Development and Structure of the Canadian Forest Fire Behavior Prediction System

Forestry Canada Fire Danger Group

Information Report ST-X-3

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Editing and Production: Catherine Carmody
Layout: Francine Langevin

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Abstract

The Canadian Forest Fire Behavior Prediction (FBP) System is a subsystem of the larger Canadian Forest Fire Danger Rating System, which also includes the Canadian Forest Fire Weather Index (FWI) System. The FBP System provides quantitative estimates of head fire spread rate, fuel consumption, fire intensity, and fire description; with the aid of an elliptical fire growth model, it gives estimates of fire area, perimeter, perimeter growth rate, and flank and back fire behavior. The FBP System has evolved since the mid-1970s from a series of regionally developed burning indexes to an interim edition of the nationally developed FBP System issued in 1984 to the present complete edition. Sixteen discrete fuel types are included, covering most major boreal forest fuel types in Canada. Fire behavior models for spread rate and fuel consumption were derived from a database of over 400 experimental, wild, and prescribed fire observations. The FBP System is intended to supplement the experience and judgment of operational fire managers.

Résumé

La Méthode canadienne de prévision du comportement des incendies de forêt (PCI) fait partie de la Méthode canadienne d'évaluation des dangers d'incendie de forêt, laquelle englobe également la Méthode canadienne de l'Indice Forêt-Météo (IFM). La première de ces trois méthodes permet l'estimation quantitative de la vitesse de propagation du front de l'incendie (ou suivant la pente), la consumation de combustible, l'intensité de l'incendie et la description de ce dernier; avec l'aide du modèle elliptique de croissance de l'incendie, elle permet d'estimer l'aire et le périmètre de l'incendie, la vitesse de croissance de ce dernier ainsi que le comportement de l'incendie sur ses flancs et son arrière. Depuis le milieu des années 70, la Méthode PCI a évolué, à partir d'une série d'indices de combustion élaborés à l'échelon régional jusqu'à sa forme achevée actuelle en passant par sa publication sous forme de méthode nationale provisoire, en 1984. On tient compte de 16 types précis de combustibles, qui englobent la plupart des principaux types trouvés dans les forêts boréales du Canada. Les modèles du comportement des incendies, en ce qui concerne la vitesse de propagation et la consumation des combustibles, sont tirés d'un corpus de plus de 400 observations d'incendies expérimentaux, échappés et dirigés. La Méthode PCI devrait servir à étayer l'expérience et le jugement des chefs de l'intervention contre les incendies.

Preface

The Canadian Forest Fire Danger Rating System (CFFDRS), of which the Canadian Forest Fire Behavior Prediction (FBP) System is a part, has been developed by the members of the Forestry Canada Fire Danger Group. The Fire Danger Group is a national working group composed of at least one member from each of the Forestry Canada establishments supporting a fire research program. The Fire Danger Group members responsible for the development of the FBP System are:

Charles E. Van Wagner
Petawawa National Forestry Institute
Chalk River, Ontario

Brian J. Stocks
Great Lakes Forestry Centre
Sault Ste. Marie, Ontario

Bruce D. Lawson
Pacific Forestry Centre
Victoria, British Columbia

Martin E. Alexander
Northern Forestry Centre
Edmonton, Alberta

Timothy J. Lynham
Great Lakes Forestry Centre
Sault Ste. Marie, Ontario

Robert S. McAlpine
Petawawa National Forestry Institute
Chalk River, Ontario

The development of the FBP System was based on fire behavior data collected from experimental burning projects and wildfire documentation. Data of this sort are difficult to obtain and were only gathered through the continued logistical and cooperative support of forest fire management agencies across Canada.

Development of the FBP System was aided tremendously by the creation of the FBP System computer program, which allowed extensive testing of algorithms and procedures. Derry McKenna, the programmer responsible for the FBP System computer program, died of Hodgkin's disease soon after completing the first working version of the program.

1.0 Introduction

The development of systems for evaluating daily forest fire danger has been a continuous activity of Forestry Canada and its predecessor agencies since the mid-1920s. During the four decades that followed, four distinct fire danger rating systems appeared and were used to a varied extent throughout Canada. The present Canadian Forest Fire Danger Rating System (CFFDRS) began to take shape in 1968 with the adoption of a comprehensive modular approach (Muraro 1969). This allowed separate parts of the whole system to be developed and improved independently of each other. All the parts of the CFFDRS, available as of 1987, appeared together in an official binder (Canadian Forestry Service 1987) to which new parts could be added. Stocks et al. (1989) present a recent description of the overall concept.

The first major subsystem of the CFFDRS to be completed was the Canadian Forest Fire Weather Index (FWI) System. The FWI System was first introduced across the country in 1971 and has undergone several revisions; it provides relative measures of fuel moisture and fire behavior potential. The present version dates from 1984 (Van Wagner 1987; Van Wagner and Pickett 1985) and incorporates the best features of previous forest fire danger rating systems and new components where needed. The FWI System represented a further step in the long continuous path of fire danger rating research in Canada.

The second major subsystem of the CFFDRS was conceived, in the original modular approach, as a series of regionally developed guides to actual, rather than relative, fire behavior characteristics in specific fuel types of local importance. These "Burning Indexes" (Kiil 1971; Lawson 1972; Van Wagner 1974a) or "Fire Behavior Indexes" (Lawson 1977; Stocks 1977; Quintilio 1978) were developed during the 1970s and issued as regional supplements to the FWI System. These supplements, together with the FWI System, formed the first truly national system of fire danger rating in Canada.

A discussion paper describing a revised approach to a national scheme for predicting fire behavior characteristics in specific fuel complexes was distributed in the early 1980s (C.E. Van Wagner et al. 1982, unpublished). The concept introduced therein became known as the Canadian Forest Fire Behavior Prediction (FBP) System in 1984, when the interim edition of the FBP System was first issued for field trials and user response (Lawson et al. 1985). Only the rate of spread component for 14 major Canadian fuel types was issued in the interim edition. The interim edition was released so that the existing information could be used by fire management agencies without further delay while research continued on the remaining components. The present version increases the number of fuel types, incorporates estimates of fuel consumption and fire intensity, and provides comprehensive models for crown fires and fire growth.

The purpose of this report is the scientific documentation of the FBP System. While no computer program is included with this report, lists of equations (Appendix 1) and symbols (Appendix 2) can be found herein. A standard computer program in FORTRAN for the FBP System is available on request and will be maintained and updated by the Petawawa National Forestry Institute, Chalk River, Ontario. The standard FORTRAN program includes input–output examples to serve as a check against independently produced programs. User needs for operational programs involving the FBP System can be met by the private sector or by the user agencies.

Philosophically, the FBP System reflects the long-established Forestry Canada approach to fire behavior research, as described by Van Wagner (1971). Field observation and documentation of readily measured variables on experimental fires in forest stands and clearcut logging slash, followed by analysis of the data using simple mathematical models and correlation techniques, are the basis of the approach. Well-documented prescribed fires and wildfires have been used as well, the latter being particularly useful at the extreme end of the fire behavior scale, where experimental fires are difficult to schedule and manage. Laboratory-based fire research in moisture physics and heat transfer theory provides the models and framework by which field data are analyzed and explained.

2.0 System Structure

Structurally, the FBP System consists of four fire behavior components as primary outputs: rate of spread, fuel consumption, head fire intensity, and fire description (surface or crown) (Fig. 1). Secondary output components consist of head fire spread distance, elliptical fire area and perimeter, and flank and back rates of spread and fire intensities.

Interspersed through the text of this document are flowcharts that illustrate, at different levels of resolution, the logical advancement towards the final outputs. The flowcharts that appear near the beginning of the major sections—Primary Components and Secondary Components—show overall system structure, while those that introduce various subsections show individual procedures. The flowcharts are intended to provide the reader with reference points to where he/she is in the overall system.

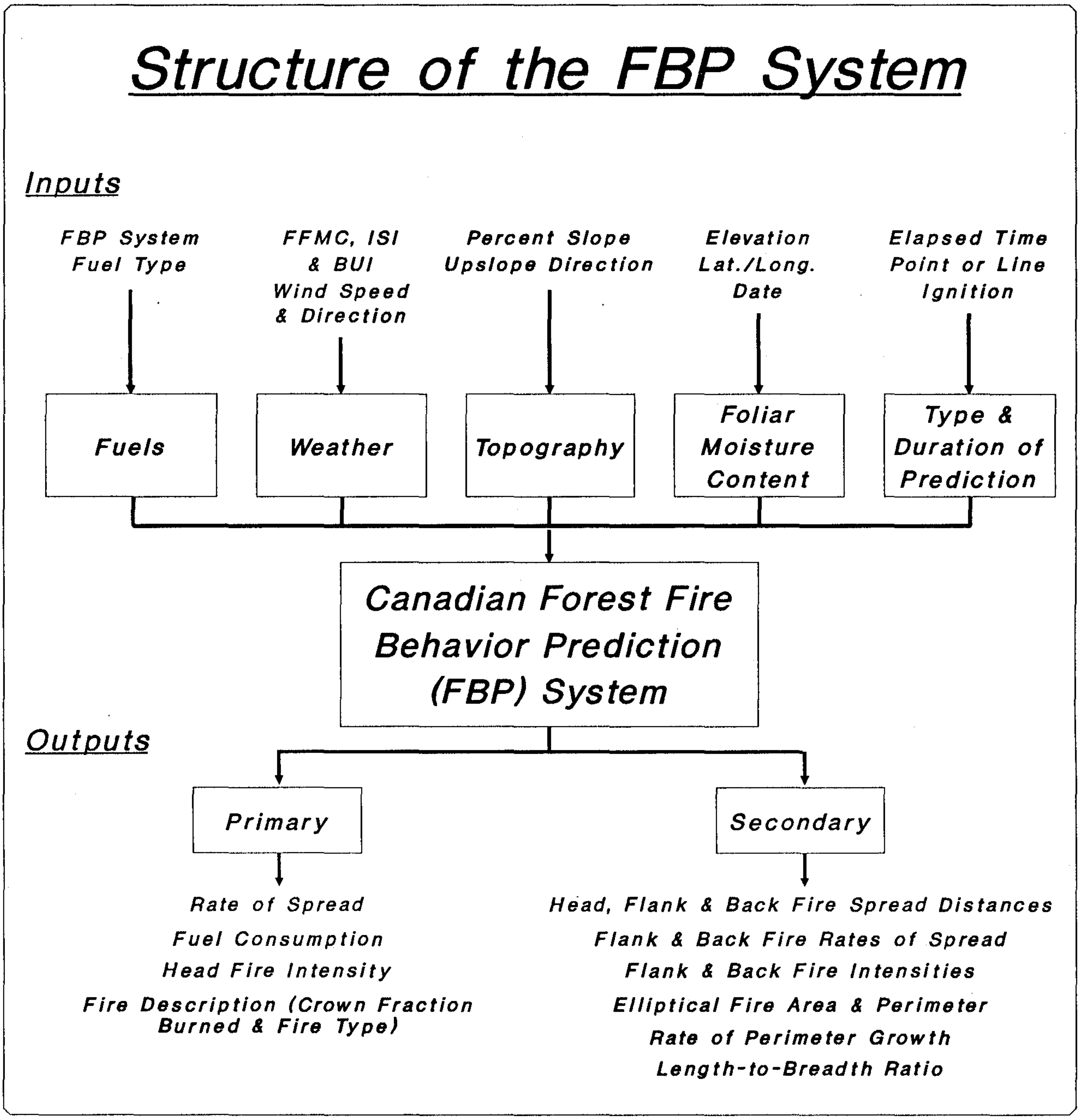


Figure 1. Fire Behavior Prediction (FBP) System structure.

FBP System inputs are drawn from the three major groups of variables affecting fire behavior: fuels, weather, and topography. Other inputs, such as latitude/longitude, season (date), and elapsed time (from ignition), are included to estimate fuel condition or spread distance. The FBP System now predicts:

- the effect of variable fuel consumption on spread rate,
- fuel consumption itself, to permit computation of intensity,
- the onset of crowning,
- the transition from surface fire to crown fire, and
- the behavior of the crown fire.

Although the form of the rate of spread equations for the full range of fire behavior is retained from the interim edition, the expanded FBP System provides for variation about the rate of spread equation and an estimate of crown involvement. Additional inputs are

Table 1. FBP System database summary.

Fuel type	Number of fires in database: Experimental	Wild or prescribed	Total	Number of fires used in analysis: Rate of spread	Fuel consumption
C-1	7	1	8	8	7
C-2	18	30	48	48	13
C-3	41	22	63	63	41
C-4	15	20	35	35	15
C-5	19	1	20	20	10
C-6	12	0	12	12	11
C-7	8	5	13	13	3
M-1[a]	–	–	–	–	–
M-2[a]	–	–	–	–	–
M-3	5	0	5	5	5
M-4	1	0	1	1	1
D-1	32	3	35	35	26
S-1	48	11	59	53	56
S-2	49	21	70	52	68
S-3	28	5	33	16	33
O-1a[b]	52	6	58	58	–
O-1b[b]	74	–	74	74	–
Total[c]	**415**	**119**	**534**	**493**	**289**

[a] M-1 and M-2 were derived from the C-2 and D-1 fuel type models, not from independent data.
[b] The O-1 fuel type is based on Australian grass fire data.
[c] While only 495 original fire observations exist, some observations are used in more than one fuel type, accounting for the extra 39 fires listed here.

required for these enhancements; for example, the Buildup Index (BUI) from the FWI System is used as an indicator of available fuel weight to modify the rate of spread and to predict surface fuel consumption. Since foliar moisture content is assumed to have an important influence on the initiation of crowning and the crown spread rate, a method was developed to estimate foliar moisture content from such simple inputs as date, geographic location, and elevation.

The output from the spread component of the FBP System is head fire rate of spread on any given terrain under equilibrium conditions. By defining rate of spread as the forward movement of the fire front per unit time after having reached an equilibrium state, crowning and spotting are implicitly accounted for in terms of their influence on overall spread rate. The period of accelerating rate of spread from point ignition to equilibrium spread rate is accounted for separately within the elliptical fire growth model in the secondary components section. Neither ease-of-ignition nor spotting distances are outputs of the FBP System at this time, although threshold conditions for minimum sustained spread can be inferred from the rate of spread equations.

The fuel consumption component predicts the amount of forest floor, surface woody fuel, and crown foliage to be consumed. Fuel consumption is dependent on fuel dryness and the degree of crowning predicted. Standard fuel loads are assumed for all fuel types except grass. The fuel consumption component assumes that all fuel consumption takes place in the active fire front, although it is known that some fuel consumption occurs in a separate smoldering phase behind the front. A similar simplification has been made with crown fuel consumption; only crown foliage is assumed to contribute to head fire intensity, even though it is known that in high intensity crown fires, woody twigs as well as foliage are consumed in the active fire front. These simplifications allow the FBP System to utilize Byram's fire intensity concept of energy release rate per unit length of fire front in the head fire intensity component.

3.0 FBP System Database

Primary rate of spread equations, as well as the preliminary fuel consumption equations, for most FBP System fuel types, were developed from a large fire behavior database. This database was compiled from well-documented experimental fires conducted by Forestry Canada fire researchers in cooperation with Canadian fire management agencies, and supplemented with data from prescribed burns and large-scale wildfires. This database currently consists of observations from more than 300 fires from Canadian sources and some selected fires in the United States near the Canadian border. Table 1 provides a summary of the database by fuel type.

4.0 Fuel Type Description

Fuel type has been defined as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions" (Merrill and Alexander 1987). More specifically, a fuel type is a fuel complex of sufficient homogeneity and extending over an area of sufficient size that equilibrium fire behavior can be maintained over a considerable time period.

The FBP System organizes fuel types into five major groups, with a total of 16 discrete fuel types recognized at present (Table 2). Users are required to select the fuel type best suited to the particular situation. The above list represents as broad a range of conditions in Canadian fuel types as allowed by the existing fire behavior database. Fuel types lacking sound Canadian fire behavior data have been included because of their significance to the Canadian landscape (e.g., boreal mixedwood and grass). The list of fuel types is not intended to be comprehensive or fixed for the future; additions and refinements will be made as data become available.

Fuel types in the FBP System are described qualitatively, rather than quantitatively, using terms describing stand structure and composition, surface and ladder fuels, and the forest floor cover and organic (duff) layer. The major distinguishing features of each fuel type are briefly summarized in Table 3 and are described in more detail below; these will be used to classify fuel types from forest inventory type descriptions. FBP System fuel type descriptions do not rigorously or quantitatively follow forest inventory patterns; however, knowledgeable fire managers will develop methods to classify their land base and vegetation data for fire planning (e.g., De Groot 1988). These methods can also be used to assign fuel data on potential or active fires to an appropriate FBP System fuel type.

Table 2. FBP System fuel types.

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

4.1 Fuel Type Classification Terminology

The fuel type classifications in Table 3, and the detailed fuel type descriptions in section 4.2 are defined in terms of forest floor cover and organic layer, surface and ladder fuels, and stand structure and composition. The following explanations of terminology are intended to aid the user with fuel type classification.

Forest floor cover and organic layer: Descriptions of forest floor cover are based on the composition of the fire-carrying fuel (needle litter, dead grass litter, lichen, feather moss) and its distribution (sparse or scattered, discontinuous or continuous). Organic (duff) layers are described by depth (shallow (0–5 cm), moderately shallow (5–10 cm), moderately deep (10-20 cm), and deep (>20 cm), and relative compaction (uncompacted, moderately compacted, and compacted).

Table 3. Summary of Canadian Forest Fire Behavior Prediction (FBP) System fuel type characteristics.

Forest floor and organic layer	Surface and ladder fuels	Stand structure and composition
Fuel Type C-1 (Spruce–Lichen Woodland)		
Continuous reindeer lichen; organic layer absent or shallow, uncompacted.	Very sparse herb/shrub cover and down woody fuels; tree crowns extend to ground.	Open black spruce with dense clumps; assoc. sp. jack pine, white birch; well-drained upland sites.
Fuel Type C-2 (Boreal Spruce)		
Continuous feather moss and/or *Cladonia*; deep, compacted organic layer.	Continuous shrub (e.g., Labrador tea); low to moderate down woody fuels; tree crowns extend nearly to ground; arboreal lichens, flaky bark.	Moderately well-stocked black spruce stands on both upland and lowland sites; *Sphagnum* bogs excluded.
Fuel Type C-3 (Mature Jack or Lodgepole Pine)		
Continuous feather moss; moderately deep, compacted organic layer.	Sparse conifer understory may be present; sparse down woody fuels; tree crowns separated from ground.	Fully stocked jack or lodgepole pine stands; mature.
Fuel Type C-4 (Immature Jack or Lodgepole Pine)		
Continuous needle litter; moderately compacted organic layer.	Moderate shrub/herb cover; continuous vertical crown fuel continuity; heavy standing dead and down, dead woody fuel.	Dense jack or lodgepole pine stands; immature.
Fuel Type C-5 (Red and White Pine)		
Continuous needle litter; moderately shallow organic layer.	Moderate herb and shrub (e.g. hazel); moderate dense understory (e.g. red maple, balsam fir); tree crowns separated from ground.	Moderately well-stocked red and white pine stands; mature; assoc. sp. white spruce, white birch, and aspen.
Fuel Type C-6 (Conifer Plantation)		
Continuous needle litter; moderately shallow organic layer.	Absent herb/shrub cover; absent understory; tree crowns separated from ground.	Fully stocked conifer plantations; complete crown closure regardless of mean stand height; mean stand crown base height controls ROS and crowning.
Fuel Type C-7 (Ponderosa Pine–Douglas-fir)		
Continuous needle litter; absent to shallow organic layer.	Discontinuous grasses, herbs, except in conifer thickets, where absent; light woody fuels; tree crowns separated from ground except in thickets.	Open ponderosa pine and Douglas-fir stands; mature uneven-aged; assoc. sp. western larch, lodgepole pine; understory conifer thickets.
Fuel Type D-1 (Leafless Aspen)		
Continuous leaf litter; shallow, uncompacted organic layer.	Moderate medium to tall shrubs and herb layers; absent conifer understory; sparse, dead, down woody fuels.	Moderately well-stocked trembling aspen stands; semimature; leafless (i.e., spring, fall or diseased).

Table 3. Continued.

Forest floor and organic layer	Surface and ladder fuels	Stand structure and composition
Fuel Types M-1 and M-2 (Boreal Mixedwood)		
Continuous leaf litter in deciduous portions of stands; discontinuous feather moss and needle litter in conifer portions of stands; organic layers shallow, uncompacted to moderately compacted.	Moderate shrub and continuous herb layers; low to moderate dead, down woody fuels; conifer crowns extend nearly to ground; scattered to moderate conifer understory.	Moderately well-stocked mixed stand of boreal conifers (e.g., black/white spruce, balsam/subalpine fir) and deciduous species (e.g., trembling aspen, white birch). Fuel types are differentiated by season and percent conifer/ deciduous sp. composition.
Fuel Types M-3 and M-4 (Dead Balsam Fir Mixedwood)		
Continuous leaf litter in deciduous portions of stands; discontinuous feather moss, needle litter and hardwood leaves in mixed portions of stands; organic layers moderately compacted, 8–10 cm.	Dense continuous herbaceous cover after greenup; down woody fuels low initially, but becoming heavy several years after balsam mortality; ladder fuels dominated by dead balsam understory.	Moderately well-stocked mixed stand of spruce, pine and birch with dead balsam fir, often as an understory. Fuel types differentiated by season and age since balsam mortality.
Fuel Type S-1 (Jack or Lodgepole Pine Slash)		
Continuous feather moss; discontinuous needle litter; moderately deep, compacted organic layer.	Continuous slash, moderate loading and depth; high foliage retention; absent to sparse shrub and herb cover.	Slash from clearcut logging; mature jack or lodgepole pine stands.
Fuel Type S-2 (White Spruce–Balsam Slash)		
Continuous feather moss and needle litter; moderately deep, compacted organic layer.	Continuous to discontinuous slash (due to skidder trails); moderate foliage retention; moderate loading and depth; moderate shrub and herb cover.	Slash from clearcut logging; mature or overmature white spruce, subalpine fir or balsam fir stands.
Fuel Type S-3 (Coastal Cedar–Hemlock–Douglas-fir Slash)		
Continuous feather moss or compacted old needle litter below fresh needle litter from slash; moderately deep to deep, compacted organic layer.	Continuous slash, high foliage retention (cedar), moderate for other species; heavy loading, deep slash; sparse to moderate shrub and herb cover.	Slash from clearcut logging; mature to overmature cedar, hemlock, or Douglas-fir stands.
Fuel Type O-1 (Grass)		
Continuous dead grass litter; organic layer absent to shallow and moderately compacted.	Continuous standing grass (current year crop). Standard loading is 0.3 kg/m^2, but other loading can be accommodated; percent cured or dead must be estimated. Sparse or scattered shrubs and down woody fuel. Subtypes for both early spring matted grass and late summer standing cured grass are included.	Scattered tress, if present, do not appreciably affect fire behavior.

