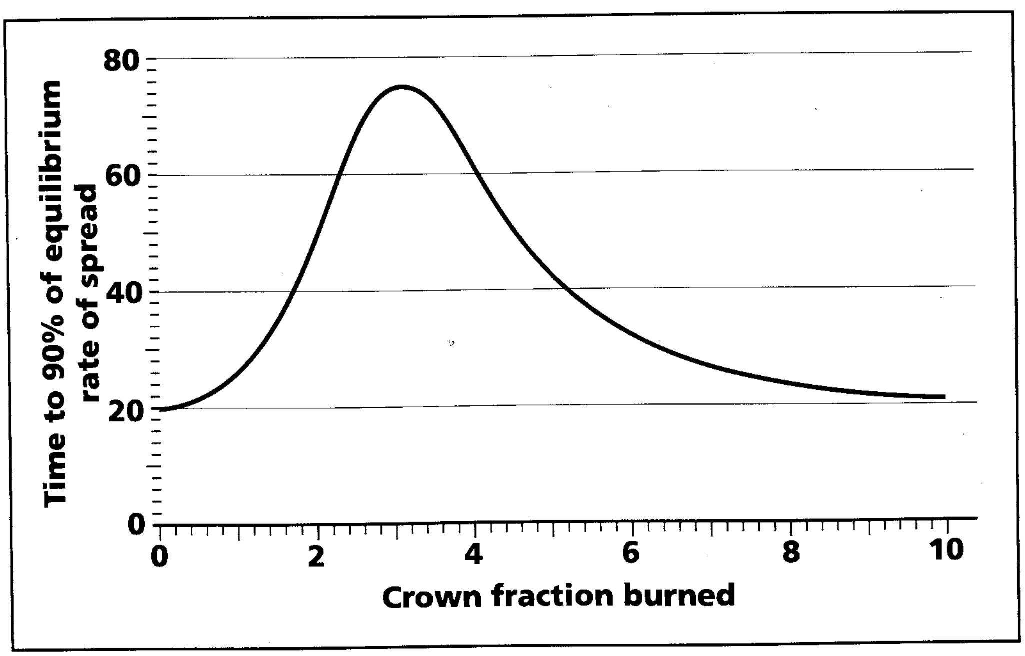
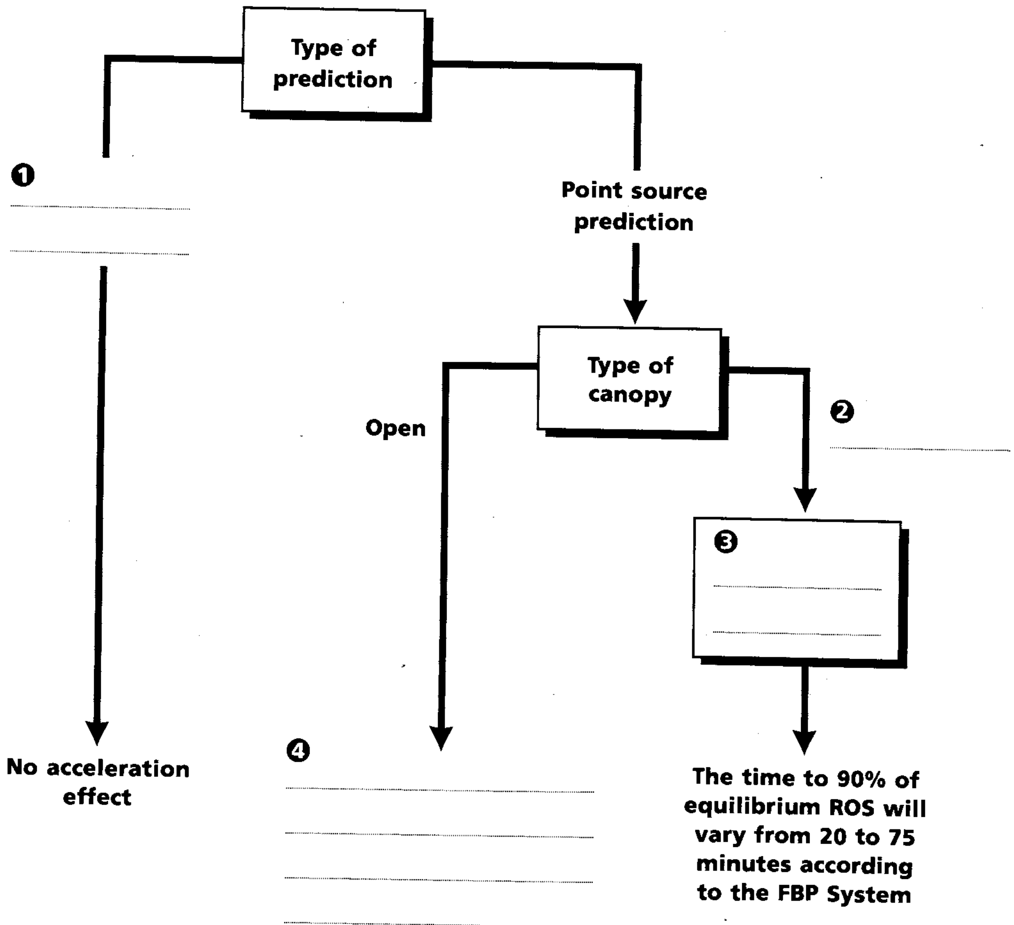


Figure 42. Acceleration curve for closed canopy fuel types showing the time to reach 90% of equilibrium rate of spread as a function of crown fraction burned.

Exercise 5.

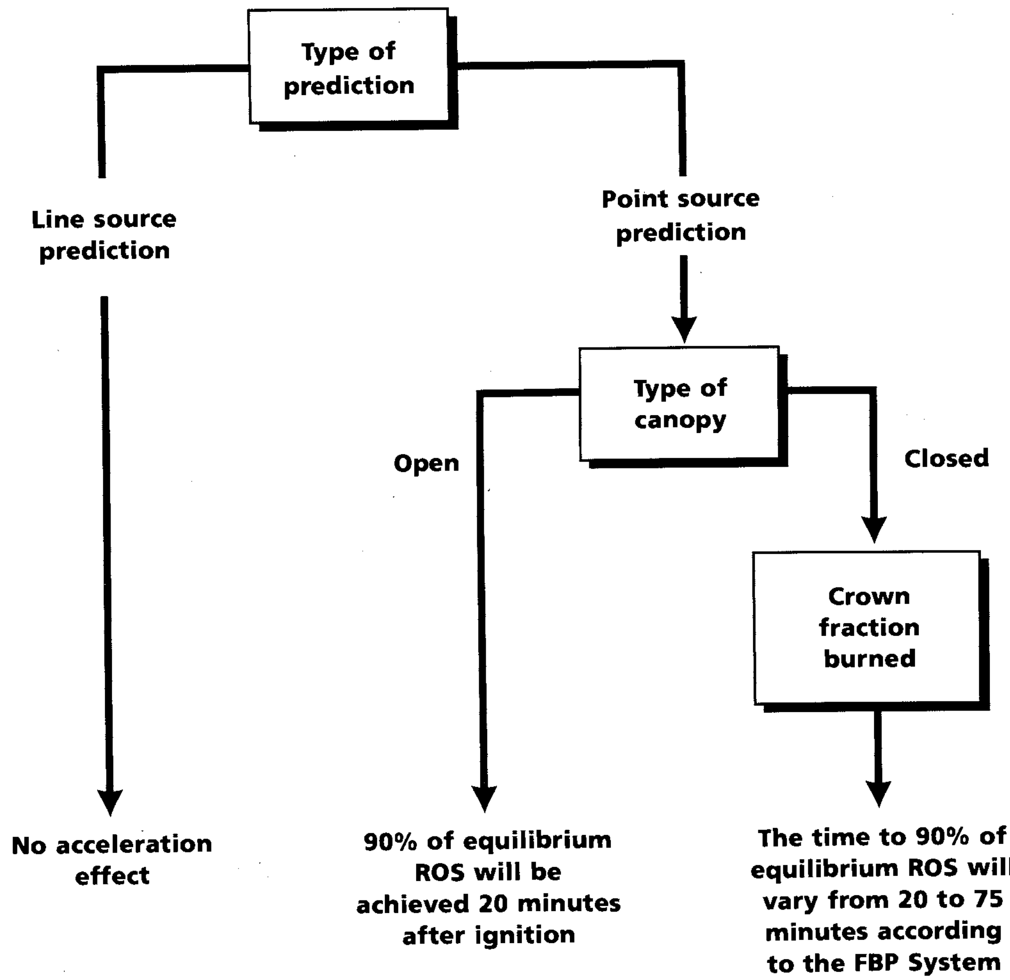
Approaches used in dealing with fire acceleration in the FBP System

Using the information presented in Sections 4.2.1, 4.2.1.1, and 4.2.1.2 fill in the blanks in the following flow chart.



Suggested answers:

Approaches used in dealing with fire acceleration in the FBP System



Exercise 6.

Acceleration effect on rate of spread

Using Table 19 (below), determine the elapsed time to 90% of equilibrium rate of spread for each situation.

Fuel type	Crown fraction burned (CFB)	Elapsed time to 90% of equilibrium rate of spread (min)
C-4 Immature Jack or Lodgepole Pine	0.1	______
C-4 Immature Jack or Lodgepole Pine	0.33	______
C-4 Immature Jack or Lodgepole Pine	0.9	______
C-1 Spruce–Lichen Woodland	0.6	______
C-3 Mature Jack or Lodgepole Pine	0.33	______
D-1 Leafless Aspen	0.2	______
S-2 Spruce/Balsam fir Slash	n/a[a]	______

[a]n/a = not applicable.

Table 19. Elapsed time since ignition to reach 90% of equilibrium rate of spread in closed canopy fuel types (min)

CFB[a]	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	20.0	20.1	20.2	20.4	20.8	21.3	22.0	22.8	23.7	24.8
0.1	26.1	27.5	29.1	30.9	32.9	35.1	37.5	40.0	42.8	45.8
0.2	48.9	52.1	55.4	58.7	61.9	64.9	67.6	70.0	72.0	73.5
0.3	74.5	74.9	74.7	74.1	73.0	71.6	69.9	68.0	65.9	63.7
0.4	61.5	59.3	57.1	54.9	52.9	50.9	49.0	47.3	45.6	44.0
0.5	42.5	41.1	39.8	38.6	37.5	36.4	35.4	34.5	33.6	32.8
0.6	32.0	31.3	30.7	30.0	29.5	28.9	28.4	27.9	27.4	27.0
0.7	26.6	26.2	25.9	25.6	25.2	24.9	24.7	24.4	24.2	23.9
0.8	23.7	23.5	23.3	23.1	22.9	22.8	22.6	22.5	22.3	22.2
0.9	22.1	22.0	21.9	21.8	21.7	21.6	21.5	21.4	21.3	21.3

[a]CFB = crown fraction burned.

Example: the elapsed time to 90% of equilibrium rate of spread for a fire in a closed canopy fuel type with a CFB of 0.22 (i.e., 0.2 and 0.02) is 55.4 minutes.

Suggested answers:

Acceleration effect on rate of spread

Fuel type	Crown fraction burned (CFB)	Elapsed time to equilibrium rate of spread (min)
C-4 Immature Jack or Lodgepole Pine	0.1	*26.1*
C-4 Immature Jack or Lodgepole Pine	0.33	*74.1*
C-4 Immature Jack or Lodgepole Pine	0.9	*22.1*
C-1 Spruce–Lichen Woodland	0.6	*20.0*[a]
C-3 Mature Jack or Lodgepole Pine	0.33	*74.1*
D-1 Leafless Aspen	0.2[b]	*20.0*[b]
S-2 Spruce/Balsam fir Slash	n/a[c]	*20.0*[d]

[a] C-1 is an open canopy fuel type and the time to acceleration is always 20 minutes regardless of the crown fraction burned.

[b] It is actually not possible in the FBP System to obtain a crown fraction burned above 0.0 for the D-1 fuel type; therefore, the time to 90% of the equilibrium rate of spread for D-1 will always be 20 minutes.

[c] n/a = not applicable.

[d] S-2 is an open canopy fuel type; therefore, the time to 90% of equilibrium rate of spread is always 20 minutes.

4.2.1.3 Acceleration Adjusted Head Fire Rate of Spread

Given that acceleration has an impact on rate of spread for point source predictions, it is possible to calculate the rate of spread at any particular time since ignition. This process involves the calculation of the predicted head fire rate of spread at an elapsed time since ignition ("t" minutes) using Equations 14 and15.

$$\mathbf{ROS_t = ROS_{eq} \times (1 - e^{-at})} \qquad \mathbf{(14)}$$

where ROS_t = head fire rate of spread at "t" minutes (m/min),
ROS_{eq} = equilibrium rate of spread (m),
t = elapsed time since ignition (min), and
a = a variable that influences the impact of CFB on ignition.

$$\mathbf{a = 0.115 - (18.8 \times CFB^{2.5} \times e^{(-8 \times CFB)})} \qquad \mathbf{(15)}$$

where a = a variable that influences the impact of CFB on acceleration, and
CFB = Crown fraction burned.

Note: for all surface fires and all open fuel types (i.e., for a CFB = 0.0), "a" = 0.115, and if "t" (i.e., the elapsed time since ignition in Equation 14) = 20 minutes then the multiplier $(1 - e^{-at}) = 0.9$. This implies that the ROS after 20 minutes for all open fuel types (and closed fuel types with no crown involvement) will be 90% of the equilibrium ROS.