Surface and ladder fuels: These fuels consist of components above the top of the litter layer. Herbaceous vegetation cover, if significant, is described by species composition and distribution/cover (sparse or scattered, moderate, or dense/continuous); shrub cover, by species composition, height class (low, medium, tall), and density of cover as for herbaceous vegetation; conifer understory, by species composition, height relative to live tree crowns, and distribution (absent, sparse or scattered, moderate, dense). Other ladder fuels are described if significant or absent (tree crowns extending to the ground or widely separated from ground, flaky bark on trees).

Down woody fuels in forest stands and in logging slash fuel types are described by distribution and fuel load, with the addition of slash bed depth and foliage retention considered in slash types. Down woody fuels in stands may be sparse or scattered, low to moderate, or continuous/heavy. Slash fuels may be discontinuous (broken up by skid trails) or continuous, of low, moderate, or heavy load, and shallow (<0.5 m), moderate (0.5–1.0 m) or deep (>1.0 m). Retention of foliage on slash may be low (<20%), moderate (20–50%), or high (>50%).

Stand structure and composition: Stand density in terms of overstory stocking and crown closure are described as open (crown closure incomplete, although overstory clumping may be significant), moderately well-stocked (crown closure incomplete or variable with season), fully stocked (complete crown closure), or dense. Other stand structure features of importance to fire spread and crowning may be classified (overstory species composition, stand height, height to live crown, live crown length or crown ratio, stand maturity, horizontal and vertical fuel continuity).

4.2 Detailed Descriptions of FBP System Fuel Types

4.2.1 Coniferous Group

Fuel type C-1 (spruce–lichen woodland): This fuel type is characterized by open, parklike black spruce (*Picea mariana* (Mill.) B.S.P.) stands occupying well-drained uplands in the subarctic zone of western and northern Canada. Jack pine (*Pinus banksiana* Lamb.) and white birch (*Betula papyrifera* Marsh.) are minor associates in the overstory. Forest cover occurs as widely spaced individuals and dense clumps. Tree heights vary considerably but bole branches (live and dead) uniformly extend to the forest floor and layering development is extensive. Woody surface fuel accumulation is very light and scattered. Shrub cover is exceedingly sparse. The ground surface is fully exposed to the sun and covered by a nearly continuous mat of reindeer lichens, averaging 3–4 cm in depth above mineral soil.

Fuel type C-2 (boreal spruce): This fuel type is characterized by pure, moderately well-stocked black spruce stands on lowland (excluding *Sphagnum* bogs) and upland sites. Tree crowns extend to or near the ground and dead branches are typically draped with bearded lichens (*Usnea* sp.). The flaky nature of the bark on the lower portion of stem boles is pronounced. Low to moderate volumes of down woody material are present. Labrador tea (*Ledum groenlandicum* Oeder) is often the major shrub component. The forest floor is dominated by a carpet of feather mosses and/or ground-dwelling lichens (chiefly *Cladonia*). *Sphagnum* mosses may occasionally be present, but they are of little hindrance to surface fire spread. A compacted organic layer commonly exceeds a depth of 20–30 cm.

Fuel type C-3 (mature jack or lodgepole pine): This fuel type is characterized by pure, fully stocked (1000–2000 stems/ha) jack pine or lodgepole pine (*P. contorta* Dougl.) stands that have matured at least to the stage of complete crown closure. The base of live crown is well above the ground. Dead surface fuels are light and scattered. Ground cover is feather moss over a moderately deep (approximately 10 cm), compacted organic layer. A sparse conifer understory may be present.

Fuel type C-4 (immature jack or lodgepole pine): This fuel type is characterized by pure, dense jack or lodgepole pine stands (10 000–30 000 stems/ha) in which natural thinning mortality results in a large quantity of standing dead stems and dead down woody fuel. Vertical and horizontal fuel continuity is characteristic of this fuel type. Surface fuel loadings are greater than in fuel type C-3 and organic layers are shallower and less compact. Ground cover is mainly needle litter and suspended within a low (*Vaccinium* sp.) shrub layer.

Fuel type C-5 (red and white pine): This fuel type is characterized by mature stands of red pine (*P. resinosa* Ait.) and eastern white pine (*P. strobus* L.) in various proportions, sometimes with small components of white spruce (*Picea glauca* (Moench) Voss), and old white birch or aspen (*Populus* sp.). The understory is of moderate density, usually red maple (*Acer rubrum* L.) or balsam fir (*Abies balsamea* (L.) Mill.). A shrub layer, usually beaked hazel (*Corylus cornuta*

Marsh.), may be present in moderate proportions. The ground surface cover is a combination of herbs and pine litter. The organic layer is usually 5–10 cm deep.

Fuel type C-6 (conifer plantation): This fuel type is characterized by pure conifer plantations, fully stocked with closed crowns and no understory or shrub layer present. The forest floor is covered by needle litter with an underlying duff layer up to 10 cm deep. The rate of spread and crown fire relationships allow for variation in crown base height.

Fuel type C-7 (ponderosa pine–Douglas-fir): This fuel type is characterized by uneven-aged stands of ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in various proportions. Western larch (*Larix occidentalis* Nutt.) and lodgepole pine may be significant stand components on some sites and elevations. Stands are open with occasional clumpy thickets of multiaged Douglas-fir and/or larch as a discontinuous understory. Canopy closure is less than 50% overall, although thickets are closed and often dense. Woody surface fuel accumulations are light and scattered. Except within Douglas-fir thickets, the forest floor is dominated by perennial grasses, herbs, and scattered shrubs. Within tree thickets, needle litter is the predominant surface fuel. Duff layers are nonexistent to shallow (< 3 cm).

4.2.2 Deciduous Group

Fuel type D-1 (leafless aspen): This fuel type is characterized by pure, semimature trembling aspen (*Populus tremuloides* Michx.) stands before bud break in the spring or following leaf fall and curing of the lesser vegetation in the autumn. A conifer understory is noticeably absent, but a well-developed medium to tall shrub layer is typically present. Dead and down roundwood fuels are a minor component of the fuel complex. The principal fire-carrying surface fuel consists chiefly of deciduous leaf litter and cured herbaceous material that are directly exposed to wind and solar radiation. In the spring the duff mantle (F and H horizons) seldom contributes to the available combustion fuel due to its high moisture content.

4.2.3 Mixedwood Group

Fuel types M-1 (boreal mixedwood–leafless) and M-2 (boreal mixedwood–green): These fuel types are characterized by stand mixtures consisting of the following coniferous and deciduous tree species in varying proportions: black spruce, white spruce, balsam fir, subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), trembling aspen, and white birch. On any specific site, individual species can be present or absent from the mixture. In addition to the diversity in species composition, stand mixtures exhibit wide variability in stand structure and development, but are generally confined to moderately well-drained upland sites. Two phases associated with the seasonal variation in the flammability of the boreal mixedwood forest are recognized: the leafless stage occurring during the spring and fall (fuel type M-1) and the green stage (fuel type M-2). Rate of spread in both fuel types is weighted according to the proportion (expressed as a percentage) of softwood and hardwood components. In the summer, when the deciduous overstory and understory are in leaf, fire spread is greatly reduced with maximum spread rates only one-fifth that of spring or fall fires under similar burning conditions.

Fuel types M-3 (dead balsam fir mixedwood–leafless) and M-4 (dead balsam fir mixedwood–green): These fuel types are characterized by mixedwood stands in which balsam fir grows, often as an understory species, in a heterogeneous mix with spruce, pine, and birch. These stands are found in the Great Lakes–St. Lawrence and Boreal Forest regions of Canada, and are not to be confused with the pure balsam fir stands typical of Nova Scotia and New Brunswick. Repeated annual defoliation (due to spruce budworm attack) causes balsam fir mortality, followed by peeling bark, draped lichen (Spanish moss or old man's beard, *Usnea* sp.) development, top breakage, and windthrow, peaking 5–8 years after mortality. The volume of down woody material is initially low, but increases substantially with progressive stand decomposition following mortality. The forest floor is a mixture of feather mosses, conifer needles, and hardwood leaves. The organic layer is moderately compacted and 8–10 cm deep.

After mortality, spring fires in this fuel type behave extremely vigorously with continuous crowning and downwind spotting, while summer fires are hampered by the proliferation of green understory vegetation resulting from the opening of stand canopy. As sufficient surface fuel accumulates through stand decomposition (usually after 4–5 years) during summer, fires will spread through the fuel complex, although not as vigorously as in spring. Forest fire behavior potential is greatest 5–8 years after mortality, decreasing gradually as the surface fuels decompose and the understory vegetation continues to proliferate.

4.2.4 Slash Group

Fuel type S-1 (jack or lodgepole pine slash): This fuel type is characterized by slash resulting from tractor or skidder clearcut logging of mature jack or lodgepole pine stands. The slash is typically one or two seasons old, retaining up to 50% of the foliage, particularly on branches closest to the ground. No postlogging treatment has been applied and slash fuels are continuous. Tops and branches left on site result in moderate fuel loads and depths. Ground cover is continuous feather moss mixed with discontinuous fallen needle litter. Organic layers are moderately deep and fairly compact.

Fuel type S-2 (white spruce–balsam slash): This fuel type is characterized by slash resulting from tractor or skidder clearcut logging of mature to overmature stands of white spruce and subalpine fir or balsam fir. Slash is typically one to two seasons old, retaining from 10% to 50% of the foliage on the branches. No postlogging treatment has been applied. Fuel continuity may be broken by skid trails unless winter logged. Tops have been left on site and most branch fuels have broken off during skidding of logs to landings, resulting in moderate fuel loads and depths. Quantities of shattered large and rotten woody fuels may be significant. Ground cover is feather moss with considerable needle litter fallen from the slash. Organic layers are moderately deep and compact.

Fuel type S-3 (coastal cedar–hemlock–Douglas-fir slash): This fuel type is characterized by slash resulting from high-lead clearcut logging of mature to overmature coastal British Columbia mixed conifer stands. Predominant species are western red cedar (*Thuja plicata* Donn.), western hemlock (*T. heterophylla* (Raf.) Sarg.) and Douglas-fir. Slash is typically one season old, with the cedar component retaining all its foliage in a cured condition on the branches, while the hemlock and Douglas-fir components will have dropped up to 50% of their foliage. Slash fuels tend to be continuous and uncompacted. Very large loadings of broken and rotten unmerchantable material may be present, depending on degree of stand decadence. Slash fuel depths may range from 0.5 to 2.0 m. Ground cover may be feather moss or just compact old needle litter under significant quantities of recent needle litter fallen from the slash. Organic layers are moderately deep to deep and compact. Minor to moderate shrub and herbaceous understory components may be present. This fuel type may also be applied to wet belt decadent cedar–hemlock slash of coastal and interior British Columbia where the Douglas-fir component is absent.

4.2.5 Open Group

Fuel type O-1 (grass): This fuel type is characterized by continuous grass cover, with no more than occasional trees or shrub clumps that do not appreciably affect fire behavior. Two subtypes are available for grasslands; one for the matted grass condition common after snowmelt or in the spring (O-1a), and the other for standing dead grass common in late summer to early fall (O-1b). The proportion of cured or dead material in grasslands has a pronounced effect on fire spread there and must be estimated with care.

5.0 Fine Fuel Moisture Code Options

As shown in Figure 1, weather-based inputs to the FBP System include wind speed and direction and the Fine Fuel Moisture Code (FFMC) from the FWI System. Not all of the planned FFMC adjustments have been fully developed, nor are they considered an integral part of the FBP System. FFMC adjustment processes will eventually become part of the Accessory Fuel Moisture System, a partially developed subsystem of the CFFDRS (Stocks et al. 1989).

The interim edition of the FBP System (Lawson et al. 1985) included a table to adjust standard FFMC for times throughout the afternoon and early evening, and a table to adjust FFMC for slope and aspect differences between the weather observation point and the fire behavior prediction point. These tables were adapted from earlier research, but were regarded as interim products while research continued on a comprehensive mathematical model of FFMC adjustments for latitude, elevation, slope/aspect, and time of day. In addition, Van Wagner (1977a) published a method of computing FFMC at hourly intervals.

The simple FFMC adjustment table in the interim edition of the FBP System required no additional weather observations for the afternoon and evening times of interest. The table assumed a "standard" afternoon pattern of change in temperature and relative humidity, and was derived from previously published versions (Van Wagner 1972; Canadian Forestry Service 1973, 1974; Alexander 1982). This table was restricted to afternoon hours to simplify data requirements and to stress times and FFMC ranges normally of interest in fire behavior prediction. Recent technological developments in electronic weather data collection and transmission capabilities have made the hourly computational procedure for the FFMC operationally feasible, requiring in turn an updating of Van Wagner's original method. The 1977 hourly FFMC model is currently under revision.

The current (Van Wagner 1977a; Alexander et al. 1984) hourly FFMC computational method utilizes hourly measurements of dry bulb temperature, relative humidity, wind speed and total rainfall (over the hour). Other time intervals of weather observation and FFMC computation are possible. The computational method has been embedded into computer programs that can be started and stopped at any time of the day and can be run with a given diurnal weather cycle repeated any number of times, or with a series of different cycles, using actual or forecasted weather. This makes the hourly FFMC computational method preferable for fire behavior prediction to the standard FFMC, which has a standard diurnal curve embedded in it, and to the single diurnal curve in the Van Wagner (1972) table. This computational method accounts for local diurnal weather cycles that can vary considerably from the standard diurnal cycle, depending on latitude, season, topography (mountain and valley effects), and coastal effects. Due to local effects, particularly latitude and season, the minimum fine fuel moisture content may occur as late in the day as 1800 to 2000; this lags considerably behind the time of peak temperature and minimum relative humidity, although wind speed has generally dropped considerably from its mid-afternoon peak. The traditional fire danger peak at 1600 therefore remains a reasonable assumption.

Figure 2 shows the three available options for computing FFMC (and Initial Spread Index, ISI) operationally for the FBP System. All options use an actual or forecasted wind speed for the time and area of interest to calculate the ISI. With option 1 the standard daily FFMC can be used with an updated afternoon wind speed to compute a wind-adjusted ISI. Option 2 provides more range in the time period (from 1200 to 2000) for which an adjusted FFMC (and ISI) can be calculated without additional weather data; however, the assumed standard diurnal weather curve is a restriction. Option 3 provides the most representative FFMC and ISI but demands the most weather data.

One final point should be made, regarding use of hourly FFMC computations with the FBP System. Differences will exist between the standard daily FFMC (calculated from noon LST weather observations) and the mid-afternoon FFMC values computed from actual hourly weather data with the hourly FFMC program (Van Wagner 1977a; Alexander et al. 1984). The hourly computed FFMC should be regarded as the "true" value in this case and archived as the reference FFMC against which fire behavior analysis would be based.

6.0 Foliar Moisture Content

Conifer foliar moisture content (FMC) has an important bearing on two features of fire behavior in coniferous forests, namely the initiation of crowning and the crown fire spread rate (Van Wagner 1977b). For all fuel types (except C-6, conifer plantation) the effect of foliar moisture content on the crown fire spread rate is not taken into account due to the statistical nature of the models. However, initiation of crowning and conifer plantation crown fire spread rate require an estimate of foliar moisture content. Foliar moisture content varies from a minimum of 85% to a maximum of 120%, depending on the season. A period of relatively low values in the spring and early summer is referred to here as the spring dip. This dip is mainly physiological, resulting from a temporary increase in dry weight rather than from a real decrease in cellular water content (Little 1970b; Gary 1971). For practical purposes its date is assumed to be regionally constant from year to year and to not be affected by annual differences in weather. A method was designed to estimate foliar moisture content from simple information such as location, elevation, and date. All equations are listed at the end of this section.

As field data for the development of the process, nine Canadian foliar moisture studies were available, ranging in location from longitude 67° to 124° west, and from latitude 46° to 59° north (Table 4). The data show foliar moisture content trends over time, based on periodic samples of one or more coniferous tree species during spring and summer. At two of the locations, Castlegar and Foothills, Alberta, samples were taken at multiple elevations.

The first stage in the procedure was the design of a standard curve to represent the course of the spring dip in foliar moisture content. Only the first six data sources listed in Table 4, in relatively flat locations, were used for this purpose. First, the plotted trends of foliar moisture content over date were smoothed subjectively and the dates marking the beginning, the minimum value, and the end of the spring dip were estimated, along with the foliar moisture content values at each date. Where more than one tree species was sampled or more than one year's data were available, the results were averaged for the location (Table 5). From these data a standard spring-dip curve was designed, symmetrical about its minimum point, with a duration of 100 days and a range of 85% to 120% foliar moisture content. This curve was rendered algebraically by two parabolas, one for the central section and the other (inverted) for the symmetrical ends.

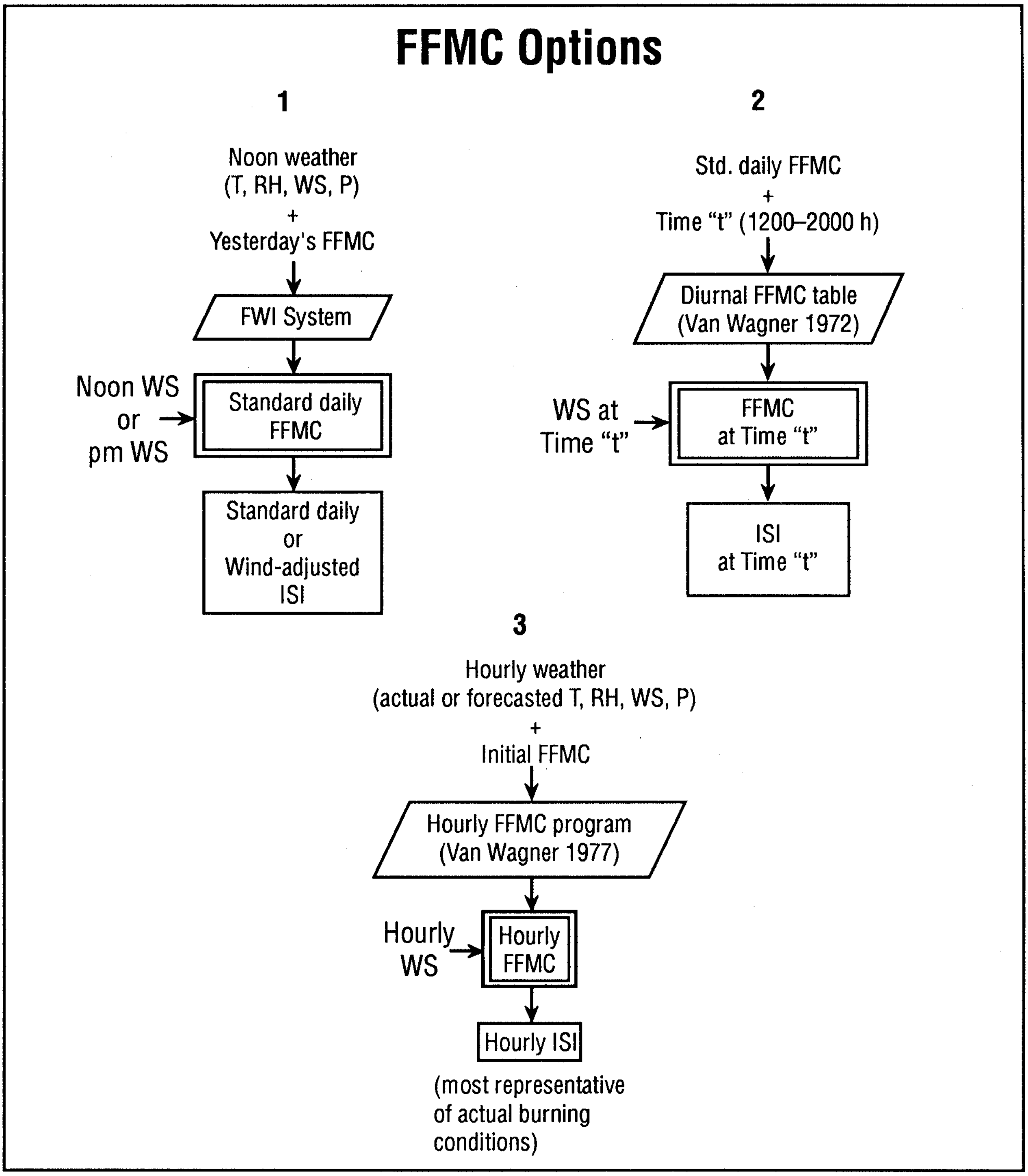


Figure 2. Three Fine Fuel Moisture Code (FFMC) computational options in the Accessory Fuel Moisture System of the CFFDRS (T = temperature, RH = relative humidity, WS = wind speed, P = precipitation, "t" = specific time of day).

Table 4. Canadian data sources for the spring dip in conifer foliage moisture content.

Location	Lat. (°)	Long. (°)	Elev. (m ASL)	Reference	No. of yrs. sampled
Fredericton	45.9	66.7	50	Little 1970a, 1970b; unpublished data[a]	4
Petawawa	46.0	77.4	150	Van Wagner 1967	6
Kapuskasing	49.5	82.4	200	Springer & Van Wagner 1984	
Lesser Slave Lake	55.2	114.5	580	Chrosciewicz 1986	2
Big Fish Lake	59.2	116.0	850	Unpublished data[b]	2
Victoria	48.5	123.8	100	Russell & Turner 1975	1
Castlegar	49.2	117.9	610	Unpublished data[c]	1
Swan Hills	54.5	115.5	1 005	Fuglem & Murphy 1980	1
Foothills	53.0	117.0	1 065	Fuglem & Murphy 1980	1

[a] Data on file at Forestry Canada Maritime Forestry Centre.
[b] Data collected by Canadian Forestry Service in 1984 and 1985, communicated by M.E. Alexander.
[c] Data collected by Selkirk College in 1974, communicated by J.A. Turner.

Table 5. Average moisture content and average date of minimum moisture content (D_0) for the spring dip in old conifer foliage at the first six locations in Table 4.

Location	Average moisture content (%) Min.	Max.	Range	Average D_0 (Julian date)[a]	Species[b] sampled
Fredericton	81	125	44	147	bF
Petawawa	94	121	27	146	wP, rP, jP, wS, bF
Kapuskasing	82	106	24	154	bS
Lesser Slave Lake	84	121	37	158	jP, bS, wS, bF
Big Fish Lake	75	95	20	180	bS
Victoria	103	149	46	121	dF, wH
Means	**86.5**	**119.5**	**33.0**		

[a] For reference, 1 June is Julian day 152 on nonleap years.
[b] bF — balsam fir; wP — eastern white pine; rP — red pine; jP — jack pine; wS — white spruce; bS — black spruce; dF — Douglas-fir; wH — western hemlock.

The second stage was the design of a method of calculating the date of minimum foliar moisture content for any location, based on latitude and longitude. From the general nature of climatic isotherms in Canada, it was judged probable that the isoline of any given value of date of minimum foliar moisture content would form a curve of decreasing slope from northwestern Canada, gradually becoming parallel to latitude in the east. The procedure was then as follows:

1) The latitudes of the six relatively flat locations were normalized to a common D_0 (date of minimum foliar moisture content), multiplying each latitude by the average D_0 and dividing by the specific D_0.
2) The natural logarithms of the normalized latitudes (minus 46, a value found by trial to best represent the asymptotic latitude) were plotted over longitude (for ease of calculation, the x-axis was represented by 150° west longitude).
3) A least squares solution for the semilogarithmic curve was determined. The date of minimum foliar moisture content could then be calculated for any location, based on latitude and longitude.

The third stage was the introduction of elevation. Analysis of two specific locations, Castlegar and Foothills, with data from several elevations showed a delay in date of minimum foliar moisture content of 0.02 and 0.04 day/m of elevation above base level, respectively. The entire set of dates of minimum foliar moisture content, for all nine locations, were then simply graphed over elevation above sea level. Least squares analysis gave an altitude effect of 0.026 day/m with an R-square of 0.44. This graphed pattern seemed reasonable and the result intermediate between those from the above two specific locations; it was therefore adopted. Accordingly, all nine values for date of minimum foliar moisture content were normalized with respect to sea level by subtracting 0.026 times elevation from each. The procedure described above for the second step was then followed again, except that the value best representing the asymptotic latitude was found to be 42.

All equations for computing the date of minimum foliar moisture content, and the foliar moisture content for any date based on latitude and longitude with an option to include elevation are listed below:

To compute the date of minimum foliar moisture content given latitude and longitude,

$$\mathrm{LATN} = 46 + 23.4 \times e^{-0.0360 \times (150 - \mathrm{LON})} \qquad (1)$$

$$D_0 = 151 \times \left(\frac{\mathrm{LAT}}{\mathrm{LATN}}\right) \qquad (2)$$

To compute the date of minimum foliar moisture content, given latitude, longitude, and elevation,

$$\mathrm{LATN} = 43 + 33.7 \times e^{-0.0351 \times (150 - \mathrm{LON})} \qquad (3)$$

$$D_0 = 142.1 \times \left(\frac{\mathrm{LAT}}{\mathrm{LATN}}\right) + 0.0172 \times \mathrm{ELV} \qquad (4)$$

To compute foliar moisture content from the Julian date and the date of minimum foliar moisture content,

$$\mathrm{ND} = \left| D_j - D_0 \right| \qquad (5)$$

$$\mathrm{FMC} = 85 + 0.0189 \times \mathrm{ND}^2 \qquad \mathrm{ND} < 30 \qquad (6)$$

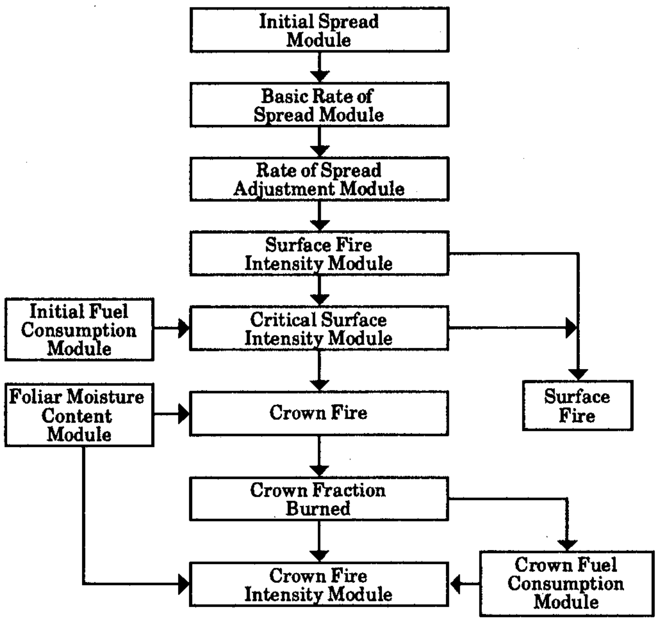
$$\mathrm{FMC} = 32.9 + 3.17 \times \mathrm{ND} - 0.0288 \times \mathrm{ND}^2 \qquad 30 \le \mathrm{ND} < 50 \qquad (7)$$

$$\mathrm{FMC} = 120 \qquad \mathrm{ND} \ge 50 \qquad (8)$$

where LAT is degrees latitude; LATN is normalized latitude; LON is degrees longitude; ELV is elevation above sea level (m); D_j is Julian date; D_0 is date of minimum FMC (Julian); ND is number of days between D_j and D_0; FMC is foliar moisture content (%).

There are weaknesses in this scheme. First, it ignores the effect of the newly flushed foliage that begins to appear near the end of the spring dip. This new growth, although very high moisture, contributes little dry weight at first, then gradually approaches the moisture content of the old foliage as its weight increases. To avoid this complication, foliar moisture content is simply put equal to 120% after the spring dip is over. Second, the locations used were simply those for which data were available; they do not by any means represent the full geographical range of the phenomenon.

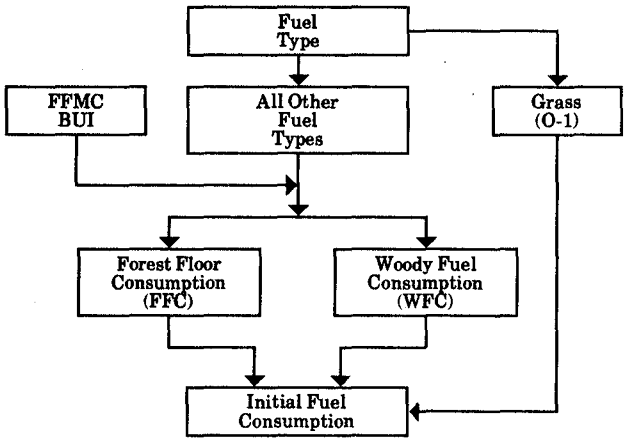
7.0 Primary Components



Primary FBP System

7.1 Initial Fuel Consumption

Fuel consumption in the FBP System is broken into two distinct sections: surface and total. The outputs of the surface fuel consumption models are used in determining the onset of crown fire initiation. However, total fuel consumption includes the crown fuels consumed, which cannot be calculated until the degree of crown involvement is estimated. This section presents the surface fuel consumption models required for the subsequent rate of spread models.



Initial Fuel Consumption

Experimental fires and well-documented prescribed burns are the primary source of the fuel consumption data used in the FBP System (e.g., Muraro 1975; Stocks 1987a,b; Stocks 1989; Quintilio et al. 1977). Surface fuel consumption, which is the sum of woody fuel consumption and forest floor consumption, expressed in kilograms per square metre (ovendry weight), has been regressed against the Buildup Index (BUI) using nonlinear regression techniques. The same general form of the equation (the S-shaped function) that was used in the regressions of initial rate of spread versus the Initial Spread Index (ISI), is used for the surface fuel consumption versus the BUI. Fuel consumption data are less abundant (because accurate fuel consumption measurements cannot be made on wildfires) and more scattered than was the case with initial rate of spread data. For this reason data were pooled for some fuel types (C-2 and M-3/M-4; C-3 and C-4; and C-5 and C-6). The results are shown in Figures 3 and 4.

Exceptions to the surface fuel consumption versus the BUI regression are the standing fuel types C-1 and C-7, the grass fuel type O-1, and the slash fuel types S-1, S-2, and S-3. In the case of fuel type C-1, the surface fuel consumption is regressed against the fine fuel moisture content (FFMC) rather than the BUI because the materials available for combustion consist of reindeer lichen and some fine fuels, with little or no organic layer. For fuel type C-7, the forest floor consumption is regressed against the FFMC and the woody fuel consumption against the BUI. The surface fuel consumption is the sum of the two predicted values. The surface fuel consumption is held constant for the grass fuel type O-1 because there is no organic layer and all the grass is assumed to be consumed in the fire front. The standard fuel load for grass fuel types is 0.3 kg/m^2 unless otherwise measured. For the slash fuel types, the forest floor consumption and the woody fuel consumption were regressed separately against the BUI and the predicted values must be summed to obtain the predicted surface fuel consumption.

As fuel consumption data are somewhat sparse and scattered, curve fitting once again involved a degree of reliance on informal experience, using both monotonic and asymptotic curve shapes, and applying a leveling-off function at high BUI or FFMC values. Equations for all fuel consumption curves are listed below:

C-1

$$SFC = 1.5 \times \left[1 - e^{(-0.230 \times [FFMC - 81])}\right] \quad (9)$$

If SFC < 0, then set SFC = 0.

C-2, M-3, and M-4

$$SFC = 5.0 \times \left[1 - e^{(-0.0115 \times BUI)}\right]^{1.00} \quad (10)$$

C-3 or C-4

$$SFC = 5.0 \times \left[1 - e^{(-0.0164 \times BUI)}\right]^{2.24} \quad (11)$$

C-5 or C-6

$$SFC = 5.0 \times \left[1 - e^{(-0.0149 \times BUI)}\right]^{2.48} \quad (12)$$

C-7 — Compute the forest floor and woody fuel consumptions separately and add together to get the total surface fuel consumption:

$$FFC = 2 \times \left[1 - e^{(-0.104 \times [FFMC - 70])}\right] \quad (13)$$

If FFC < 0, then set FFC = 0.

$$WFC = 1.5 \times \left[1 - e^{(-0.0201 \times BUI)}\right] \quad (14)$$

$$SFC = FFC + WFC \quad (15)$$

D-1

$$SFC = 1.5 \times \left[1 - e^{(-0.0183 \times BUI)}\right] \quad (16)$$

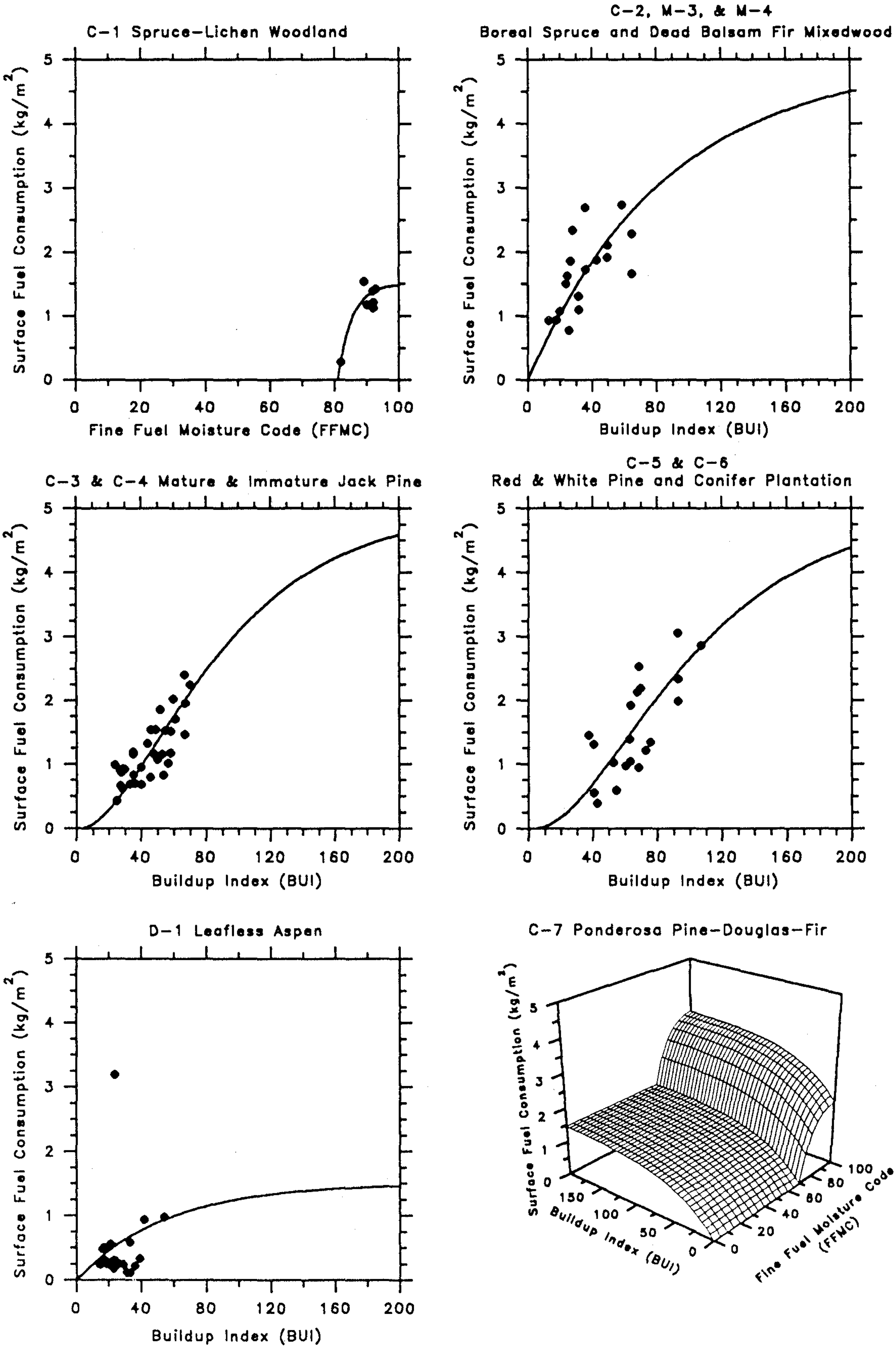


Figure 3. Fuel consumption curves, showing the S-shaped asymptotic curves for fuel types C-1, C-2, C-3, C-4, C-5, C-6, C-7, M-3, M-4, and D-1.

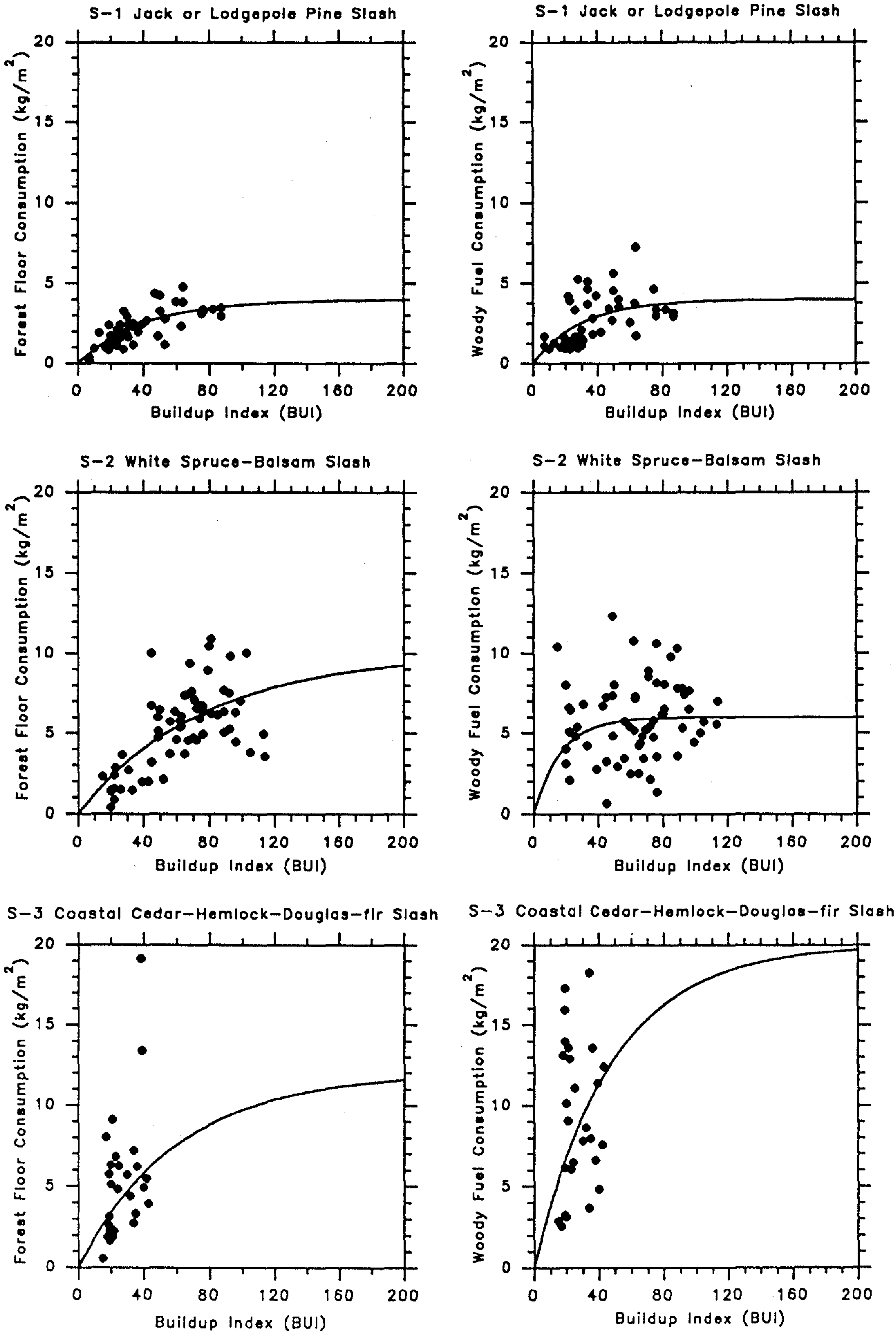


Figure 4. Forest floor consumption–BUI and woody fuel consumption–BUI curves, showing the S-shaped asymptotic curves for slash fuel types.

M-1 or M-2

$$\mathrm{SFC} = \left[\frac{\mathrm{PC}}{100} \times (\mathrm{SFC\ for\ C\text{-}2})\right] \tag{17}$$

$$+ \left[\frac{\mathrm{PH}}{100} \times (\mathrm{SFC\ for\ D\text{-}1})\right]$$

O-1

$$\mathrm{SFC} = \mathrm{GFL} \tag{18}$$

S-1

$$\mathrm{FFC} = 4.0 \times \left[1 - e^{(-0.025 \times \mathrm{BUI})}\right] \tag{19}$$

$$\mathrm{WFC} = 4.0 \times \left[1 - e^{(-0.034 \times \mathrm{BUI})}\right] \tag{20}$$

S-2

$$\mathrm{FFC} = 10.0 \times \left[1 - e^{(-0.013 \times \mathrm{BUI})}\right] \tag{21}$$

$$\mathrm{WFC} = 6.0 \times \left[1 - e^{(-0.060 \times \mathrm{BUI})}\right] \tag{22}$$

S-3

$$\mathrm{FFC} = 12.0 \times \left[1 - e^{(-0.0166 \times \mathrm{BUI})}\right] \tag{23}$$

$$\mathrm{WFC} = 20.0 \times \left[1 - e^{(-0.0210 \times \mathrm{BUI})}\right] \tag{24}$$

All slash types

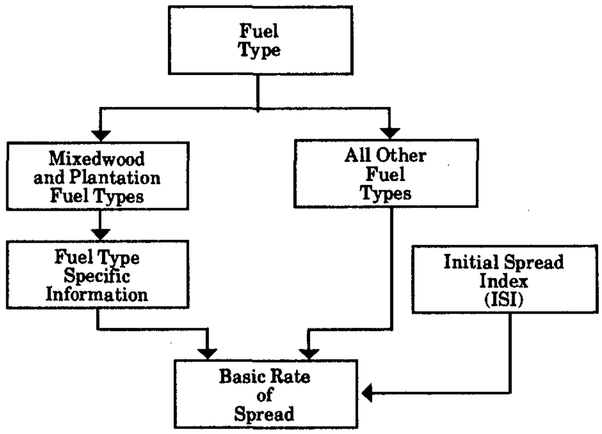
$$\mathrm{SFC} = \mathrm{FFC} + \mathrm{WFC} \tag{25}$$

where SFC is the surface fuel consumption; FFMC is the fine fuel moisture code value from the FWI System; FFC is the forest floor consumption; WFC is the woody fuel consumption; PC and PH are percent conifer and percent hardwood composition, respectively; and GFL is the grass fuel load (standard value 0.3 kg/m^2).