4.2.1.4 Time to Crown Fire Initiation

In Section 4.1.2.2 it was shown that if the predicted equilibrium head fire rate of spread (ROS) exceeded the critical surface fire rate of spread (RSO), crown fire initiation would occur. For point source fires, which in the FBP System accelerate continuously from zero towards their equilibrium ROS, it is possible to determine the time to crown fire initiation (using Equation 16), if applicable. This calculation, though not considered an output of the FBP System may be useful in a variety of fire management situations.

$$ti = \frac{\ln(1 - RSO/ROS_{eq})}{-a} \quad (16)$$

where ti = elapsed time to crown fire initiation (min),
RSO = critical surface fire rate of spread (m/min),
ROS_{eq} = equilibrium head fire rate of spread (m/min),
a = a variable that influences the impact of CFB on acceleration, (see Equation 15).

4.2.2 Head Fire Spread Distance

For line source fire growth projections, the head fire spread distance is obtained by multiplying the equilibrium head fire rate of spread by the elapsed time or duration of prediction (Equation 17).

$$DH = ROS_{eq} \times ET \qquad (17)$$

where DH = head fire spread distance for a line source prediction (m),
ROS_{eq} = equilibrium head fire rate of spread (m/min),
ET = elapsed time or duration of prediction (min).

For point source predictions, the process is slightly more complicated because it is necessary to account for the acceleration process. Equation 18 and Figures 43 and 44 indicate that for point source predictions the head fire spread distance (D) will be dependent upon the elapsed time since ignition (t), the equilibrium head fire rate of spread (ROS_{eq}), and the crown fraction burned, which is used to calculate the value "a" (see Equation 15).

$$D = ROS_{eq} \times \left(t + \frac{e^{-at}}{a} - \frac{1}{a}\right) \qquad (18)$$

where D = head fire spread distance for point source predictions (m),
ROS_{eq} = equilibrium head fire rate of spread (m/min),
t = elapsed time since ignition (min),
a = a variable that influences the impact of CFB on acceleration (see Equation 15).

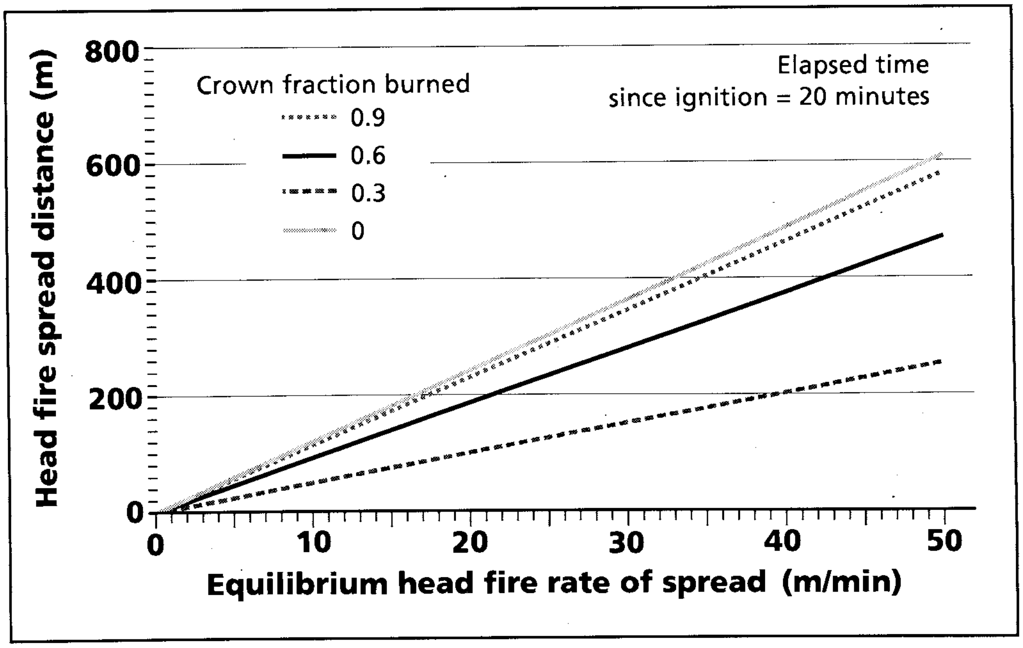


Figure 43. Head fire spread distance for point source predictions for an elapsed time since ignition of 20 minutes.

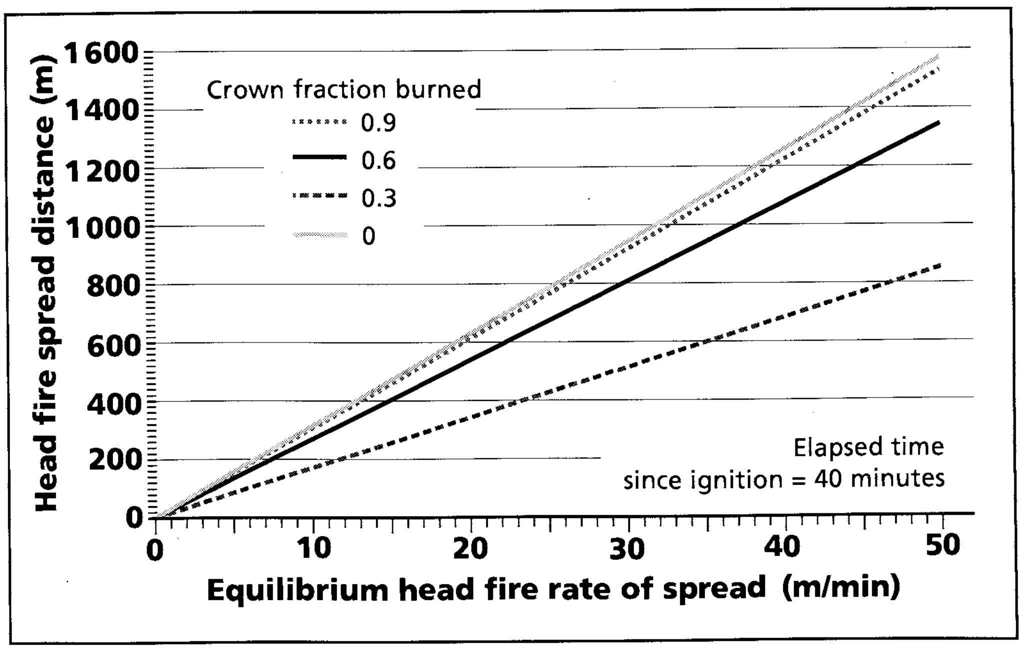


Figure 44. Head fire spread distance for point source predictions for an elapsed time since ignition of 40 minutes.