7.2 Rate of Spread

7.2.1 Basic Rate of Spread Equations

The final rate of spread predicted by the FBP System is the result of the initial rate of spread modified by a BUI function, a slope effect, and a crowning effect. To derive initial rate of spread equations, data



Basic Rate of Spread

from the FBP database were grouped into subsets according to fuel type. Some large wildfires known to have burned through several forest fuel types were included in more than one fuel type subset. For all rate of spread equations derived from the FBP System database, the independent variable was the ISI. Since the ISI comprises functions of the FFMC and wind speed, all fuel type subsets were tested for multiple correlation of rate of spread with the FFMC and wind speed separately. No advantage was found over using the ISI alone, and therefore all equations express rate of spread in relation to ISI.

The predicted rate of spread is the head fire spread rate on level terrain under equilibrium conditions. Initiating fire behavior, including the time required for acceleration to equilibrium spread rate, is not considered at this point in the process. By defining rate of spread as the forward movement of the fire front per unit time after having reached equilibrium, crowning and spotting are automatically accounted for in terms of their influence on the overall spread rate.

7.2.1.1 Natural and cutover fuel types

Scatterplots of rate of spread versus ISI for natural conifer fuel types (C-1, C-2, C-3, C-4, C-5, and C-7) are shown in Figures 5 and 6. The equation form chosen for all fuel types was an S-shaped asymptotic curve with parameters for each fuel type estimated using nonlinear techniques. The general equation for initial rate of spread (RSI) is:

$$\mathrm{RSI} = a \times \left[1 - e^{(-b \times \mathrm{ISI})}\right]^{c} \tag{26}$$

where a, b, and c are parameters specific to each fuel type. This curve form met two requirements: passing

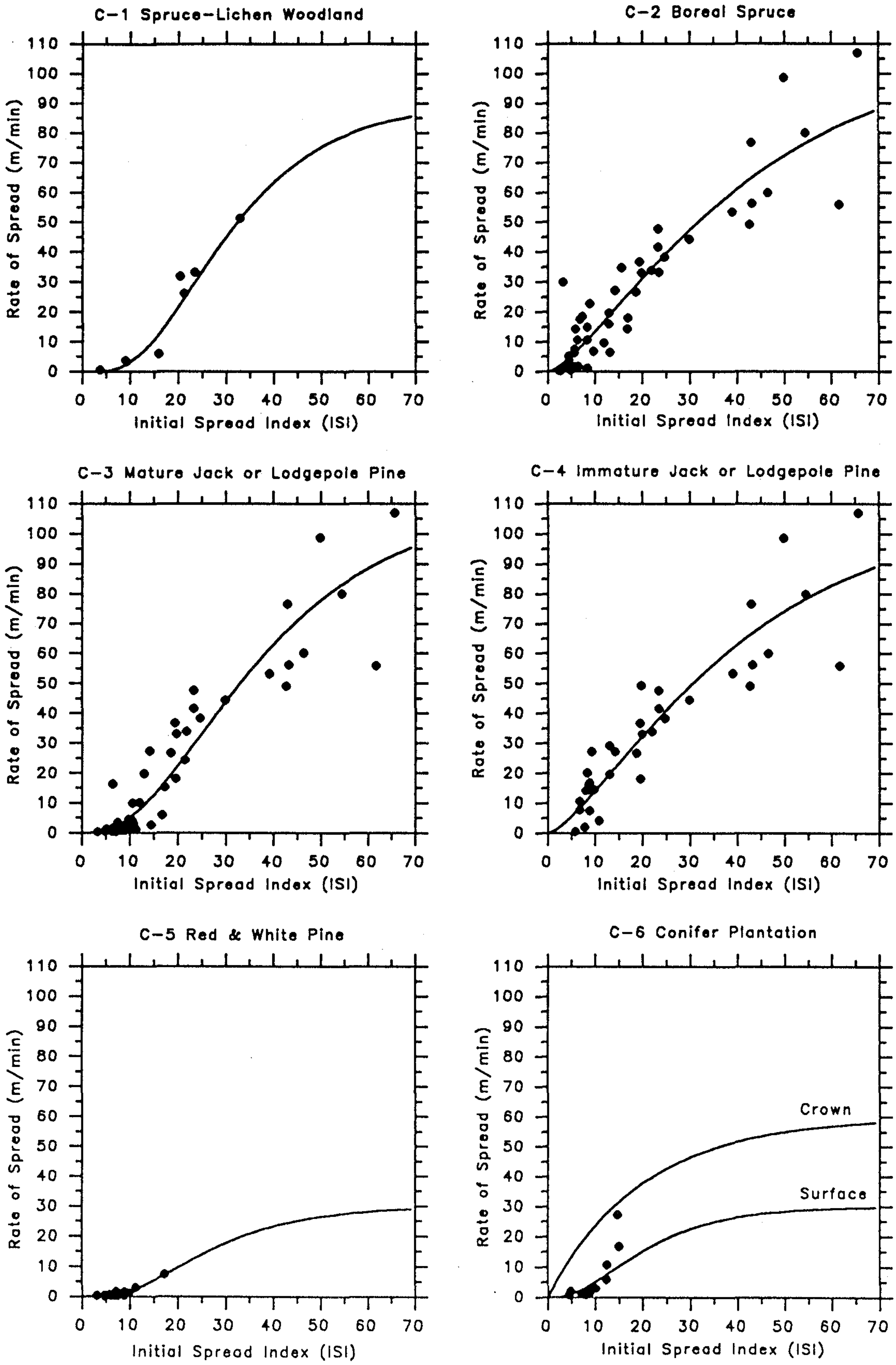


Figure 5. Basic rate of spread–ISI curves for fuel types C-1, C-2, C-3, C-4, C-5, and C-6.

through the origin and leveling off at high ISI values. The steepest portion of the S-shaped curve coincides with the transition period between surface and crown fire. The principle that rate of spread levels off at very high ISI values was adopted as an appropriate conservative approach in the absence of concrete knowledge. In general, experimental fire data are used in the low to moderate ISI range, while wildfire data form the bulk of the high to extreme ISI data. This is primarily because wildfire problems and resource restrictions usually preclude the conducting of experimental fires under severe fire danger conditions.

Scatterplots of observed rate of spread versus ISI for leafless aspen (D-1) and slash (S-1, S-2, and S-3) fuel types are shown in Figure 6. High to extreme ISI data are not available for these fuel types; however, a leveling-off function, based on informal experience, is applied. The boreal mixedwood fuel types (Fig. 7) represent a wide diversity with respect to conifer/deciduous composition. Recognizing this diversity and having no data on fire behavior in boreal mixedwood fuel types, the rate of spread equation for these fuel types is therefore a blend of C-2 and D-1. The RSI for fuel type M-1 is therefore:

$$\mathrm{RSI} = \left[\frac{\mathrm{PC}}{100} \times (\mathrm{RSI\ for\ C\text{-}2})\right] + \left[\frac{\mathrm{PH}}{100} \times (\mathrm{RSI\ for\ D\text{-}1})\right] \tag{27}$$

where PC is percent conifer and PH is percent hardwood. The equation for fuel type M-2 is then:

$$\mathrm{RSI} = \left[\frac{\mathrm{PC}}{100} \times (\mathrm{RSI\ for\ C\text{-}2})\right] + 0.2 \times \left[\frac{\mathrm{PH}}{100} \times (\mathrm{RSI\ for\ D\text{-}1})\right] \tag{28}$$

The equation for fuel type M-2 is similar to fuel type M-1 except the hardwood component is multiplied by 0.2. Although no rate of spread data exist for hardwood fuel types under summer or "leaf-out" conditions, the assumption is made that the rate of spread is 20% of that achieved under leafless conditions. For mixedwood fuel types M-3 and M-4, which include a dead balsam fir component, the initial rate of spread equation should be used with the following equations to compute the a, b, and c parameters:

Table 6. Rate of spread parameter values for all fuel types except mixedwood.

Fuel type	a	b	c
C-1	90	0.0649	4.5
C-2	110	0.0282	1.5
C-3	110	0.0444	3.0
C-4	110	0.0293	1.5
C-5	30	0.0697	4.0
C-6	30	0.0800	3.0
C-7	45	0.0305	2.0
D-1	30	0.0232	1.6
S-1	75	0.0297	1.3
S-2	40	0.0438	1.7
S-3	55	0.0829	3.2
O-1a	190	0.0310	1.4
O-1b	250	0.0350	1.7

M-3

$$a = 170 \times e^{\left(\frac{-35.0}{\mathrm{PDF}}\right)} \tag{29}$$

$$b = 0.082 \times e^{\left(\frac{-36.0}{\mathrm{PDF}}\right)} \tag{30}$$

$$c = 1.698 - 0.00303 \times \mathrm{PDF} \tag{31}$$

M-4

$$a = 140 \times e^{\left(\frac{-35.5}{\mathrm{PDF}}\right)} \tag{32}$$

$$b = 0.0404 \tag{33}$$

$$c = 3.02 \times e^{(-0.00714 \times \mathrm{PDF})} \tag{34}$$

where PDF is the percent dead balsam fir. Figure 7 shows the curves generated for various parameter combinations (hardwood/softwood composition and percent dead balsam fir) for the mixedwood fuel types. Coefficient values a, b, and c for all remaining natural and cutover fuel types are found in Table 6.

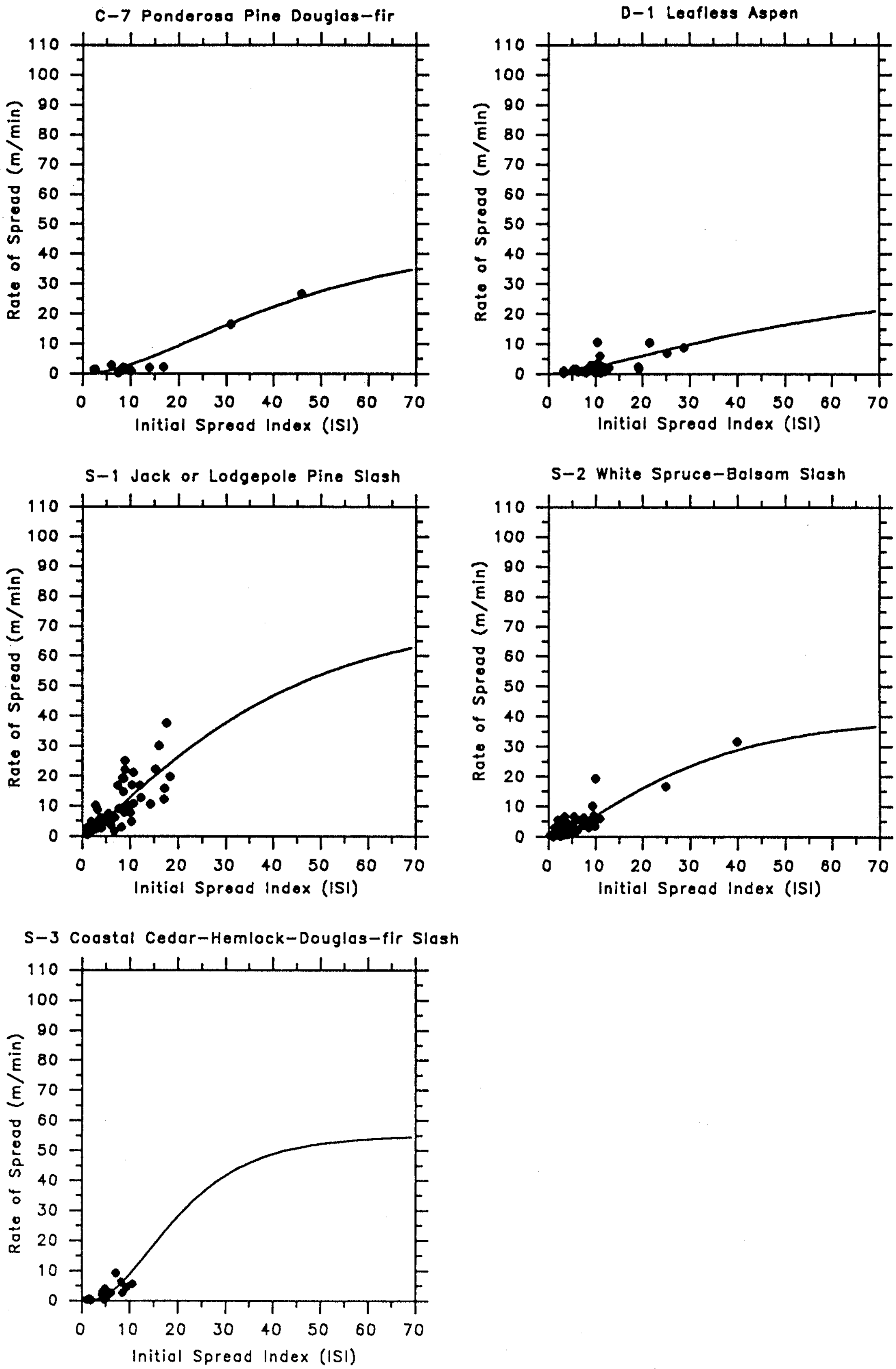


Figure 6. Basic rate of spread–ISI curves for ponderosa pine–Douglas-fir (C-7), deciduous (D-1), and slash (S-1, S-2, and S-3) fuel types.

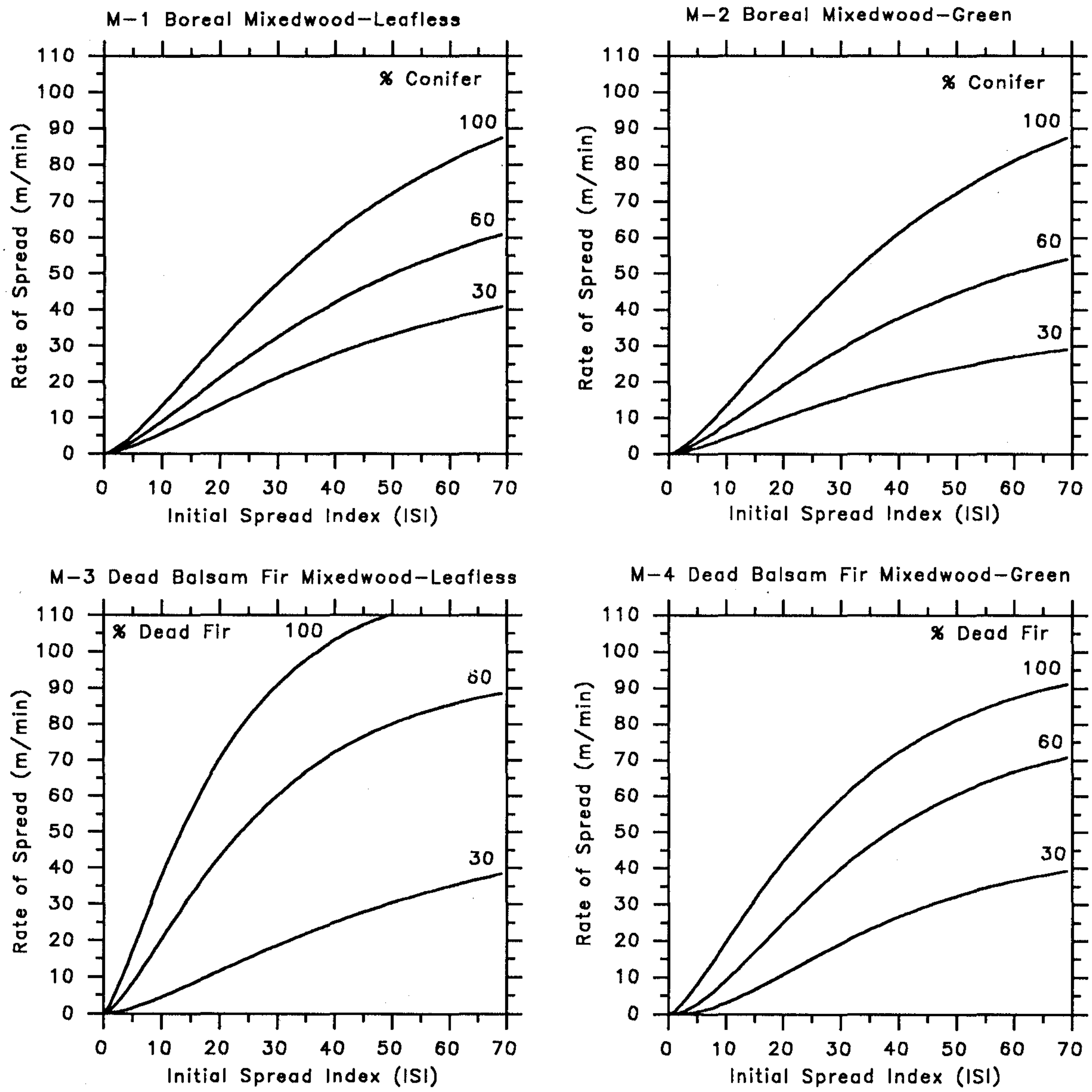


Figure 7. Basic rate of spread–ISI curves for boreal mixedwood (M-1 and M-2) and dead balsam fir mixedwood (M-3 and M-4).

7.2.1.2 Plantation fuel types

Since conifer plantations are more structured and have less variability than naturally regenerated areas, they are more easily modeled in a complex separation of surface and crown fire. This separation has been addressed by Van Wagner (1989); however, the model utilizes concepts discussed later in this document. It is therefore presented in section 7.2.5.

7.2.1.3 Grass fuel types

There is no body of Canadian fire behavior data for the grass fuel type. An early grass-fire hazard index was developed by Wright and Beall (1938); however, it was based on small test fires for which no quantitative rates of spread were recorded. Spread rate estimates for fuel type O-1 (grass) are based on regression functions derived from Australian grass fire data (J.S. Gould and N.P. Cheney 1991, Australian Natl. Bushfire Res. Inst., personal correspondence). Data were available for tall grass and short (cut) grass, the tall grass being representative of midsummer fields of dry grass, and the cut grass of early spring grass fuel matted down by snow loads. Percent cured or the proportional number of grass stems that have dried out and are no longer green and growing is considered to have an important influence

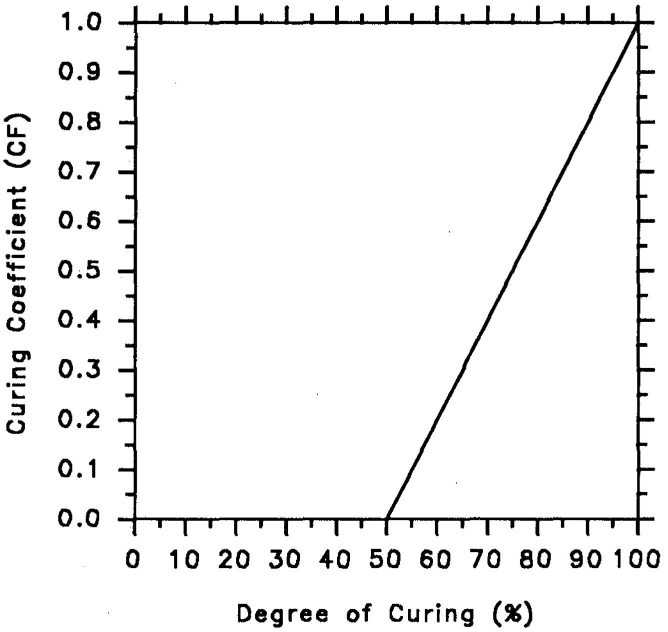


Figure 8. Relationship between the curing coefficient and degree of grass curing.

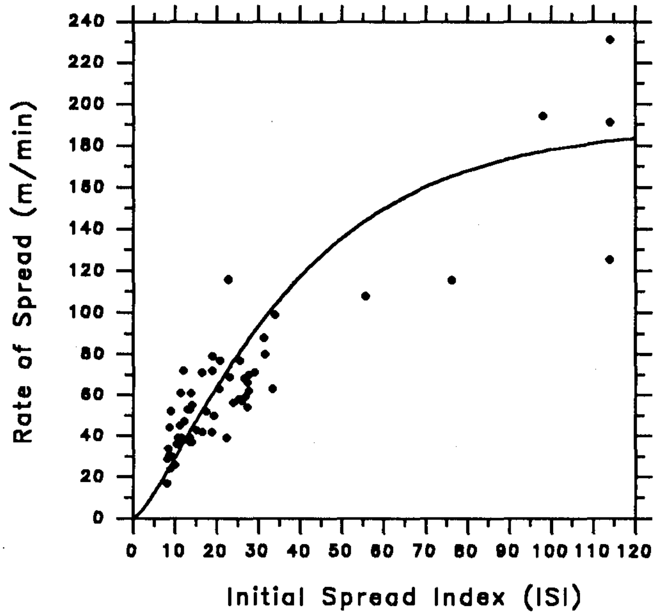


Figure 9. Relationship between basic rate of spread and the Initial Spread Index for cut (or matted down) fully cured grass (0-1a).

on grassland fire behavior. In the absence of any definitive research on this subject, a simple linear relationship was adopted on the basis that fire spread in grassland is judged to be unlikely when the degree of curing is less than 50% (Wright and Beall 1938) and the rate of fire spread in grasslands varies in rough proportion to the percentage of cured or dead material (Van Wagner 1975). The following equation is used to adjust rate of spread for grass fuels when the degree of curing is less than 100% (see also Fig. 8):

$$\mathrm{CF} = 0.02 \times C - 1.0 \qquad C > 50 \tag{35}$$

where CF is the grass curing coefficient and C is the degree of curing (%); however when $C \leq 50$, CF $= 0$.