4.2.3 Back Fire Rate of Spread and Spread Distance

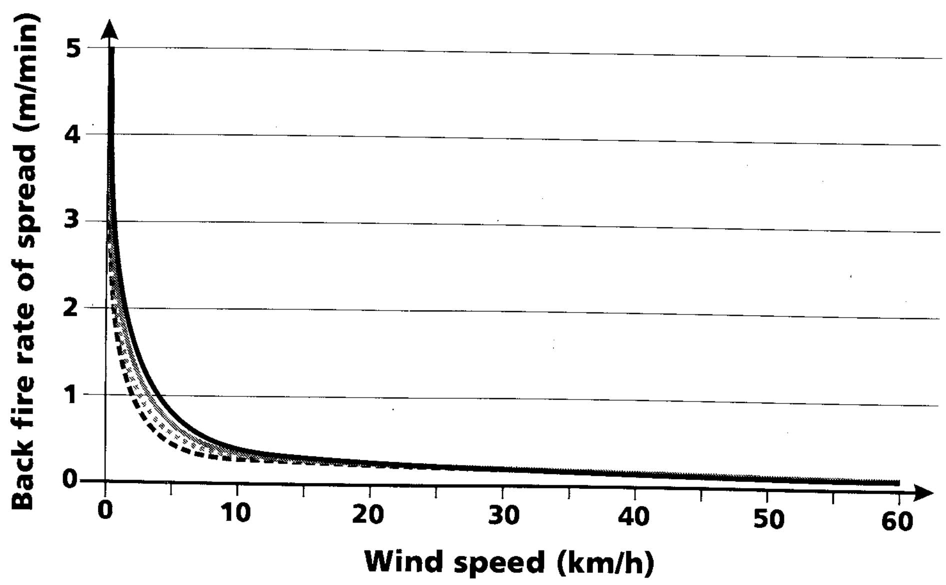
In most wildfire situations, the rate of spread of the back fire[8] is very slow because the fire is burning directly into the wind. At very low wind speeds, however, the contribution of the back fire to the overall length of the fire increases significantly. For example, in a calm wind situation, the fire will spread equally in all directions so the head fire and back fire rates of spread would be the same. To account for both of these situations, the FBP System approach to back fire rate of spread (Fig. 45) assumes

(1) the back fire rate of spread will equal the head fire rate of spread for zero wind speed situations, and

(2) the back fire rate of spread will decrease rapidly, as the wind speed increases, to a very small (<0.05 m/min), near constant value.

It should be noted that the back fire rate of spread values can be adjusted for wind and slope interaction and the buildup effect in the same manner as the head fire rate of spread prediction. For a point source fire, acceleration of the back fire is also handled in the same manner as for a head fire.

Once the back fire rate of spread has been calculated, the back fire spread distance can be predicted using the techniques outlined in Section 4.2.2, substituting the predicted back fire rate of spread for the predicted head fire rate of spread, where appropriate.



Note: the various curves represent different head fire ROS values.

Figure 45. Conceptual illustration of the back fire rate of spread function.

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[8] The term back fire as used in the FBP System refers to the rear portion of a wildfire that is generally burning into the wind. This term is not to be confused with a line of fire ignited ahead of a wildfire in order to slow its progress, which is called a "backfire".

4.2.4 Length-to-breadth Ratio

The length-to-breadth ratio (LB) is simply defined as the total length of a fire (i.e., the head fire spread distance plus the back fire spread distance) divided by its maximum breadth, based on the assumption the fire is elliptical in shape (Fig. 46). The FBP System has two length-to-breadth functions; one for the open O-1 fuel type and one for all other fuel types (i.e., forest stands and slash). In both instances, the length-to-breadth ratios are

(1) calculated solely from the wind speed (or wind speed vector for a fire on a slope),

(2) based on empirical data (primarily from Australia for the open fuel type and from Canada for the forest stands and slash), and

(3) s-shaped curves that level off at extreme wind speeds.

Figure 47 shows both of the length-to-breadth curves used in the FBP System. The equations, curves, and plotted data points can also be found in the Forestry Canada Fire Danger Group (1992) report.

There are two other points to note about the length-to-breadth ratios:

(1) When the wind speed (or wind speed vector) is less than 1.0 km/h the length-to-breadth ratio equals 1.0.

(2) The length-to-breadth ratio can vary during acceleration (i.e., gradually change from a circle to its equilibrium fire shape). Thus, predictions that are made during the acceleration period, which use the length-to-breadth ratio as an input, should be considered with caution.

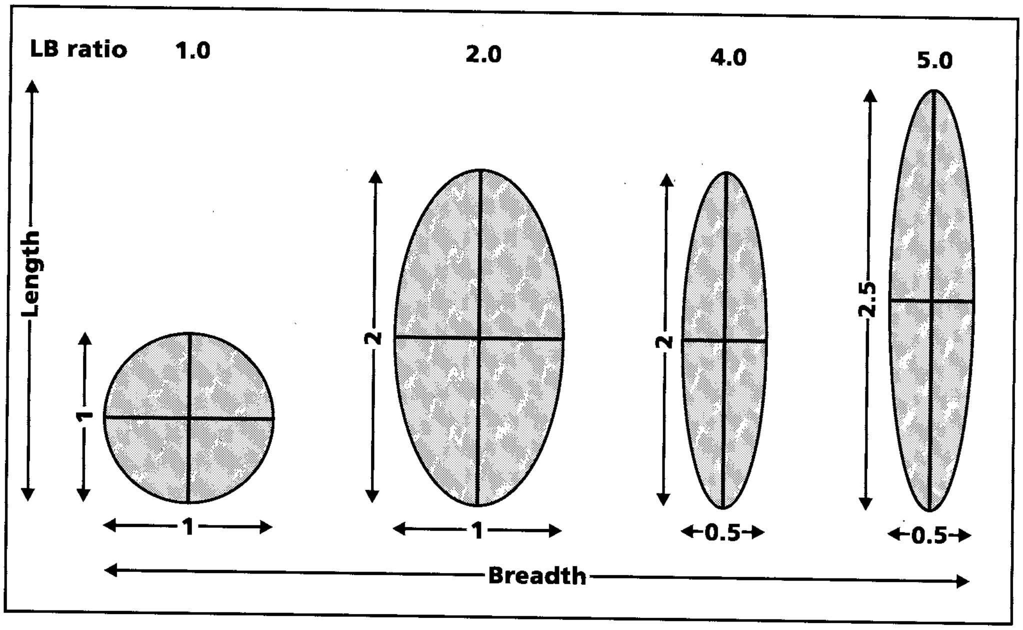

Figure 46. Examples of elliptical fire shapes with various length-to-breadth (LB) ratios (adapted from Alexander and Lanoville 1989).