The first step in arriving at a rate of spread equation was to take the rates of spread from the Australian data and to run separate regressions of rate of spread versus the ISI for tall and short grass. This yielded the curves in Figures 9 and 10, which are described by the general rate of spread equation 26 and the appropriate regression coefficients (a, b, and c) from Table 6.

The rate of spread is then adjusted for the grass curing effect by multiplying it by the curing coefficient (equation 35), yielding the following complete rate of spread equation:

$$\mathrm{ROS} = a \times \left[1 - e^{(-b \times \mathrm{ISI})}\right]^{c} \times \mathrm{CF} \tag{36}$$

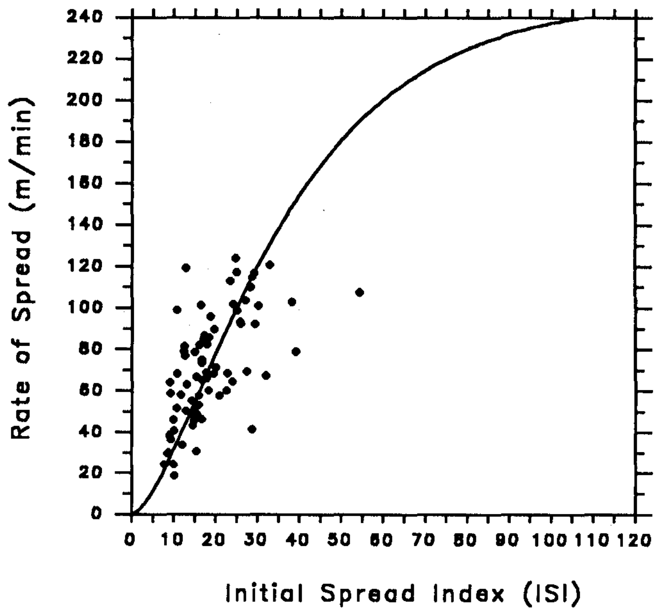
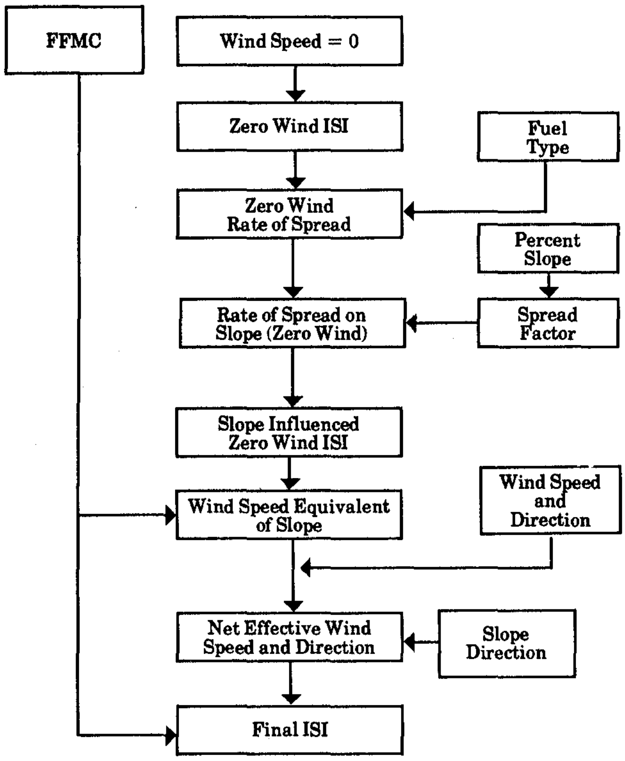


Figure 10. Relationship between basic rate of spread and the Initial Spread Index for natural (standing) fully cured grass (0-1b).

where ROS is the surface fire rate of spread; a, b, c are fuel-type-specific constants from Table 6; and CF is the grass curing coefficient from equation 35. No further adjustment (i.e., fuel weight, crown involvement) to the spread rate of grass fuel is necessary; thus this spread rate can be considered as the final predicted head fire rate of spread.

7.2.2 Slope Effect on Fire Spread



Initial Spread Index

A new approach has been adopted to allow for the additive effects of wind speed and slope on fire spread, in a variety of situations. The old method had a series of four potential wind-slope interactions from which the user was asked to select one and apply the pertinent rules. This method required the user to know the direction of fire spread in relation to wind and slope direction before the rate of spread prediction was made. To utilize a more general model, which would not have cutoffs at any particular combination of slope and wind (as was the case in the 1984 interim edition), an approach using vectors to determine fire rate of spread and spread direction was chosen for the final version of the FBP System. Essentially, the influences of wind and slope on rate of spread are added together. To add the influences equitably, the slope is converted to an "equivalent wind speed." This equivalent wind speed is added (using vector addition to account for differences in directions) to the "observed" wind speed to derive a "net effective wind" (both speed and direction). The net effective wind speed is then used for all subsequent calculations including the ISI and the length-to-breadth (LB) ratio. A more detailed discussion of the concepts presented here can be found in McAlpine et al. (1991).

The first step in this new process is the same as in the old method; namely, determine the percent ground slope:

$$\%\,\text{Ground slope} = \frac{\text{Elevation rise}}{\text{Horizontal ground dist.}} \times 100 \qquad (37)$$

Several methods are available to determine percent slope. Measurement of contour interval (change in elevation) over a set distance is easiest if a map is available. Slope measurement should always be done straight up the slope, that is, the direction of maximum slope from the projection point. Slope angle (measured on site) can be converted to a percent slope with the equation:

$$\%\,\text{Ground slope} = 100 \times \tan(\alpha) \qquad (38)$$

where α is the number of degrees the line of slope is above the horizonal. The percent ground slope is then used to compute the spread factor (SF) (Van Wagner 1977c):

$$\text{SF} = e^{3.533 \times \left(\frac{\text{GS}}{100}\right)^{1.2}} \qquad (39)$$

where GS is the percent ground slope. Equation 39 is not recommended for slopes in excess of 60%. Beyond this 60% limit, the spread factor increases extremely rapidly, with minor increases in ground slope, and no data are available to ascertain if the function is valid above this cutoff. Figure 11 shows the relationship presented in equation 39.

To determine the influence of the slope on the rate of spread if no wind was present, a zero wind ISI (ISZ) is computed by using the standard ISI equations (Van Wagner 1987) (see equations 45, 46, 52, 53), the FFMC, and a wind speed of 0 km/h. The zero wind ISI is then used with the appropriate rate of spread equation for the selected fuel type to yield the zero wind rate of spread. The zero wind rate of spread is then multiplied by the spread factor to produce the slope-adjusted zero wind rate of spread (RSF):

$$\text{RSF} = \text{RSZ} \times \text{SF} \qquad (40)$$

where RSZ is the zero wind rate of spread and SF is the slope factor.

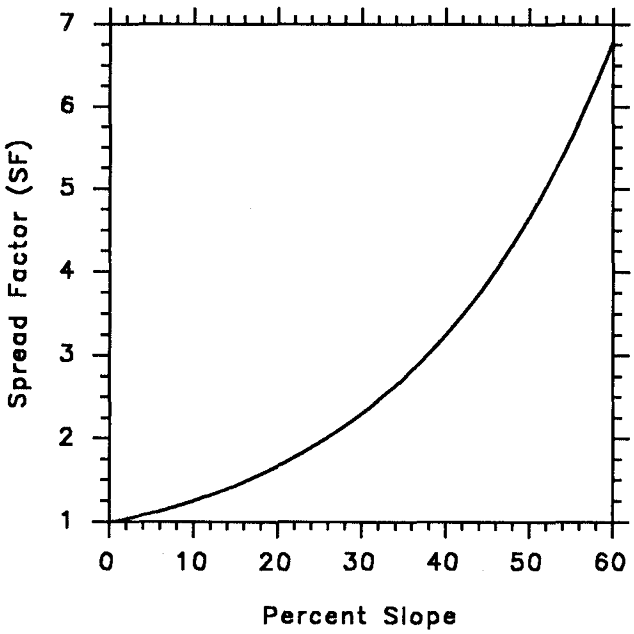


Figure 11. Relationship between percent ground slope and the spread factor used in adjusting rate of spread for sloped topography (Van Wagner 1977).

At this point we have computed a rate of spread in the observed fuel moisture conditions with a slope influence, but with the wind effect removed. The slope-adjusted zero wind rate of spread is now converted into a wind speed, or what can be considered as the wind speed equivalent of the observed slope. The conversion of the slope into a wind speed equivalent allows the addition of the observed wind and the computed wind speed equivalent of the slope. This is done by inverting the rate of spread–ISI equations, so that when we enter a rate of spread value (in this case the slope-adjusted zero wind rate of spread), an ISI value is given. Since most of the rate of spread–ISI equations follow the same form, the general equation for ISI from rate of spread is:

$$\mathrm{ISF} = \frac{\ln\left[1 - \left(\frac{\mathrm{RSF}}{a}\right)^{\frac{1}{c}}\right]}{-b} \tag{41}$$

where ISF is the ISI with slope influence and zero wind; RSF is the zero wind rate of spread multiplied by the slope factor; and a, b, c are fuel-type-specific rate of spread equation constants.

Equation 41 will not work for two fuel type groups: mixedwood (M-1 and M-2) and grass (O-1). For fuel types M-1 and M-2, the following single equation form is used:

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

where ISF is the ISI with slope influence and zero wind; RSF is the zero wind rate of spread multiplied by the slope factor; a, b, c are fuel-type-specific rate of spread equation constants for the softwood component (C-2) of the mixedwood fuel type; and PC is the percent conifer composition.

For the O-1 (grass) fuel type, the equation is of the form:

$$\mathrm{ISF} = \frac{\ln\left[1 - \left(\frac{\mathrm{RSF}}{\mathrm{CF} \times a}\right)^{\frac{1}{c}}\right]}{-b} \tag{43}$$

where ISF is the ISI with slope influence and zero wind; RSF is the zero wind rate of spread multiplied by the slope factor; and CF is the percent cured/dead material factor from equation 35.

The next step in the procedure is to compute the slope equivalent wind speed (WSE). This is done by reversing the ISI equations and allowing the ISI and FFMC to be combined to derive the wind speed:

$$\mathrm{WSE} = \frac{\ln\left[\frac{\mathrm{ISF}}{0.208 \times f(F)}\right]}{0.05039} \tag{44}$$

where ISF is the ISI with slope influence and zero wind; and $f(F)$ is the FFMC function from the ISI equation as follows:

$$f(F) = 91.9 \times e^{(-0.1386 \times m)} \times \left[1 + \frac{m^{5.31}}{4.93 \times 10^{7}}\right] \tag{45}$$

where

$$m = \frac{147.2 \times (101 - \mathrm{FFMC})}{59.5 + \mathrm{FFMC}} \tag{46}$$

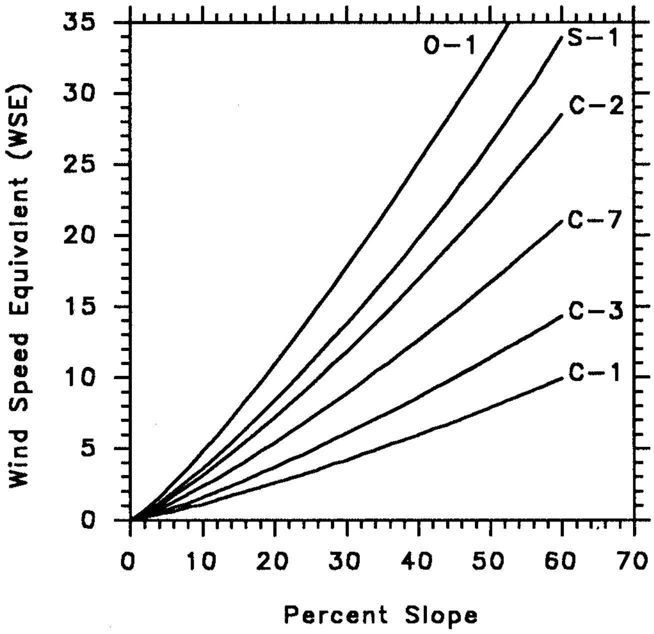


Figure 12. Equivalent wind speeds of measured percent slope for several fuel types; FFMC has been set to 89.

This wind speed equivalent value is the effect the percent slope would have on the rate of spread if it were a wind speed. Figure 12 shows the wind speed equivalent value for several fuel types over a range of percent slope conditions. The computed WSE value can now be added to the observed wind speed to determine the net effective wind influencing the fire. At this point the difference in wind direction and slope direction is used to add the two wind vectors (observed wind and wind speed equivalent) together.[1] The vector addition is done through the set of equations as follows:

$$\mathrm{WSX} = \Big[\mathrm{WS} \times \sin(\mathrm{WAZ})\Big] + \Big[\mathrm{WSE} \times \sin(\mathrm{SAZ})\Big] \tag{47}$$

$$\mathrm{WSY} = \Big[\mathrm{WS} \times \cos(\mathrm{WAZ})\Big] + \Big[\mathrm{WSE} \times \cos(\mathrm{SAZ})\Big] \tag{48}$$

$$\mathrm{WSV} = \sqrt{(\mathrm{WSX}^2 + \mathrm{WSY}^2)} \tag{49}$$

$$\mathrm{RAZ} = \arccos\left(\frac{\mathrm{WSY}}{\mathrm{WSV}}\right) \tag{50}$$

where WSX is the resultant vector magnitude in the x-direction; WSY is the resultant vector magnitude in the y-direction; WAZ is the wind azimuth (direction); SAZ is the uphill slope azimuth (direction); WSV is the net effective wind speed; and RAZ is the net effective wind direction.

Equations 47 to 50 may appear to have the sine and cosine functions reversed from what would be found in a standard algebra textbook. This apparent anomaly is caused by the way a compass reads direction; compass bearing values increase in a clockwise manner, while in algebra the angle values increase counterclockwise. The reverse in the use of the sine and cosine functions solves this problem. Algebra is also not limited to positive directions; negative values are quite possible. To convert possible negative-calculated RAZ values into more understandable compass directions, equation 51 is applied:

If WSX < 0, then

$$\mathrm{RAZ} = 360 - \mathrm{RAZ} \tag{51}$$

This net effective wind speed is then used for all subsequent computations involving a wind speed, including the ISI and the length-to-breadth (LB) ratio. The net effective wind direction (RAZ) is used as the fire spread direction. The ISI equation[2] (Van Wagner 1987) is given below for reference:

$$\mathrm{ISI} = 0.208 \times f(W) \times f(F) \tag{52}$$

where

$$f(W) = e^{0.05039 \times \mathrm{WSV}} \tag{53}$$

and where $f(F)$ is given above (equations 45 and 46) and WSV is the net effective wind speed.

The value for wind direction in this application should be considered carefully. Normally the wind direction given by weather stations is the direction from which the wind blows, not the direction it is blowing to. For this application we require the direction the wind is blowing to; therefore, the weather-station-recorded wind direction must be corrected by 180°.

---

1 A wind vector is simply a wind speed with a direction associated with it.

2 The ISI used in the FBP System has been slightly modified at the extreme end. In cases of very low FFMC values and high wind speed, measurable ISI values were being calculated that would result in predicted fire spread. To correct the problem, the $f(W)$ parameter of the ISI equation has the added condition:

If WS>40

$$f(W) = 12 \times \left[1 - e^{-0.0818 \times (\mathrm{WSV} - 28)}\right] \tag{53a}$$

This equation would replace equation 53 if the wind speed vector was greater than 40 km/h.

The fire shape or length-to-breadth equations follow in the elliptical functions section. The ISI calculated above is a function not only of wind speed and FFMC but also of the slope. As such it is not equal to the standard ISI calculated for the FWI System and should be differentiated. This ISI is a local site-specific ISI influenced by the topography.

This method automatically accounts for many of the sticky problems encountered if the wind and slope rate of spread vectors are added. For instance, if the wind is blowing directly down slope and is precisely balanced by the uphill influence of the slope, by adding rate of spread vectors a zero spread rate would result. By adding wind speeds we can get a zero net wind speed, but this would still result in a measurable spread rate.

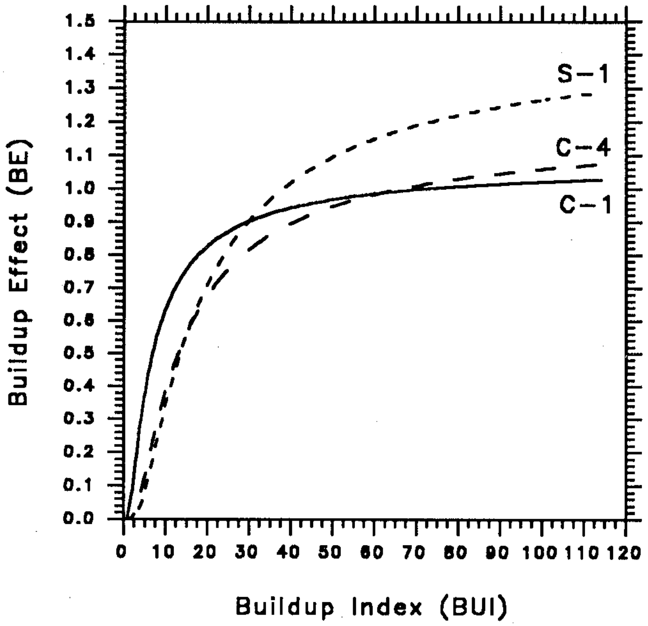
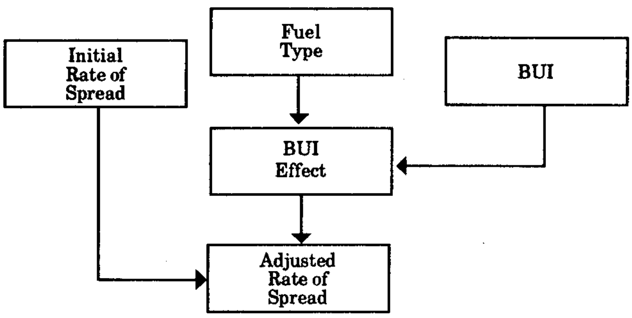


Figure 13. Buildup effect function at combinations of q and BUI_0 for C-1, C-4, and S-1 fuel types.

7.2.3 Buildup Effect on Spread Rate



Rate of Spread Adjustment

The basic rate of spread equations provided in section 7.2.1 are based on the ISI only. But the ISI is dependent on one fuel moisture code, namely the FFMC, whose timelag is only about one day of normal weather. This means that the ISI will stabilize within two or three days following complete fuel saturation, implying that there should be no increase in the rate of spread even if dry weather persists for several days. Logically, as the whole fuel complex dries, more and more fuel is available for combustion, and the increasing fuel consumption should influence the rate of spread to some extent. In the FWI System, the primary relative measure of the increasing weight of fuel available for combustion as a dry spell progresses is the Buildup Index (BUI), which has a practical timelag of about 10 days of normal weather. It will register a distinct effect for up to about a month after fuel saturation. Unfortunately, no amount of statistical analysis of the available fire data could demonstrate any secondary effect of the BUI on spread rate. This lack was judged to be due to shortcomings in the empirical data. In fact, the data were collected without concern for covering a full range of BUI values. Buildup effect (BE), a function of BUI, was therefore designed in the form of a multiplier to the basic ISI spread equation. It assumes that the rate of spread must be zero when BUI is at zero, rise quickly with increasing BUI, and finally level off at an infinite BUI value. The concept q was then introduced, defined as the proportion of maximum possible spread rate (for any given ISI) that is reached at a standard BUI called BUI_s (set at 50, having been calculated as the average BUI for all fires in the FBP database). Somewhat subjectively, each fuel type was assigned a q-value, ranging from 0.70 to 1.00, depending on the rate at which increasing dryness in depth might influence the spread rate. But each empirical fuel-type data set has its own specific average BUI (BUI_0), at which the derived ISI-based spread rate equation should presumably best apply. Therefore, the buildup effect must be expressed in terms of BUI_0 as well as q to be in a general form for all fuel types. With BUI_s at 50, the buildup effect (BE) has the form:

$$BE = e^{\left[50 \times \ln(q) \times \left(\frac{1}{BUI} - \frac{1}{BUI_0}\right)\right]} \tag{54}$$

where BUI_0 is the average BUI for the fuel type. This function equals 1 when $BUI = BUI_0$ or $q = 1$, as it should (Fig. 13). The values of BUI_0 and q are listed

Table 7. Values of BUI_0, q, and maximum BE for each fuel type.

Fuel type	BUI_0	q	Max. BE
C-1	72	0.90	1.076
C-2	64	0.70	1.321
C-3	62	0.75	1.261
C-4	66	0.80	1.184
C-5	56	0.80	1.220
C-6	62	0.80	1.197
C-7	106	0.85	1.134
D-1	32	0.90	1.179
M-1	(50)[a]	(0.80)	1.250
M-2	(50)	(0.80)	1.250
M-3	(50)	(0.80)	1.250
M-4	(50)	(0.80)	1.250
S-1	38	0.75	1.460
S-2	63	0.75	1.256
S-3	31	0.75	1.590
O-1	–	1.00	1.000

[a] Values in parentheses have been set arbitrarily.