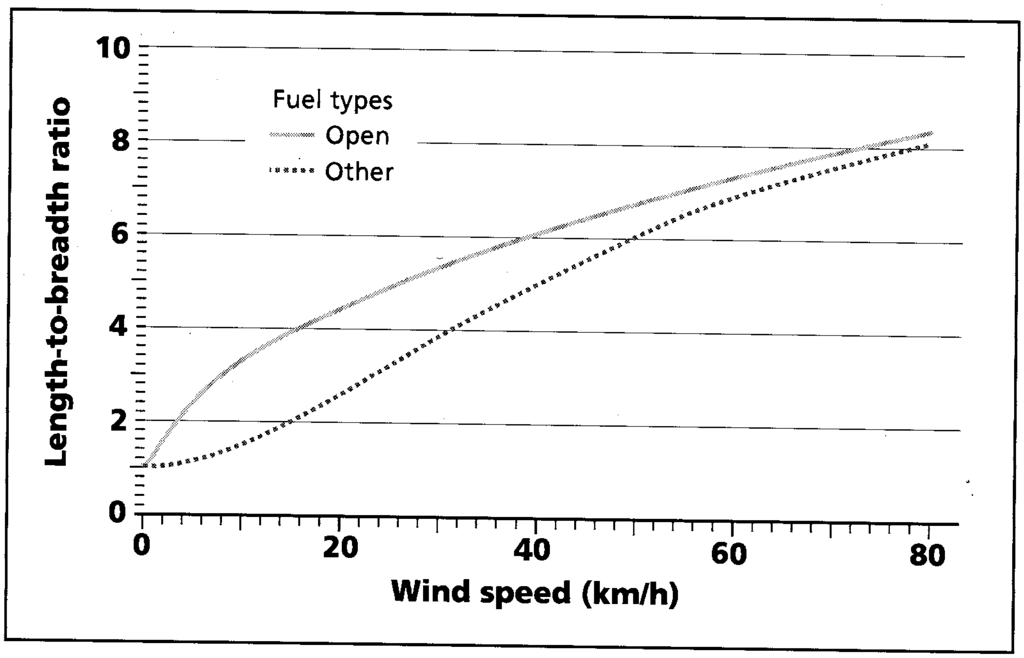

Figure 47. Length-to-breadth ratio curves used in the FBP System.

4.2.5 Flank Fire Rate of Spread and Spread Distance

The flank fire rate of spread refers to the spread rate that occurs at the maximum breadth of an elliptical fire (see Figure 39). In the FBP System it is calculated from the head and back fire rates of spread and the length-to-breadth ratio (Equation 19). Figure 48 shows the sensitivity of the flank fire rate of spread to these variables and the fact that as the length-to-breadth ratio increases the flank fire rate of spread decreases (assuming the head fire and back fire rate of spread remain constant).

$$FRS = \frac{ROS + BROS}{LB \times 2} \qquad (19)$$

where FRS = flank fire rate of spread (m/min),
ROS = head fire rate of spread (m/min),
BROS = back fire rate of spread (m/min), and
LB = length of breadth ratio.

Flank fire spread distance is also relatively easy to calculate using Equation 20.

$$DF = \frac{DH + DB}{LB \times 2} \qquad (20)$$

where DF = flank fire spread distance (m),
DH = head fire spread distance (m),
DB = back fire spread distance (m), and
LB = length-to-breadth ratio.

Both the flank fire rate of spread and spread distance values include adjustments for slope, buildup effect and acceleration because these values are already accounted for in the head fire and back fire rates of spread and spread distance values.

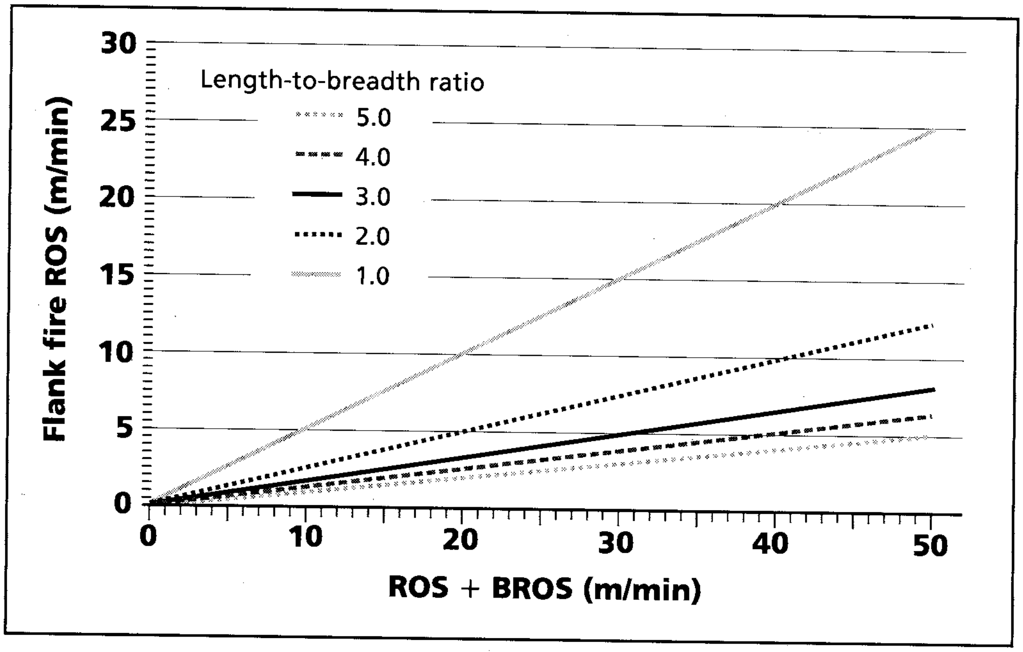

Figure 48. Flank fire rate of spread curves for selected head fire rate of spread (ROS) and back fire rate of spread (BROS) values and length-to-breadth ratios.

4.2.6 Elliptical Fire Area

The predicted fire area derived by the FBP System is the area within an ellipse of a specified size and shape. The calculation is based on the total fire length (i.e., head fire spread distance plus back fire spread distance) and the length-to-breadth ratio (Equation 21). For example, in Figure 49 the elliptical fire area for a fire with a total spread distance of 2000 m and a length-to-breadth ratio of 2.0 is 157 ha.

$$A = \frac{\frac{\pi}{4 \times LB} \times D_T^2}{10\,000} \qquad (21)$$

where A = elliptical fire area (ha),
D_T = total spread distance (m), and
LB = length-to-breadth ratio.