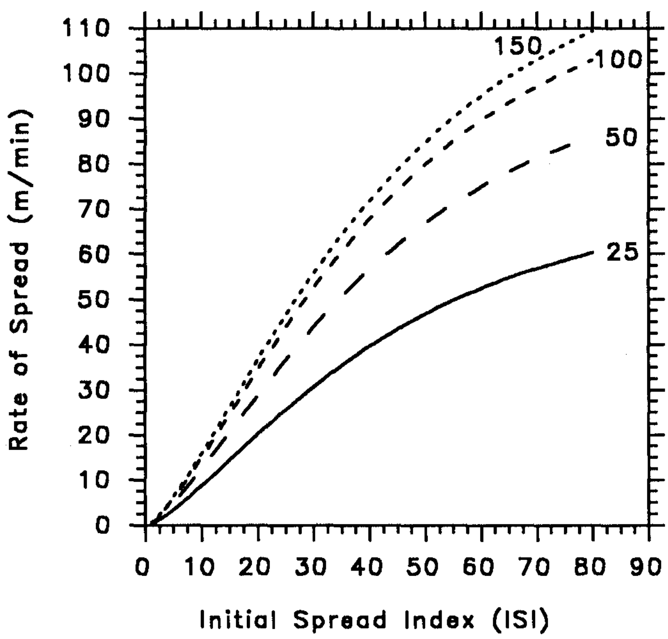


Figure 14. Effect of varying BUI on rate of spread for fuel type C-2.

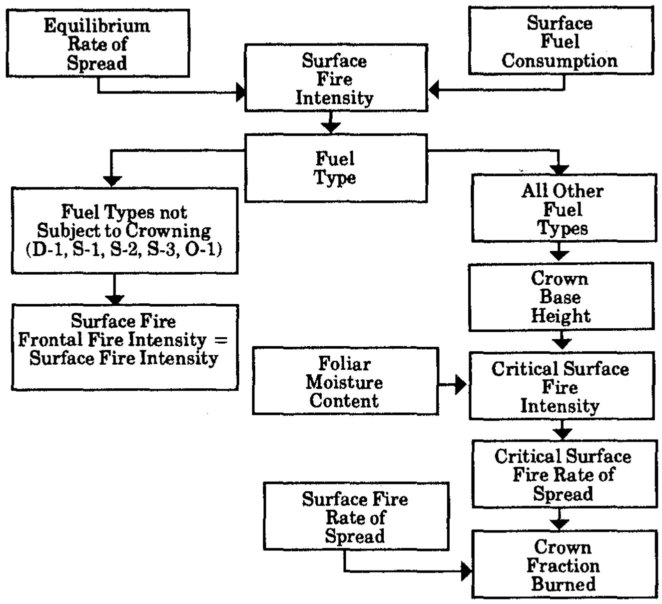
for each fuel type in Table 7, along with the maximum possible values of the buildup effect. The function BE could then be readily calculated for any fuel type and BUI, and applied as a secondary factor to the primary ISI-based spread rate equation:

$$ROS = RSI \times BE \tag{55}$$

where ROS is the rate of spread (m/min); RSI is the intermediate surface rate of spread adjusted for slope; and BE is the function described above.

The buildup effect can greatly influence the rate of spread prediction, depending on the ISI, the BUI value, and the fuel type. Figure 14 illustrates the effect of various values of BUI on the eventual predicted rate of spread for the boreal spruce (C-2) fuel type.

7.2.4 Crowning Effect on Spread Rate



Crown Fire Routine

7.2.4.1 Transition from surface fire to crown fire

As the spread rate increases, a point is eventually reached at which the crowns become involved in the fire. Van Wagner (1977b) defines this point as the critical surface fire intensity (CSI) for crowning in terms of the crown base height (CBH) (the height above ground that the live crown base begins) and the foliar moisture content (FMC):

$$CSI = 0.001 \times CBH^{1.5} \times (460 + 25.9 \times FMC)^{1.5} \tag{56}$$

Once the critical surface fire intensity has been calculated, it can be compared with a predicted surface fire intensity. If the predicted surface fire intensity is the lesser, the fire is classed as a surface fire; if

Table 8. Crown base height (CBH) and crown fuel load (CFL) for fuel types subject to crowning.

Fuel type	CBH (m)	CFL (kg/m^2)
C-1	2	0.75
C-2	3	0.80
C-3	8	1.15
C-4	4	1.20
C-5	18	1.20
C-6	7	1.80
C-7	10	0.50
M-1	6	0.80
M-2	6	0.80
M-3	6	0.80
M-4	6	0.80

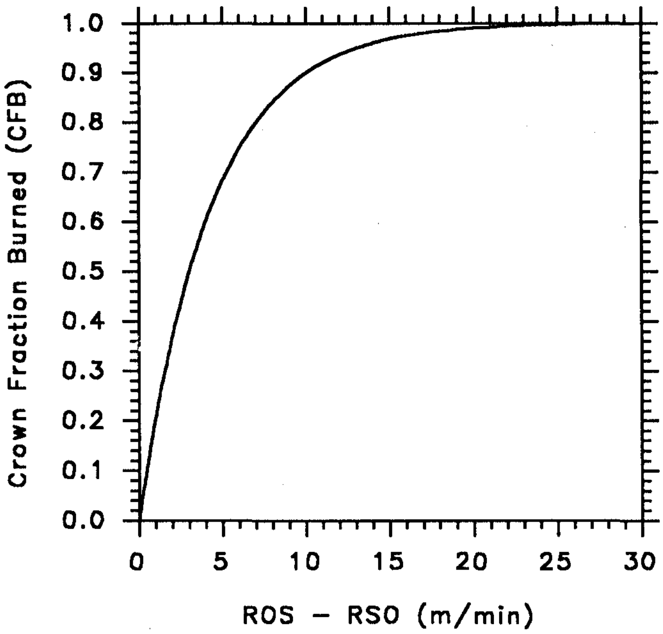


Figure 15. Transition function (crown fraction burned) for determining degree of crown involvement (ROS, surface fire spread rate; RSO, critical surface fire spread rate).

the predicted surface fire intensity is the greater, then crowning is assumed and the computation proceeds to the next step in order to determine the degree of crown involvement. Predicted surface fire intensity is calculated as documented in section 7.4; namely, equation 69 is used, substituting the surface fire rate of spread (after BUI adjustment) for the final rate of spread (ROS); and the surface fuel consumption as calculated in section 7.1 replaces the total fuel consumption (TFC).

Crown base height is a critical factor in the crowning criterion; however, the theory on which the crown fire criterion is based was itself dependent on empirical data for its final quantitative form. The crown base height assigned to each fuel type is therefore the result of some trial. While the independent fuel type description incorporates some indication of the crown base height, the assigned value for each fuel type had to match the general pattern of crown involvement. The final assigned crown base height values represent the real forest structure as well as possible (Table 8).

The FBP System incorporates a gradual transition from surface to crown fire. There are two reasons for this transition process. First, wind speed in the FWI System represents an average value with no indication of the variability. In reality, wind speed varies greatly about its average value. This suggests that within a certain range of mean wind speeds, the fire should alternate between the surface phase during the lulls in wind speed and the crown phase during the wind gusts. In this situation, the fire would spread at a rate between that of a surface fire and crown fire. Second, considering the variability within fuel types, it is more appropriate to predict the degree of crowning rather than to identify each fire as surface or crown.

The degree of crown involvement was assumed to depend upon the amount by which the predicted surface fire intensity exceeded the critical surface fire intensity. This is more easily handled in terms of spread rate rather than intensity. The degree of crown involvement therefore depends on the amount by which the predicted surface spread rate exceeded the spread rate associated with the critical surface fire intensity. The transition function was scaled so that crown involvement was 90% complete when the surface fire spread rate exceeded the critical surface fire spread rate by 10 m/min (Fig. 15).

The critical surface fire spread rate (RSO) is found by replacing the critical surface fire intensity for the surface fire intensity in the intensity equation and working backwards:

$$RSO = \frac{CSI}{300 \times SFC} \tag{57}$$

where CSI is the critical surface fire intensity and SFC is the surface fuel consumption. The transition function, termed the crown fraction burned (CFB), becomes, then:

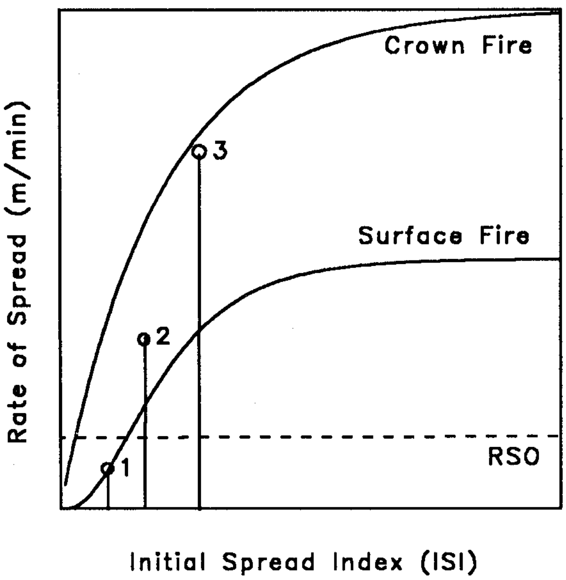


Figure 16. Dual-equation rate of spread model for fuel type C-6 (types of fire: 1, surface; 2, intermittent crown; 3, continuous crown).

$$CFB = 1 - e^{-0.23 \times (ROS - RSO)} \quad (58)$$

where ROS is the predicted fire rate of spread (m/min) and RSO is the critical surface fire spread rate. The crown fraction burned is applied in determining both the resultant crown fire spread rate in conifer plantations (section 7.2.5.2 — equation 65) and the degree of crown fuel consumption (section 7.3), leading eventually to the frontal fire intensity.

7.2.5 Conifer Plantation — Fuel Type C-6

Conifer plantations are more structured and have less variability than naturally regenerated areas, and are more easily modeled in a complex separation of surface and crown fire. Fuel complex parameters tend to have less variability within the stands, with a predictable influence on the fire behavior characteristics. This well-defined structure and low variability in parameters allowed the development of a rigorous dual-equation model to predict fire spread in conifer plantation fuel types. Ideally, it is supposed that the spread rate of any fire in a conifer stand can be visualized mathematically as some point in space between two bounding rate of spread curves. The lower curve would represent a pure surface fire with no crown involvement; the upper curve, a fire with complete crown involvement. The location of the point between these two curves would be governed by how the predicted surface fire intensity compared with the critical surface fire intensity necessary for crowning. The process of determining the final spread rate is best described with the help of a diagram.

In Figure 16, the lower curve represents all possible surface fires, the upper curve the complete crown fire. Obviously, the right end of the surface fire curve and the left end of the crown fire one are never used, but a central range of horizontal overlap does exist, depending on the secondary effects of BUI (section 7.2.3) and foliar moisture content.

7.2.5.1 Foliar moisture effect on crown fire spread

Foliar moisture content has already appeared as a factor in the transition from surface fire to crown fire. Logically it must also have some effect on the rate of fire spread through the crown layer. Because foliar moisture content in Canadian conifer forest exhibits a strong seasonal trend (see section 6.0), with distinctly lower values during spring, the implication is that crown fires should start more easily and spread faster during that season. Again, as with the BUI effect, analysis of the fire data in the FBP System database failed to yield any statistical evidence to substantiate this effect. The physical argument was then applied, as adapted for crown fire by Van Wagner (1974b) from original arguments by Thomas et al. (1964), that spread rate should be proportional to the horizontal radiant heat flux through the crown layer, inversely proportional to the foliar ignition energy, and inversely proportional to the foliar bulk density.

The effect of seasonal variation in foliar bulk density was omitted as a simplification, leaving the first and second effects to be accounted for. Expressions for crown flame temperature, T, and heat of ignition, h, in terms of foliar moisture content, were first required. A reasonable expression for the first is:

$$T = 1500 - 2.75 \times FMC \quad (59)$$

where T is crown flame temperature (degrees Kelvin) and FMC is the foliar moisture content, based on an assumed air supply twice that needed for perfect combustion (C.E. Van Wagner, unpublished report), and for the second,

$$h = 460 + 25.9 \times FMC \quad (60)$$

where h is the heat of ignition (kJ/kg), taken from Van Wagner (1977b).[3] Applying Boltzmann's fourth-power law of thermal radiation and adjusting decimal points for convenience, the foliar moisture effect (FME) is given by:

$$\mathrm{FME} = \frac{(1.5 - 0.00275 \times \mathrm{FMC})^{4.0}}{460 + (25.9 \times \mathrm{FMC})} \times 1000 \tag{61}$$

The foliar moisture effect is always applied in ratio with a normalized value of the foliar moisture effect based on the supposed average foliar moisture content (namely, 97%) found in the composite crown fire data set. Therefore, a proportionality constant is not required. The value of the normalized foliar moisture effect is 0.778. In practice, the foliar moisture effect varies from 0.966 to 0.525 within the standard foliar moisture content range of 85% to 120%.

7.2.5.2 Conifer plantation spread rate

The equations were designed from the 12 fires in the C-6 data set, which cover a wide range of behavior from gentle surface to full crown fire. Some subjective adjustment was required to match the output as well as possible to the data. The equations for surface fire spread rate in two steps and crown fire spread rate in one are:

$$\mathrm{RSI} = 30 \times \left(1 - e^{-0.08 \times \mathrm{ISI}}\right)^{3.0} \tag{62}$$

$$\mathrm{RSS} = \mathrm{RSI} \times \mathrm{BE} \tag{63}$$

$$\mathrm{RSC} = 60 \times \left(1 - e^{-0.0497 \times \mathrm{ISI}}\right)^{1.00} \times \frac{\mathrm{FME}}{\mathrm{FME_{avg}}} \tag{64}$$

where RSI is the intermediate surface fire spread rate; ISI is the initial spread index; RSS is the surface fire spread rate (m/min); BE is the buildup effect (section 7.2.3); RSC is the crown fire spread rate (m/min); FME is the foliar moisture effect (section 7.2.5.1); and $\mathrm{FME_{avg}}$ is 0.778.

The horizontal dashed line in Figure 16 represents the critical spread rate at which crowning begins (RSO). The value of the crown fraction burned (CFB) variable is first computed (section 7.2.4.1) from the difference between the predicted surface fire spread rate and the critical spread rate at which crowning begins. The resultant final spread rate (ROS) is then found from:

$$\mathrm{ROS} = \mathrm{RSS} + \mathrm{CFB} \times (\mathrm{RSC} - \mathrm{RSS}) \tag{65}$$

The amount by which the final predicted spread rate rises above surface fire spread rate therefore depends on the amount by which the surface fire spread rate exceeds the critical fire spread rate for crowning; the intermediate function is the crown fraction burned. This latter factor is also applied to the crown fuel load to obtain the predicted crown fuel consumption. The head fire intensity can then be determined from the final spread rate and the total fuel consumption (sum of surface and crown fuel consumption).

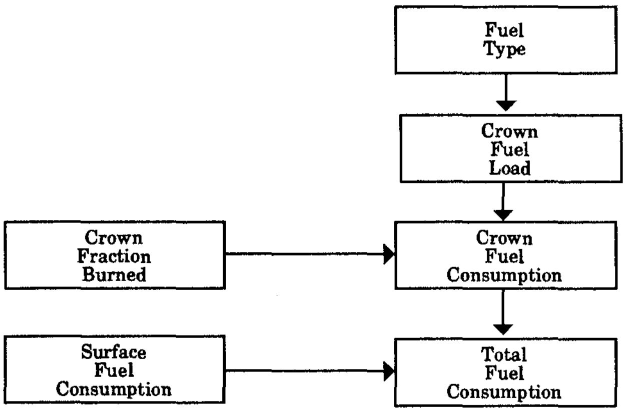
Crown fires will occupy a band of space rising to the right from the region where the surface fire spread rate first exceeds the critical spread rate for crowning to meet the curve for crown fire spread rate at ISI's high enough to produce full crowning. Three examples appear in Figure 16. The ISI at point 1 produces a surface spread rate below the critical rate for crowning; the fire therefore remains on the surface. The ISI at point 2 produces a surface fire spread rate exceeding the critical spread rate for crowning, so the fire crowns; the crown fraction burned is appreciable, but crowning is incomplete or perhaps intermittent. The ISI at point 3 produces a surface fire spread rate high enough that crown fraction burned approaches 1 and the fire spreads nearly at the crown fire spread rate (RSC) value.

The flexibility of this dual-equation model allows for variation in the crown base height. If specific information is available on crown base height, it can be used. Further, essentially the dual-equation model melds two distinct fuel types and spread models together. Conifer plantation (C-6) is the only fuel type that allows this because of the distinct separation between the surface and crown fuel layers.

7.3 Final Fuel Consumption

In section 7.1 the surface fuel consumption was calculated for all fuel types. If it is determined that there is crown fuel involvement, the fuel consumed in the tree crowns must be added to the surface fuel consumption to arrive at a total fuel consumption. If, however, the fire is classed as surface, then the surface fuel consumption becomes the total fuel

[3] The value 25.9 in equation 60 was originally reported as 26 (Van Wagner 1977b).



Final Fuel Consumption

consumption and no further fuel consumption calculation is necessary.

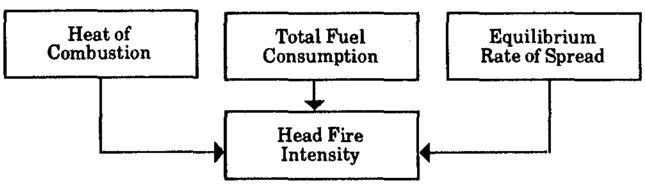
If the fire is classed as crown, the crown fraction burned will be greater than zero. To determine the crown fuel consumption, the crown fraction burned value (section 7.2.4.1) is multiplied by the crown fuel load. Crown fuel loads for fuel types prone to crowning are given in Table 8. Thus to compute total fuel consumption the following equations are used:

$$\text{CFC} = \text{CFL} \times \text{CFB} \tag{66}$$

$$\text{TFC} = \text{SFC} + \text{CFC} \tag{67}$$

where CFC is the crown fuel consumption (kg/m^2); CFL is the crown fuel load (kg/m^2); CFB is the crown fraction burned; TFC is the total fuel consumption (kg/m^2); and SFC is the surface fuel consumption (kg/m^2). For the mixedwood fuel types M-1 and M-2, the crown fuel consumption is multiplied by a factor (PC/100, where PC is the percent coniferous composition) to scale it to the amount of coniferous trees in the stand.

7.4 Head Fire Intensity



Head Fire Intensity Computation

Fire intensity (also termed frontal fire intensity and line fire intensity) has become one of the standard gauges by which fire managers estimate the difficulty of controlling a fire and select appropriate suppression action. Byram (1959) originally defined fire intensity as:

$$I = HwR \tag{68}$$

where I is the intensity of the fire (kW/m); H is the fuel low heat of combustion (kJ/kg); w is the weight of fuel consumed per unit area in the active fire front (kg/m^2); and R is the rate of forward spread (m/sec). Byram's intensity equation 68 uses the heat evolved from the weight of fuel consumed and the rate of spread to provide a measure of energy release per unit of time. Van Wagner (1977d) notes that "fire intensity thus conceived contains about as much information about a fire's behavior as can be crammed into one number." In Canada, fire intensity is considered to be "the rate of heat energy release per unit time per unit length of fire front" (Merrill and Alexander 1987).

To predict fire intensity, the FBP System employs Byram's (1959) original equation using the predicted head fire rate of spread for R, the predicted total fuel consumption (TFC) for w, and a standard value of 18 000 kJ/kg for the heat of combustion, H. Head fire rate of spread is either the final surface fire rate of spread or the final crown fire rate of spread depending on the type of fire. When a crown fire is indicated, the fuel consumption value used in the head fire intensity equation will reflect the added fuel involvement of the crown. Effectively, equation 68 is transformed for the FBP System into:

$$\text{FI} = 300 \times \text{FC} \times \text{ROS} \tag{69}$$

where FI is the predicted fire intensity (kW/m); FC is the predicted fuel consumption (either surface or total) (kg/m^2); and ROS is the predicted rate of fire spread (m/min). Note that the factor 18 000 kJ/kg has been divided by 60 to change the predicted ROS from metres per minute to metres per second.

Fire intensity in the FBP System is computed on the basis of the total fuel consumption. No attempt is made in the computational process to exclude fuel that may have been consumed by smoldering combustion after the passage of the fire front.

7.5 Fire Description

The interim edition of the FBP System classified types of fire as either surface or crown. However, fire behavior is best visualized as varying over time and space due to normal variation in wind and fuel conditions as discussed in section 7.2.4.1. A prediction of the degree of crowning was felt to be more realistic than trying to identify each fire as simply surface or crown. Type of fire has been replaced in the FBP System with fire description, based on the crown fraction burned (CFB). The crown fraction burned value indicates the proportion of tree crowns involved in the fire. If we increase fire intensity slowly (and hence degree of crown involvement) over a range extending from a surface fire to a full crown fire, we can imagine any number of intermediate steps. There is, therefore, a wide range of possible types of crown fire, ranging from a single tree torching to a full wall of flame engulfing the forest.