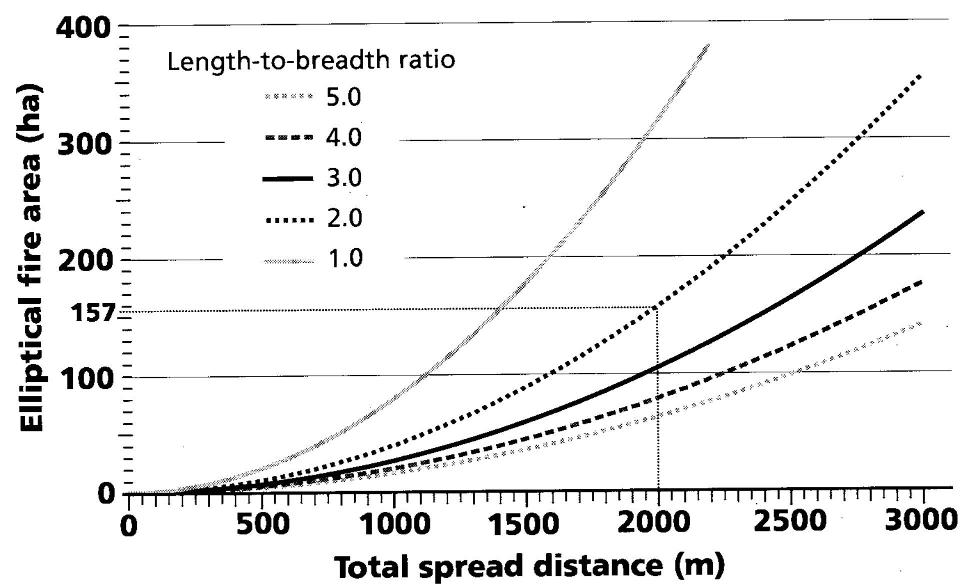

Figure 49. Elliptical fire area curves for selected total spread distances and length-to-breadth ratios.

4.2.7 Elliptical Fire Perimeter

The predicted length of a fire's perimeter is also based on the elliptical fire growth model and like the elliptical fire area calculation, it is derived from the total spread distance and the length-to-breadth ratio (Equation 22). The elliptical fire perimeter curves are, however, linear in nature rather than exponential like the fire area curves (compare Figures 49 and 50).

$$P = \pi \times \frac{D_T}{2} \times \left(1 + \frac{1}{LB}\right) \times \left[1 + \left(\frac{LB - 1}{2(LB + 1)}\right)^2\right] \qquad (22)$$

where P = elliptical fire perimeter (m),
D_T = total spread distance (m), and
LB = length-to-breadth ratio.

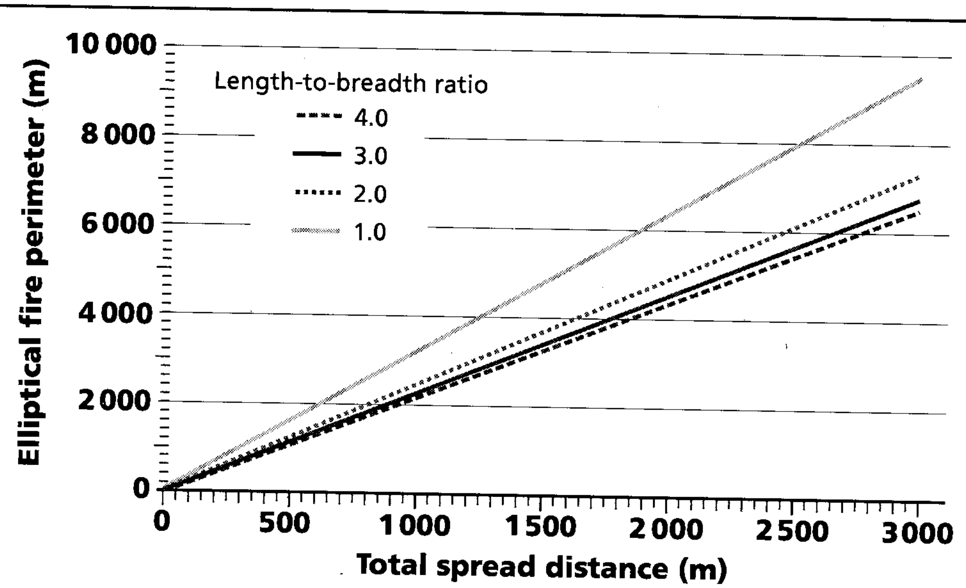

Figure 50. Elliptical fire perimeter curves for selected total spread distances and length-to-breadth ratios.

4.2.8 Perimeter Growth Rate

The rate of perimeter growth is the increase in the length of the elliptical fire perimeter over a period of time. It is calculated from the head fire and back fire rates of spread and the length-to-breadth ratio. Figure 51 shows that for a given head fire and back fire rate of spread value, the perimeter growth rate will increase as the fire becomes more circular (i.e., as the length-to-breath ratio decreases).

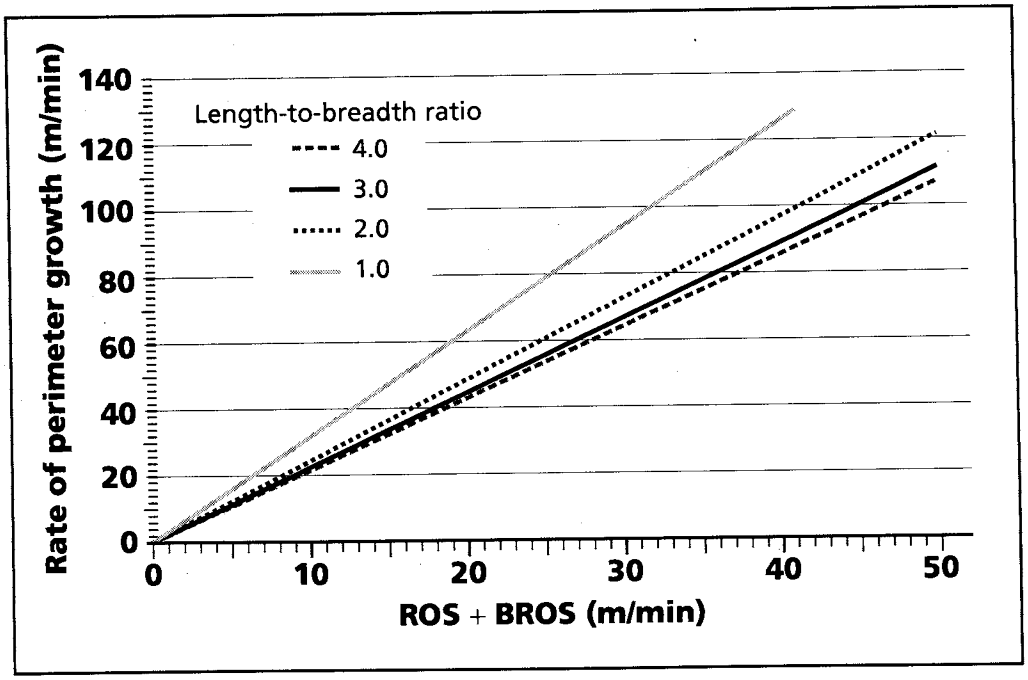

Figure 51. Perimeter growth rate values for selected head fire rates of spread (ROS), back fire rates of spread (BROS), and length-to-breadth ratios.

4.2.9 Flank and Back Fire Intensities

In order to calculate the flank and back fire intensities, it is necessary to determine the total fuel consumption at the flank and back of the fire and combine these values with the matching rate of spread prediction (see Sections 4.2.3 and 4.2.5, respectively). The total flank and back fire fuel consumption is derived in two steps. First, it is assumed that surface fuel consumption (SFC) is constant about the perimeter of the fire. Thus, the surface fuel consumption value calculated for the head fire (see Section 4.1.2.1) will be the same for the flank fire and the back fire. Second, using the SFC and the flank and back fire rate of spread values, it is possible to determine the degree of crown involvement and the amount of crown fuel consumption, making the calculation of total fuel consumption possible. The total fuel consumption values and the respective rate of spread values are then entered into the FBP System fire intensity equation (Equation 13) to obtain the flank and back fire intensities. It should be noted that more sophisticated fire growth models are available for the prediction of fire intensity at any point about the perimeter rather than just at the head, flank, and back fire positions as specified in the FBP System.

Exercise 7. Calculating selected secondary outputs

Using the information provided in Section 5 complete the table below and answer the questions on the next page.

Fuel type	Wind speed (km/h)	Length-to-breadth ratio[a] (LB)	ROS + BROS[b] (m/min)	FRS[c] (m/min)	DH[d] (m)	DB[e] (m)	DH + DB (m)	Elliptical fire area[f] (ha)	Elliptical fire perimeter[g] (m)	Elliptical fire growth rate[h] (m/min)
C-2	15	2.0	11.3	2.8	604	72	676	17.9	1 637	27.4
C-2	____	4.0	27.8	____	1 647	22	____	____	____	____
S-3	31	____	32.5	____	1 949	1	____	____	____	69.6
O-1b	____	4.0	32.3	____	1 777	157	____	73.4	____	____
O-1b	0	____	11.2	____	337	____	____	____	2 117	____
C-2	____	2.0	6.6	____	____	38	373	____	____	16.0

[a]Estimate length-to-breadth ratio from Figure 47.

[b]ROS = head fire rate of spread; BROS = back fire rate of spread.

[c]FRS = flank fire rate of spread. Estimate flank fire rate of spread using Figure 48 or calculate using Equation 19.

[d]DH = head fire spread distance.

[e]DB = back fire spread distance.

[f]Estimate elliptical fire area from Figure 49 or calculate using Equation 21.

[g]Estimate elliptical fire perimeter from Figure 50 or calculate using Equation 22.

[h]Estimate elliptical fire growth rate using Figure 51.

Suggested answers:

Calculating selected secondary outputs

Fuel type	Wind speed (km/h)	Length-to-breadth ratio[a] (LB)	ROS + BROS[b] (m/min)	FRS[c] (m/min)	DH[d] (m)	DB[e] (m)	DH + DB (m)	Elliptical fire area[f] (ha)	Elliptical fire perimeter[g] (m)	Elliptical fire growth rate[h] (m/min)
C-2	15	2.0	11.3	2.8	604	72	676	17.9	1 637	27.4
C-2	*31.3*	4.0	27.8	*3.5*	1 647	22	*1 669*	*54.7*	*3 572*	*59.5*
S-3	31	*4.0*	32.5	*4.1*	1 949	1	*1 950*	*74.7*	*4 173*	69.6
O-1b	*16*	4.0	32.3	*4.0*	1 777	157	*1 934*	73.4	*4 139*	*69.1*
O-1b	0	*1.0*	11.2	*5.6*	337	*337*	*674*	*35.7*	2 117	*35.2*
C-2	*15*	2.0	6.6	*1.6*	*335*	38	373	*5.5*	*903*	16.0

[a] Estimate length-to-breadth ratio from Figure 47.
[b] ROS = head fire rate of spread; BROS = back fire rate of spread.
[c] FRS = flank fire rate of spread. Estimate flank fire rate of spread using Figure 48 or calculate using Equation 19.
[d] DH = head fire spread distance.
[e] DB = back fire spread distance.
[f] Estimate elliptical fire area from Figure 49 or calculate using Equation 21.
[g] Estimate elliptical fire perimeter from Figure 50 or calculate using Equation 22.
[h] Estimate elliptical fire growth rate using Figure 51.

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6.0 Glossary of Abbreviations and Symbols

Abbreviation or acronym	Definition	Units	Description
a	n/a[a]	n/a	A variable that calculates the impact of the crown fraction burned on acceleration.
A	Elliptical fire area	ha	The predicted total area of an elliptically shaped fire.
BE	Buildup effect	n/a	Used to adjust the basic (or slope-adjusted rate of spread for the amount of available fuel).
BFI	Back fire intensity	kW/m	The predicted intensity at the rear of a fire (i.e., where the fire is spreading directly into the wind).
BROS	Back fire rate of spread	m/min	The predicted rate of spread at the rear of the fire (i.e., where the fire is spreading directly into the wind).
BUI	Buildup Index	n/a	An index of the FWI System based on the Duff Moisture Code (DMC) and the Drought Code (DC) that provides a numerical, relative indication of the amount of fuel available for combustion.
CBH	Crown base height	m	The height, above the ground, where the live crown base (of coniferous trees) begins. This value is a constant for each FBP System fuel type except C-6.
CFB	Crown fraction burned	n/a	The predicted degree of crown involvement in a fire expressed as the proportion of crown fuels consumed in a given area.
CFC	Crown fuel consumption	kg/m^2	The predicted amount of crown fuel consumed at the head of the fire.
CFFDRS	Canadian Forest Fire Danger Rating System	n/a	A comprehensive approach to determining fire danger in Canada consisting of four subsystems, two of which are the FWI System and the FBP System.

Abbreviation or acronym	Definition	Units	Description
CFL	Crown fuel load	kg/m^2	The amount of fuel (i.e., foliage and small twigs in the tree crowns) available for combustion. This value is a constant for each FBP System fuel type.
CSI	Critical surface fire intensity	kW/m	A semi-theoretical value, determined by the crown base height and foliar moisture content, which if exceeded will result in the ignition of fuels in the tree's crown.
C-1	Spruce–Lichen Woodland	n/a	An FBP System coniferous forest fuel type.
C-2	Boreal Spruce	n/a	An FBP System coniferous forest fuel type.
C-3	Mature Jack or Lodgepole Pine	n/a	An FBP System coniferous forest fuel type.
C-4	Immature Jack or Lodgepole Pine	n/a	An FBP System coniferous forest fuel type.
C-5	Red and White Pine	n/a	An FBP System coniferous forest fuel type.
C-6	Conifer Plantation	n/a	An FBP System coniferous forest fuel type.
C-7	Ponderosa Pine/Douglas-fir	n/a	An FBP System coniferous forest fuel type.
DB	Back fire spread distance	m	The predicted spread distance at the rear of the fire (i.e., where the fire is spreading directly into the wind).
DC	Drought Code	n/a	An index of the FWI System that provides a numerical rating of the average moisture content of the deep (10–25 cm), compact organic layers (i.e., duff).
DF	Flank fire spread distance	m	The predicted spread distance at the flank of the fire (i.e., the point on the perimeter of the fire where the spread is perpendicular to the head fire spread direction).
DH	Head fire spread distance	m	The predicted spread distance of the head fire.
DMC	Duff Moisture Code	n/a	An index of the FWI System that provides a numerical rating of the average moisture content of the loosely compact organic layers (i.e., duff) of a moderate depth (5–10 cm).