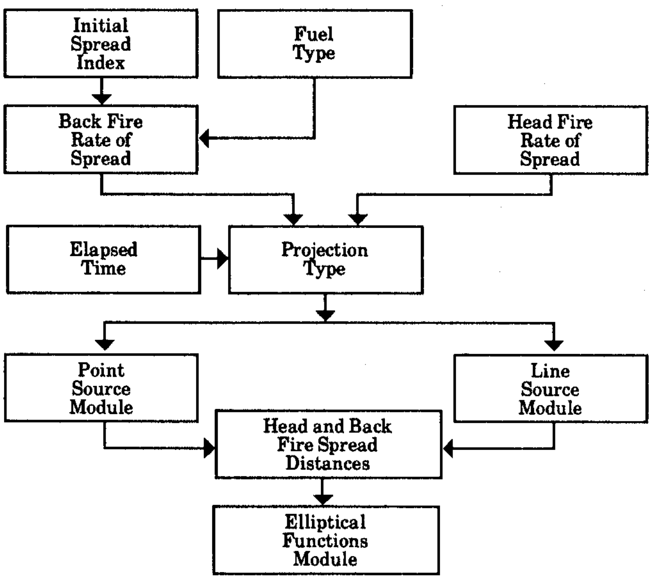
Values for crown fraction burned range from 0.0 (surface fire with no crown involvement) to 1.0 (100% crown involvement). This range can be broken down into the following fire description categories:

Crown fraction burned	Type of fire
< 0.1	surface fire
0.1 – 0.89	intermittent crown fire
> 0.9	continuous crown fire

Crown-fraction-burned limits and fire description categories assume that when less than 10% of the trees are torching, the fire can be considered a surface fire.

Values for the crown fraction burned can also be interpreted without the aid of descriptive classifications and can be quoted directly to describe the degree of crown involvement. This requires some experience with the crown fraction burned value and the resulting fire behavior; however, in time, the crown fraction burned may become a valuable term for describing fires.

8.0 Secondary Components

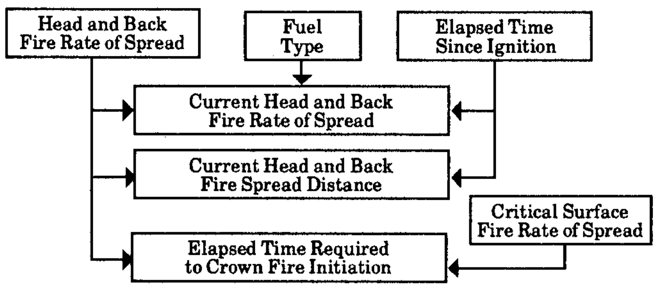


Secondary FBP System

The secondary components of the FBP System include fire growth and projection models. The elliptical growth model (Van Wagner 1969; Alexander 1985) used in the interim version of the FBP System is extended to provide more information. There are two major and several minor revisions to the elliptical growth model. The major revisions are the addition of an acceleration function for point source ignition fires and a new manner of calculating the length-to-breadth ratio. As a result the system is more accurate and has additional output components.

Two types of fire growth projection can be performed with the FBP System: a point source projection applying an elliptical fire growth model and an acceleration model to define the head, flank, and back fire spread distances, area burned, perimeter, and perimeter growth rate for a fire; and a simple line projection using the predicted head fire rate of spread and a given elapsed time to calculate the location of a fire front for some time in the future. The first step in the point source fire projection is to allow for the period of acceleration from the fires inception to the time at which equilibrium ROS has been attained.

8.1 Point Source Fire Growth Projection — Acceleration



Point Source Fire Growth

With the advent of more effective fire detection systems, a fire is often found almost immediately after ignition. Obviously, a fire that has only just started will not have attained the equilibrium head fire rate of spread value predicted by the FBP System. The problem of determining how long before the fire reaches the predicted equilibrium rate of spread is complicated by many variables. Ideally, in a homogenous fuel with no breaks, topographical influences, changes in weather or fuel moisture, the fire would accelerate smoothly over a predictable length of time. However, in forest stands, the fire generated from a point source ignition can be of insufficient intensity to induce the type of fire at equilibrium that a line source ignition fire would. The lower intensity of the point source fire is primarily the result of the lower wind speeds within the stand compared with those above the stand. As an example, immature jack pine stands of fire origin are extremely dense, causing the wind speed near the ground level to be much less than that above the canopy. Point source fires within immature jack pine stands are therefore influenced by the lower wind speed, resulting in lower spread rates and fire intensities. The lower fire intensities may be insufficient to engage the crowns (thus not accessing the ambient wind above the canopy), whereas a line source fire, with the advantage of full wind exposure, can generate higher spread rates and intensities in exactly the same fuel and weather conditions.

The two equilibrium rate of spread values (one for a point source origin fire and one for a line source origin fire) give rise to the prospect of a dual-equilibrium rate of spread; two fires burning in exactly the same fuel, weather, and topographic conditions can exhibit different fire behavior. The two types of fire are identical except that the point source fire is influenced by the wind within the canopy, while the line source is influenced by the ambient wind field above the canopy. A surface fire generated from a point source ignition could rapidly turn into a crown fire if there is a discontinuity in the fuel (allowing the ambient wind to influence the surface fire). Once established, the crown fire can then maintain itself because of the higher wind speeds above the canopy.

The FBP System predicts only one equilibrium rate of spread — the worst case or line source fire equilibrium rate of spread likely for the fuel and weather conditions. In such situations, a fire organization could overreact to a report about an initiating fire. Fire fighters arriving at the site could find a small surface fire instead of the raging crown fire predicted. In these situations, the fire, while still in the surface fire stage, is unstable. Had the right fuel-distribution conditions been present, a much different fire would have awaited the suppression crew.

Predicting when a fire will change from a lower equilibrium rate of spread to a higher equilibrium rate of spread is a probability problem. The probabilities depend on the local fuel type characteristics (size, number, and distribution of openings in the canopy), local topography (small hills and ridges), and localized weather conditions (sun exposure, time of day, wind speed and direction variation). This kind of probabilistic prediction is dependent on localized fuel distributions and detailed topographic information. This is beyond the scope of the FBP System.

The problem of accounting for the period of time required for a point source fire to attain the equilibrium rate of spread remains. To solve this problem,

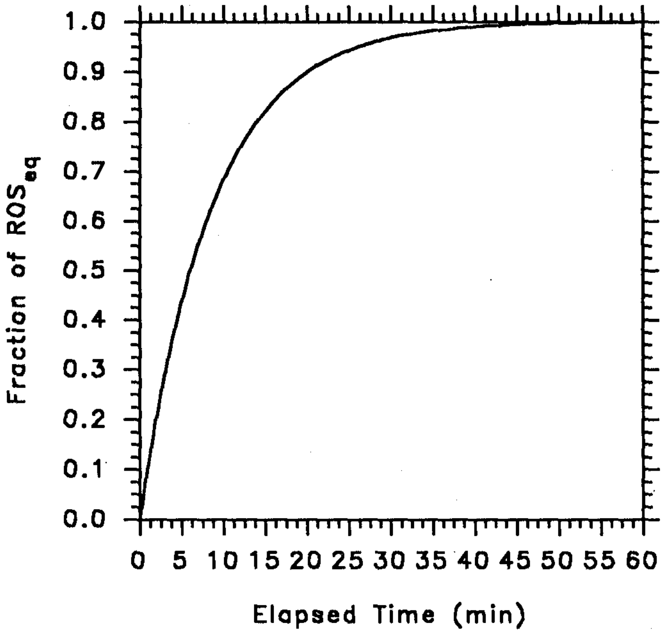


Figure 17. Open canopy fuel type acceleration model.

two assumptions are made: (1) that the fuel is continuous and homogeneous and the fire accelerates smoothly through it to some predicted final rate of spread; and (2) that the dual-equilibrium problem can be ignored for closed canopy fuel types (it does not exist for open canopy fuel types). For open fuel types, the ambient wind field extends effectively to ground level, eliminating any problem with a dual-equilibrium rate of spread. While the problem of dual equilibrium is not addressed directly in probabilistic terms for the closed canopy fuel types, it is taken into account to some degree (through changes in the elapsed time to equilibrium) by the system.

The experimental data available (both laboratory and field evidence) for open fuel types show that the time required to reach equilibrium rate of spread from a point source ignition is constant, regardless of weather conditions. The elapsed time to equilibrium rate of spread varies between 10 and 40 minutes, with a mean value of 20 minutes for the open canopy fuel types (C-1, O-1, S-1, S-2, S-3). The form of the acceleration curve relating rate of spread with elapsed time since ignition has been discussed by several authors (McArthur 1968; Cheney and Barry 1969; Luke and McArthur 1986; McAlpine 1988; Weber 1989; C.E. Van Wagner 1985, Govt. of Can. File No. PI-4-20, personal communication). There is general agreement on the appropriateness of a negative exponential curve (e.g., see Fig. 17). An equation form was chosen to allow easy mathematical integration to determine the head fire spread distance at any time since ignition. The two equations below assume a 20-minute elapsed time to 90% of equilibrium rate of spread:

$$ROS_t = ROS_{eq} \times \left(1 - e^{-\alpha t}\right) \quad (70)$$

$$D = ROS_{eq} \times \left(t + \frac{e^{-\alpha t}}{\alpha} - \frac{1}{\alpha}\right) \quad (71)$$

where ROS_t is the rate of spread at elapsed time t (m/min), ROS_{eq} is the predicted equilibrium rate of spread (m/min); t is the elapsed time (min); α is 0.115 assuming 20 minutes to 90% of ROS_{eq}; and D is the head fire spread distance (m).

This solves the problem for open canopy fuel types. Closed canopy fuel types, which are influenced by the dual-equilibrium problem, are slightly different. The field evidence for closed canopy fuel types suggests longer time periods required to reach equilibrium (at least double the open fuel types) and more variability in the time periods. The length of time required for the fire to reach equilibrium rate of spread was set to vary from 20 to 75 minutes, depending on the degree of crown involvement (measured by the crown fraction burned variable, CFB). This method allowed predicted surface fires to reach equilibrium in 20 minutes (the same as the open fuel types) because the surface fire would interact only with the wind in the stand. As the predicted rate of spread increases to eventually inducing a full crown fire, a progressively longer time period is allowed, thus compensating for differences in the ambient wind speed above the crowns and the wind speed within the stand. The acceleration time period is thus set to depend on the development rate of the fire intensity. The principles of probability can also be applied to the longer time period required for crown fire initiation: the longer the time the fire spreads on the ground, the greater the probability it will encounter a discontinuity in fuel and engage the tree crowns. The α value for use in equations 70 and 71 for closed canopy fuel types is calculated by equation 72:

$$\alpha = 0.115 - 18.8 \times CFB^{2.5} \times e^{(-8 \times CFB)} \quad (72)$$

where α is the constant replacing the α value (0.115) in equations 70 and 71, and CFB is the crown fraction burned.

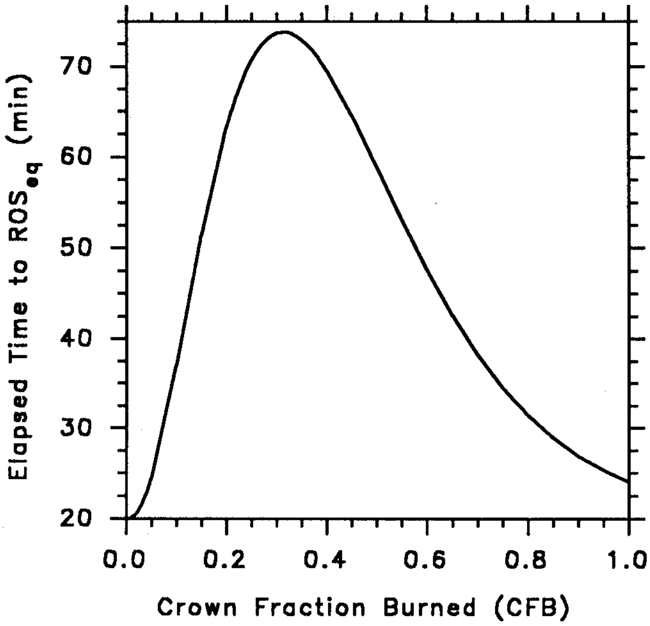


Figure 18. Elapsed time to equilibrium rate of spread (ROS_{eq}) versus crown fraction burned for closed canopy fuel types.

The maximum acceleration period generated by the combination of equations 70 and 72 does not occur at complete crown involvement, but rather at an intermediate value of the CFB variable. When the potential surface fire intensity is large enough to induce complete crown involvement, initial crown involvement is possible long before the acceleration is complete. A fire ignited under such conditions could quickly attain sufficient intensity to engage the crowns and to begin acceleration as a point source through the crowns. The crowning fire would then behave much the same way as a fire accelerating in the open with full wind exposure. Equation 72 approximates this behavior by setting the elapsed time to equilibrium to a minimum at both the low and high values of the crown fraction burned variable, while the maximum time to equilibrium spread occurs at an intermediate value (Fig. 18).

Since we assume the fire will accelerate in a predictable manner, following a curve similar to that shown in Figure 17, we can define the elapsed time to crown fire initiation, or when the fire has attained sufficient surface fire intensity to engage the crowns. This value is not definitive because of the dual-equilibrium problem discussed previously, but it is a good first estimate for operational use. The elapsed time to crown fire initiation can also be thought of as the time required for the surface fire to become unstable and, depending on local fuel continuity, to

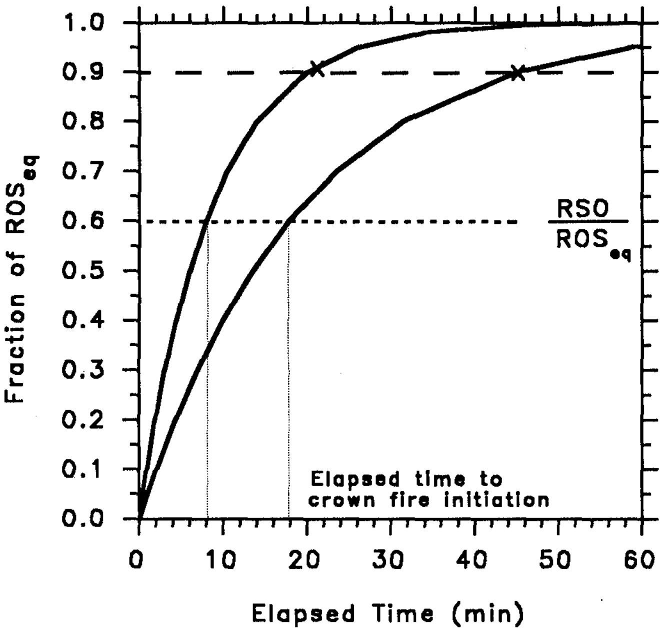


Figure 19. Closed canopy fuel type acceleration model. The curves represent two possibilities for the acceleration function.

enter the tree crowns. Equation 73 defines *ti*, the elapsed time to crown fire initiation:

$$ti = \frac{\ln\left(1 - \dfrac{RSO}{ROS}\right)}{-a} \qquad (73)$$

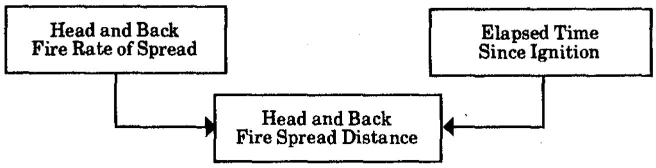
where RSO is the critical spread rate for crowning and ROS is the predicted equilibrium rate of spread. Figure 19 shows the general closed canopy acceleration mode with two acceleration curves and the associated elapsed time to crown fire initiation (dependent on the RSO:ROS ratio term in equation 73).

The ratio of critical surface fire spread rate for crowning to predicted fire spread rate (RSO:ROS) describes the amount in excess of the critical spread rate value predicted. The more severe the conditions, the less the value of the ratio and the shorter the elapsed time to crown fire initiation. Conversely, as the predicted spread rate value nears the critical spread rate value, the longer the time before crown fire initiation. Figure 19 clearly shows that when the RSO:ROS ratio exceeds 0.9 (minimal crown involvement), values for the elapsed time to crown fire initiation can become excessively long.[4] This is caused by the asymptotic nature of the acceleration curves and can be corrected by setting the value of the RSO:ROS ratio at 0.9 when the ratio exceeds 0.9.

The decision on which acceleration model, the closed canopy or open fuel type, to use is normally straightforward. However, some local fuel types that are defined as closed canopy are really open because of the nature of the stand composition. One example would be the lowland black spruce (usually regarded as C-2, closed canopy fuel) found in northern Alberta, northern Saskatchewan, and the Northwest Territories. This particular fuel complex can be considered as a blend of the C-1 and the C-2 fuel types. In such cases, it would better to use the open fuel type acceleration model to account for the rapid acceleration observed in the past. The fuel type C-7 (ponderosa pine–Douglas-fir) would be another example.

The acceleration model presented in equations 70 to 73 can be used for any initiating fire to determine the rate of spread for any time (equation 70), the head fire spread distance (equation 71), and finally the elapsed time to crown fire initiation (equation 73).

8.2 Line Source Fire Growth Projection



Line Source Fire Growth

The projection of a line of fire is much simpler than the point source acceleration procedure. For a projection of a line of fire at the head of the fire, the head fire spread distance (DH) (m) is computed as follows:

$$DH = ROS \times ET \qquad (74)$$

where ROS is the equilibrium rate of spread (m/min) and ET is the elapsed time (min). The elliptical growth model is used to compute flank fire spread rate.

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4 This occurs when there is minimal tree crown involvement. The critical surface spread rate for crowning is more than 90% of the predicted rate of spread.

8.3 Back Fire Spread Rate

In the simple elliptical fire growth model used in the 1984 interim edition of the FBP System, back fire spread was for practical purposes considered to be negligible. This assumption implies that back fire spread is set equal to zero and that the head fire spread accounts for all the length of the major axis of the ellipse that circumscribes the fire area (section 8.4). This causes an underprediction of elliptical fire area and perimeter, especially at very low wind speeds or when the length-to-breadth ratio is less than about 2.0 (Alexander 1985). The focus approach (Alexander 1985) was adopted in subsequent applications of the simple elliptical fire growth model employed in the 1984 interim edition of the FBP System (e.g., McAlpine 1986, 1987; Alexander et al. 1988; Alexander and Lanoville 1989) as a means of indirectly accounting for back fire spread. However, the focus approach, in some fuel/weather cases resulted in erratic estimates of back fire spread. This was the result of a complex interaction of the rate of spread curves and the length-to-breadth curve. A back fire rate of spread model was subsequently developed from informal experience and limited data using a slightly modified set of ISI equations:

$$Bf(W) = e^{-0.05039 \times WSV} \tag{75}$$

where $Bf(W)$ is the back fire wind function, and WSV is the wind speed vector.

$$\text{BISI} = Bf(W) \times f(F) \times 0.208 \tag{76}$$

where BISI is the ISI associated with the back fire spread rate, and $f(F)$ is the FFMC function for the ISI equation 45.

$$\text{BROS} = a \times \left(1 - e^{-b \times BISI}\right)^{c} \times BE \tag{77}$$

where BROS is the back fire rate of spread (m/min); a, b, and c are fuel type specific constants (Table 6); and BE is the buildup effect (section 7.2.3). This produces a curve (ignoring the buildup effect momentarily) that at a zero wind speed equals the head fire zero wind speed spread rate, but decays to a near constant back fire spread rate as wind speed is increased. Predicted back fire spread rates are possible below 0.025 m/min; however, the back fire is probably self-extinguishing below these spread rate values. This procedure eliminates the previous links between back fire spread rate and length-to-breadth ratio. Acceleration in back fire spread from a point source ignition is handled in the same manner as head fire spread, using the same equations (70 to 72). Back fire spread distances for non-accelerating fires are computed similarly to equation 74, namely:

$$\text{DB} = \text{BROS} \times \text{ET} \tag{78}$$

where DB equals the back fire spread distance (m), BROS is the back fire spread rate (m/min), and ET is the elapsed time (min).

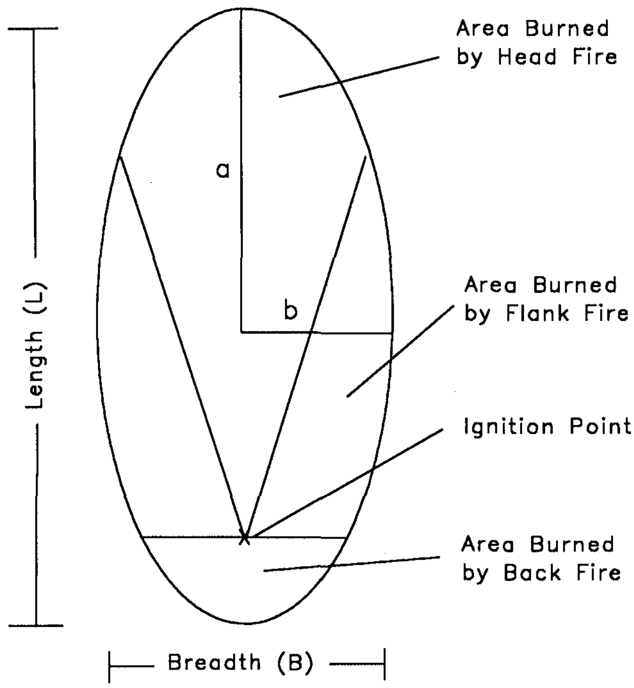

Figure 20. Simple elliptical fire growth model.

8.4 Elliptical Fire Growth

The growth pattern or general shape of a forest fire developing from a single ignition source is largely a function of surface wind velocity. Provided the wind direction remains relatively constant, wind-driven fires typically assume a roughly elliptical or oval shape (Fig. 20), although other similar shapes have been advocated (Anderson 1983; Deacon 1986).