Abbreviation or acronym	Definition	Units	Description
D_T	Total spread distance	m	The predicted total length of the fire calculated by adding the head and back fire spread distances.
D-1	Leafless aspen	n/a	An FBP System deciduous forest fuel type.
e	n/a	n/a	A mathematical value equal to about 2.7183.
ET	Elapsed time since ignition	min	The elapsed time since ignition for a line source fire.
FBP System	Canadian Forest Fire Behavior Prediction System	n/a	Provides a systematic approach to the quantitative prediction of forest fire behavior in Canada.
FFI	Flank fire intensity	kW/m	The predicted intensity at the flank of the fire (i.e., the point on the perimeter of the fire where the spread is perpendicular to the head fire spread direction).
FFMC	Fine Fuel Moisture Code	n/a	An index of the FWI System that provides a numerical rating of the moisture content of litter and other cured fine fuels.
FMC	Foliar moisture content	%	The moisture content of coniferous needles that are at least one-year old.
FRS	Flank fire rate of spread	m/min	The predicted rate of spread at the flank of the fire (i.e., the point on the perimeter of the fire that is perpendicular to the head fire spread direction).
FWI	Fire Weather Index	n/a	An index of the FWI System that combines the Initial Spread Index (ISI) and Buildup Index (BUI) to provide a numerical, relative rating of fire intensity.
FWI System	Canadian Forest Fire Weather Index System	n/a	A uniform method for assessing the relative fire danger in Canada.
H	Fuel low heat of combustion	kJ/kg	A value in Byram's fire intensity equation indicative of the fuel low heat of combustion. This value is considered a constant (18 000 kJ/kg) in the FBP System.
HFI	Head fire intensity	kW/m	The predicted intensity of the head fire determined from the head fire rate of spread (ROS), total fuel consumption (TFC), and a constant low heat of combustion value.

Abbreviation or acronym	Definition	Units	Description
I	Fire intensity	kW/m	Byram's fire intensity value calculated from the fuel low heat of combustion (H), the weight of fuel consumed per unit area in the active fire front (w), and the rate of forward spread (r).
ISI	Initial Spread Index	n/a	An index of the FWI System based on the Fine Fuel Moisture Code (FFMC) and the wind speed that provides a numerical rating of the relative expected rate of fire spread.
ISZ	Zero-wind initial spread index	n/a	The Initial Spread Index (ISI) value for a given Fine Fuel Moisture Code (FFMC) and a wind speed equal to zero. This value is used in the calculation of rate of spread on a slope.
LB	Length-to-breadth ratio	n/a	The total fire length divided by its maximum breadth.
LDT	Local daylight time	n/a	Local daylight time.
LST	Local standard time	n/a	Local standard time.
MSL	Mean sea level	n/a	Mean sea level.
M-1	Boreal Mixedwood—Leafless	n/a	An FBP System mixedwood forest fuel type.
M-2	Boreal Mixedwood—Green	n/a	An FBP System mixedwood forest fuel type.
M-3	Dead Balsam Fir/ Mixedwood—Leafless	n/a	An FBP System mixedwood forest fuel type.
M-4	Dead Balsam Fir/ Mixedwood—Green	n/a	An FBP System mixedwood forest fuel type.
O-1	Open	n/a	An FBP System fuel type group.
O-1a	Matted Grass	n/a	A subgroup of the O-1 fuel type.
O-1b	Standing Grass	n/a	A subgroup of the O-1 fuel type.
P	Elliptical fire perimeter	m	The predicted distance around the outside of an elliptically shaped fire.
PGR	Perimeter growth rate	m/min	The predicted increase in the length of the elliptical fire perimeter per unit time.
r	Rate of forward spread	m/sec	The value in Byram's fire intensity equation indicative of the fire's rate of forward spread.
ROS	Rate of spread	m/min	The predicted head fire rate of spread adjusted for the buildup effect and slope, if applicable.

Abbreviation or acronym	Definition	Units	Description
ROSt	Head fire rate of spread at "t" minutes	m/min	The predicted rate of spread of a point source fire at specified number of minutes ("t") since ignition.
RSC	Crown fire rate of spread (for the C-6 fuel type)	m/min	The predicted rate of spread for crown fires in the Conifer Plantation (C-6) fuel type.
RSF	Slope-adjusted, zero-wind rate of spread	m/min	The predicted rate of spread of a fire on a slope if the winds were calm.
RSO	Critical surface fire rate of spread	m/min	A predicted rate of spread value, which if exceeded will result in the ignition of fuels in the tree crowns.
RSS	Surface fire rate of spread (for the C-6 fuel type)	m/min	The predicted rate of spread for surface fires in the Conifer Plantation fuel type.
RSZ	Zero-wind, level ground rate of spread	m/min	The rate of spread in a zero-wind, level ground situation. This value is used in the prediction of rate of spread on a slope.
SF	Spread factor	n/a	A semi-theoretical adjustment factor used to modify (i.e., increase) rates of spread on slopes up to 60%.
SFC	Surface fuel consumption	kg/m^2	The predicted amount of surface fuel consumption for a particular fuel type, based on the BUI and/or FFMC.
S-1	Jack or Lodgepole Pine Slash	n/a	An FBP System slash fuel type.
S-2	Spruce/Balsam Slash		An FBP System slash fuel type.
S-3	Coastal Cedar/ Hemlock/ Douglas-fir Slash	n/a	An FBP System slash fuel type.
TFC	Total fuel consumption	kg/m^2	The predicted total amount of fuel consumed by the head fire.
t	Elapsed time	min	Elapsed time since ignition for point source fires.
ti	Elapsed time to crown fire initiation	min	The elapsed time to crown fire initiation for point source predictions.
w	Weight of fuel consumed per unit area in the active fire front	kg/m^2	A value in Byram's fire intensity equation that indicates the amount of fuel consumed per unit area in the active fire front.

Abbreviation or acronym	Definition	Units	Description
WSE	Slope equivalent wind speed vector	km/h degrees	The predicted impact that percent slope has on the head fire rate of spread expressed in terms of magnitude (i.e., wind speed) and direction.
WSV	Net effective wind vector	km/h degrees	This value combines the observed wind speed vector and the slope equivalent wind speed vector and is used in the prediction of fire spread on a slope.

[a] n/a = not applicable.

Note: for a more comprehensive definition of some terms, please consult the FBP System technical report (Forestry Canada Fire Danger Group (1992) and/or Merrill and Alexander (1987).