For the purposes of the FBP System, a simple elliptical fire growth model (Van Wagner 1969) that permits an estimate of fire size (area and perimeter) on the basis of head fire spread distance and wind

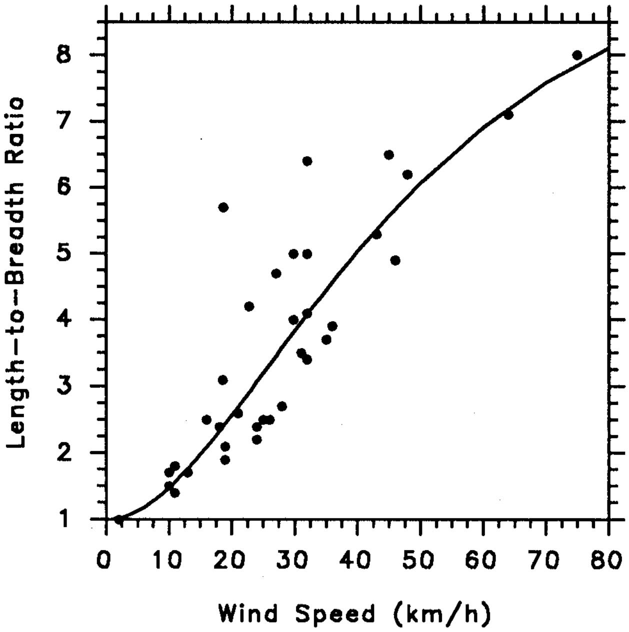

Figure 21. Length-to-breadth ratio of elliptically shaped fires in forest stands and logging slash versus wind speed. The S-shaped curve represents a plot of equation 79.

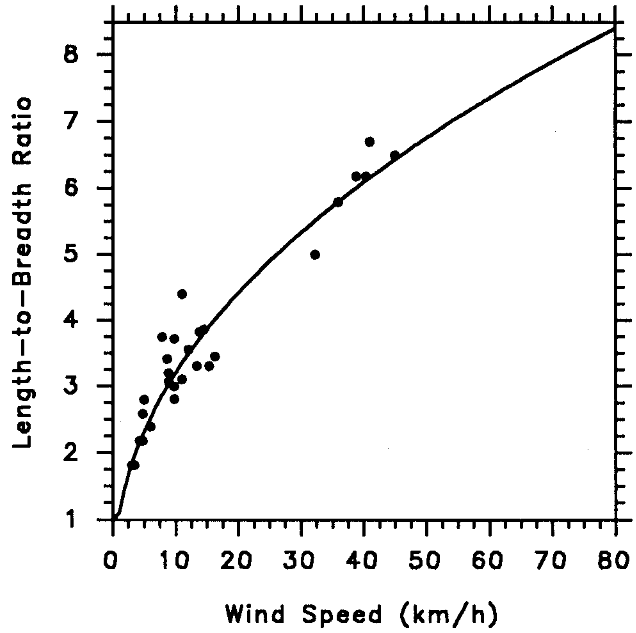

Figure 22. Length-to-breadth ratio of elliptically shaped fires as a function of wind speed for two broad fuel type categories represented by equations 79 and 80.

speed has been adopted. In addition to a constant wind direction, the fire is assumed to spread through a single fuel type, across a uniform slope, and to be unaffected by any suppression activities.

8.4.1 Fire Shape

The most fundamental property of an elliptically shaped fire is its length-to-breadth (LB) ratio (Alexander 1985) which is simply obtained by dividing the fire's total length by its maximum breadth. For example, the elliptically shaped fire portrayed in Figure 20 has an length-to-breadth ratio of about 2.0:1. In the FBP System, this ratio will be given as equal to 2.0. This means that the fire is twice as long as it is wide. A length-to-breadth ratio equal to 1.0 represents a circular fire.

An empirical relationship has been developed (Fig. 21) as a basis for determining the length-to-breadth ratio for standing-timber fuel types in lieu of the semitheoretical approach taken in the 1984 interim edition of the FBP System. The new equation, based on the data assembled for the evaluation of the original length-to-breadth function (Alexander 1985) and subsequent additional data, is as follows (see also Fig. 21):

$$LB = 1.0 + 8.729 \times \left[1 - e^{-0.030 \times WSV}\right]^{2.155} \qquad (79)$$

where WSV is the net vectored wind speed (km/h), or the observed wind speed in cases of no slope. This relationship does give slightly higher length-to-breadth ratio values when compared with the original formulation and has no upper limit with respect to wind speed. However, because of the form of the equation the value of the length-to-breadth ratio does gradually level off to a maximum possible value of 9.7.

The length-to-breadth relationship for grass fuel types (O-1) is as follows (see also Fig. 22):

$$LB = 1.1 + WSV^{0.464} \qquad WSV \geq 1.0 \qquad (80)$$

This equation is taken directly from Cheney (1981) and is based on the analysis of experimental and wildfires in Australian grasslands given in McArthur (1966). Cheney (1981) indicated that the relationship was valid for wind speeds of up to 40 km/h, but neither Luke and McArthur (1978) nor McArthur et al. (1982) set any such limit. Note that when the wind speed vector is less than 1.0 km/h, the following condition applies:

$$LB = 1.0 \qquad WSV < 1.0 \qquad (81)$$

8.4.2 Formulation of a Simple Elliptical Fire Growth Model

Van Wagner (1969) and Alexander (1985) discuss the derivation of the elliptical fire growth model equations from standard mathematical formulae. Area and perimeter can be defined in terms of the head, back, and flank fire spread distances. In terms of fire spread rates, the long and short semiaxes shown in Figure 20 can be described by the following equations:

$$a = \frac{(v + w) \times t}{2} \tag{82}$$

$$b = \frac{2 \times u \times t}{2} = u \times t \tag{83}$$

where a is the long semiaxis of the ellipse; b is the short semiaxis of the ellipse; v is the head fire rate of spread; w is the back fire rate of spread; u is the flank fire rate of spread; and t is the elapsed time since ignition. The area and perimeter of elliptically shaped fires can be determined from the following equations (Van Wagner 1969):

$$A = \frac{\pi}{2} \times (v + w) \times u \times t^2 \tag{84}$$

$$P = \pi \times t \times \left(\frac{v + w}{2} + u\right) \times \left(1 + \frac{M^2}{4}\right) \tag{85}$$

where A is the elliptical fire area; v is the head fire rate of spread; w is the back fire rate of spread; u is the flank fire rate of spread; t is the elapsed time since ignition; and M is equal to $(a - b)/(a + b)$.

McAlpine (1989) has shown that fire shape indexes such as the length-to-breadth ratio are not static during the acceleration phase of fire growth. The fire begins as a circle and gradually develops to an equilibrium fire shape. No information is available on the time required for the final fire length-to-breadth ratio to become established; however, it is assumed to coincide with the equilibrium rate of spread. As such, area and perimeter estimates made for the acceleration phase of fire growth should be regarded with caution. Actual length-to-breadth ratios for this time period will be lower than predicted, resulting in more circular fires and an underprediction of fire area and perimeter.

8.4.3 Area Burned Computation

The equation for computing the area burned by an elliptically shaped fire, as formulated in the previous section, is as follows:

$$A = \frac{\frac{\pi}{4 \times \mathrm{LB}} \times D_T^2}{10\,000} \tag{86}$$

where A is the elliptical fire area (ha); LB is the length-to-breadth ratio; and D_T is the total fire spread distance (m) (the sum of head and back fire spread distances).

The rate of area growth (Merrill and Alexander 1987) does not remain constant with, but rather increases in direct proportion to, time. Assuming steady-state rate of spread, total area burned increases as the square of the time since ignition (Van Wagner 1969). For example, the total area burned two hours after ignition will be four times the area burned after one hour. Rate of area growth can be quoted as area per unit time, such as hectares per hour, provided this is understood to apply to the current moment only.

8.4.4 Perimeter Computation

The equation for computing the perimeter of an elliptically shaped fire, as formulated earlier, is as follows:

$$P = \pi \times \frac{D_T}{2} \times \left(1 + \frac{1}{\mathrm{LB}}\right) \times \left[1 + \left(\frac{\mathrm{LB} - 1}{2(\mathrm{LB} + 1)}\right)^2\right] \tag{87}$$

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

In contrast to rate of area growth, perimeter growth rate (Merrill and Alexander 1987) does remain constant with time provided the head fire rate of spread remains unchanged (Van Wagner 1965). Thus, the perimeter growth rate is calculated as follows:

$$PGR = \pi \times \frac{\mathrm{ROS} + \mathrm{BROS}}{2} \times \left(1 + \frac{1}{\mathrm{LB}}\right) \times \left[1 + \left(\frac{\mathrm{LB} - 1}{2(\mathrm{LB} + 1)}\right)^2\right] \tag{88}$$

where PGR is the perimeter growth rate (m/min.); ROS is the equilibrium head fire rate of spread (m/min.); BROS is the back fire rate of spread (m/min.); and LB is the length-to-breadth ratio. Although the overall pattern of a free-burning fire can generally be represented by a smooth ellipse, the actual length of the perimeter tends to be underestimated by equation 88 because natural irregularities in the fire edge are not considered in the simple elliptical fire growth model.

Until the equilibrium rate of spread is attained (i.e., during the acceleration period) the perimeter growth rate can be calculated by substituting the rate of spread at time t (equation 70) into equation 88. In this case, perimeter growth rate is subject to the same restriction as rate of area growth; that is, it can be quoted as such provided it is understood that it applies to a specific moment in time.

8.4.5 Flank and Back Fire Intensity

Fire intensity about the perimeter of a fire has been discussed by other authors (Catchpole et al. 1982). The fire intensity in terms of Byram's equation ($I = HWR$) at various points about the perimeter is a function of head fire rate of spread and length-to-breadth ratio—the heat of combustion being constant and the fuel consumption assumed to be consistent around the perimeter. Since the elliptical growth model predicts flank fire spread distances from head fire rate of spread, elapsed time, and the length-to-breadth ratio, it is a simple matter to compute flank fire rate of spread. Flank fire rate of spread (at the widest point on the ellipse; see Fig. 20) is defined as:

$$\mathrm{FRS} = \frac{\mathrm{ROS} + \mathrm{BROS}}{\mathrm{LB} \times 2} \tag{89}$$

where FRS is the flank fire rate of spread (m/min); ROS is the surface fire rate of spread (m/min); BROS is the back fire rate of spread (m/min); and LB is the length-to-breadth ratio.

Once we have ascertained the respective surface fire rates of spread at these points, the surface fire intensity must now be calculated as in equation 69, substituting flank or back fire rate of spread for head fire rate of spread. Surface fuel consumption is assumed to be constant as previously stated. These flank and back fire surface fire intensity values are then tested, in the same way as those for the head fire surface intensity were, to determine degree of crown involvement. Values calculated for flank and back fire intensity include not only the fire intensity, but also the crown fraction burned, indicating the degree (if any) of crowning (see section 7.5 on fire description).

For an initiating fire, where an acceleration function is used to determine the head fire rate of spread, an acceleration function must be used for the flank fires as well. Equation 70 is used, substituting the flank and back fire rates of spread for the equilibrium rate of spread ($\mathrm{ROS_{eq}}$) and proceeding as outlined above.

Other points about the perimeter can be evaluated for fire intensity and rate of spread in this same manner. Catchpole et al. (1982) provide equations to determine rate of spread at any point about the perimeter of an elliptically shaped fire based on head fire rate of spread (RSS in our case) and length-to-breadth ratio. These rates of spread could be treated in the same manner as the flank and back fire rates (i.e., test against the critical rate of spread, etc.) to determine the intensity at any point on the perimeter of the fire. This, however, is not included as part of the FBP System as it requires extensive and complex mathematical computations for each fire intensity estimation and further input values.

9.0 Concluding Remarks

This edition of the FBP System represents the best available information on fire behavior in Canada. It is the result of 25 years of research activity by Forestry Canada fire researchers and reflects the traditional Canadian approach of gathering detailed fire behavior data through experimental burning programs and supplementing this data with wildfire observations to statistically derive models consistent with physical theory. Although the FBP System gives Canadian fire managers information on site-specific fire behavior for a number of important fuel types, continued monitoring and documentation of wildfires by fire management agencies is critical to verify existing relationships and to provide key information for future model development. Research into improved fire behavior prediction will require continued support from fire management agencies through logistical assistance and continuous evaluation and feedback.

The FBP System is intended to significantly supplement, rather than replace, the experience and judgment of operational fire managers. Agencies that combine in a systematic fashion the outputs of the FBP System with local fire experience and improved decision-support systems will benefit the most. The effective use of quantitative fire behavior prediction requires continued improvements in fire weather forecasting, fire weather data collection, and information-handling capability. Fire management information systems that link site-specific fire behavior prediction tools with decision-support guidelines should be of demonstrable value in improving fire management effectiveness across Canada.

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Appendix I Equation Summary

PRIMARY COMPONENTS

Foliar Moisture Content Determination

$$\mathrm{LATN} = 46 + 23.4 \times e^{-0.0360 \times (150 - \mathrm{LON})} \tag{1}$$

$$D_0 = 151 \times \left(\frac{\mathrm{LAT}}{\mathrm{LATN}}\right) \tag{2}$$

$$\mathrm{LATN} = 43 + 33.7 \times e^{-0.0351 \times (150 - \mathrm{LON})} \tag{3}$$

$$D_0 = 142.1 \times \left(\frac{\mathrm{LAT}}{\mathrm{LATN}}\right) + 0.0172 \times \mathrm{ELV} \tag{4}$$

$$\mathrm{ND} = \left| D_j - D_0 \right| \tag{5}$$

$$\mathrm{FMC} = 85 + 0.0189 \times \mathrm{ND}^2 \qquad \mathrm{ND} < 30 \tag{6}$$

$$\mathrm{FMC} = 32.9 + 3.17 \times \mathrm{ND} - 0.0288 \times \mathrm{ND}^2 \qquad 30 \le \mathrm{ND} < 50 \tag{7}$$

$$\mathrm{FMC} = 120 \qquad \mathrm{ND} \ge 50 \tag{8}$$

Surface Fuel Consumption

C-1

$$\mathrm{SFC} = 1.5 \times \left[1 - e^{(-0.230 \times [\mathrm{FFMC} - 81])}\right] \tag{9}$$

If SFC < 0, then set SFC $= 0$.

C-2, M-3, and M-4

$$\mathrm{SFC} = 5.0 \times \left[1 - e^{(-0.0115 \times \mathrm{BUI})}\right]^{1.00} \tag{10}$$

C-3 or C-4

$$SFC = 5.0 \times \left[1 - e^{(-0.0164 \times BUI)}\right]^{2.24} \tag{11}$$

C-5 or C-6

$$SFC = 5.0 \times \left[1 - e^{(-0.0149 \times BUI)}\right]^{2.48} \tag{12}$$

C-7
Compute the forest floor consumption (FFC) and woody fuel consumption (WFC) separately and add together to get the total surface fuel consumption (SFC):

$$FFC = 2 \times \left[1 - e^{(-0.104 \times [FFMC - 70])}\right] \tag{13}$$

If FFC < 0, then set FFC $= 0$.

$$WFC = 1.5 \times \left[1 - e^{(-0.0201 \times BUI)}\right] \tag{14}$$

$$SFC = FFC + WFC \tag{15}$$

D-1

$$SFC = 1.5 \times \left[1 - e^{(-0.0183 \times BUI)}\right] \tag{16}$$

M-1 or M-2

$$SFC = \left[\frac{PC}{100} \times (\text{SFC for C-2})\right] + \left[\frac{PH}{100} \times (\text{SFC for D-1})\right] \tag{17}$$

O-1

$$SFC = GFL \tag{18}$$

S-1

$$FFC = 4.0 \times \left[1 - e^{(-0.025 \times BUI)}\right] \tag{19}$$

$$WFC = 4.0 \times \left[1 - e^{(-0.034 \times BUI)}\right] \tag{20}$$

S-2

$$FFC = 10.0 \times \left[1 - e^{(-0.013 \times BUI)}\right] \tag{21}$$

$$\mathrm{WFC} = 6.0 \times \left[1 - e^{(-0.060 \times \mathrm{BUI})}\right] \tag{22}$$

S-3

$$\mathrm{FFC} = 12.0 \times \left[1 - e^{(-0.0166 \times \mathrm{BUI})}\right] \tag{23}$$

$$\mathrm{WFC} = 20.0 \times \left[1 - e^{(-0.0210 \times \mathrm{BUI})}\right] \tag{24}$$

All slash fuel types

$$\mathrm{SFC} = \mathrm{FFC} + \mathrm{WFC} \tag{25}$$

Rate of Spread Equations

General Rate of Spread Equation

C-1 to C-5, and C-7

$$\mathrm{RSI} = a \times \left[1 - e^{(-b \times \mathrm{ISI})}\right]^c \tag{26}$$

Fuel Type Specific Rate of Spread Equations

M-1 (leafless)

$$\mathrm{RSI} = \left[\frac{\mathrm{PC}}{100} \times (\mathrm{RSI\ for\ C{-}2})\right] + \left[\frac{\mathrm{PH}}{100} \times (\mathrm{RSI\ for\ D{-}1})\right] \tag{27}$$

M-2 (green)

$$\mathrm{RSI} = \left[\frac{\mathrm{PC}}{100} \times (\mathrm{RSI\ for\ C{-}2})\right] + 0.2 \times \left[\frac{\mathrm{PH}}{100} \times (\mathrm{RSI\ for\ D{-}1})\right] \tag{28}$$

See the table at end of this appendix for complete listing of fuel-type-specific regression parameter values.

Rate of spread coefficient parameters foı. M-3 and M-4

M-3

$$a = 170 \times e^{\left(\frac{-35.0}{\mathrm{PDF}}\right)} \tag{29}$$

$$b = 0.082 \times e^{\left(\frac{-36.0}{\text{PDF}}\right)} \tag{30}$$

$$c = 1.698 - 0.00303 \times \text{PDF} \tag{31}$$

M-4

$$a = 140 \times e^{\left(\frac{-35.5}{\text{PDF}}\right)} \tag{32}$$

$$b = 0.0404 \tag{33}$$

$$c = 3.02 \times e^{(-0.00714 \times \text{PDF})} \tag{34}$$

O-1 (grass)

$$\text{CF} = 0.02 \times C - 1.0 \qquad C > 50 \tag{35}$$

If $C \leq 50$, then $\text{CF} = 0$.

$$\text{ROS} = a \times \left[1 - e^{(-b \times \text{ISI})}\right]^{c} \times \text{CF} \tag{36}$$

Effect of Slope on Rate of Spread

$$\%\,\text{Ground slope} = \frac{\text{Elevation rise}}{\text{Horizontal ground distance}} \times 100 \tag{37}$$

$$\%\,\text{Ground slope} = 100 \times \tan(\alpha) \tag{38}$$

$$\text{SF} = e^{3.533 \times \left(\frac{\text{GS}}{100}\right)^{1.2}} \qquad \text{GS} < 60 \tag{39}$$

$$\text{RSF} = \text{RSZ} \times \text{SF} \tag{40}$$

$$\text{ISF} = \frac{\ln\left[1 - \left(\frac{\text{RSF}}{a}\right)^{\frac{1}{c}}\right]}{-b} \tag{41}$$

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

$$\mathrm{ISF} = \frac{\ln\left[1 - \left(\dfrac{\mathrm{RSF}}{\mathrm{CF} \times a}\right)^{\frac{1}{c}}\right]}{-b} \tag{43}$$

$$\mathrm{WSE} = \frac{\ln\left[\dfrac{\mathrm{ISF}}{0.208 \times f(F)}\right]}{0.05039} \tag{44}$$

$f(F)$ Function from the ISI calculation procedure (from the FWI System)

$$f(F) = 91.9 \times e^{(-0.1386 \times m)} \times \left[1 + \frac{m^{5.31}}{4.93 \times 10^{7}}\right] \tag{45}$$

where

$$m = \frac{147.2 \times (101 - \mathrm{FFMC})}{59.5 + \mathrm{FFMC}} \tag{46}$$

Wind speed equivalent (WSE) calculation

$$\mathrm{WSX} = \left[\mathrm{WS} \times \sin(\mathrm{WAZ})\right] + \left[\mathrm{WSE} \times \sin(\mathrm{SAZ})\right] \tag{47}$$

$$\mathrm{WSY} = \left[\mathrm{WS} \times \cos(\mathrm{WAZ})\right] + \left[\mathrm{WSE} \times \cos(\mathrm{SAZ})\right] \tag{48}$$

$$\mathrm{WSV} = \surd(\mathrm{WSX}^2 + \mathrm{WSY}^2) \tag{49}$$

$$\mathrm{RAZ} = \arccos\left(\frac{\mathrm{WSY}}{\mathrm{WSV}}\right) \tag{50}$$

If WSX <0, then

$$\mathrm{RAZ} = 360 - \mathrm{RAZ} \tag{51}$$

ISI equation (from the FWI System)

$$\mathrm{ISI} = 0.208 \times f(W) \times f(F) \tag{52}$$

where

$$f(W) = e^{0.05039 \times \mathrm{WSV}} \tag{53}$$

If WS > 40, then

$$f(W) = 12 \times \left[1 - e^{-0.0818 \times (\mathrm{WSV} - 28)}\right] \tag{53a}$$

BUI Effect on Surface Fire Rate of Spread

$$\mathrm{BE} = e^{\left[50 \times \ln(q) \times \left(\frac{1}{\mathrm{BUI}} - \frac{1}{\mathrm{BUI}_0}\right)\right]} \tag{54}$$

$$\mathrm{ROS} = \mathrm{RSI} \times \mathrm{BE} \tag{55}$$

Critical Surface Fire Intensity

$$\mathrm{CSI} = 0.001 \times \mathrm{CBH}^{1.5} \times (460 + 25.9 \times \mathrm{FMC})^{1.5} \tag{56}$$

$$\mathrm{RSO} = \frac{\mathrm{CSI}}{300 \times \mathrm{SFC}} \tag{57}$$

$$\mathrm{CFB} = 1 - e^{-0.23 \times (\mathrm{ROS} - \mathrm{RSO})} \tag{58}$$

Conifer Plantation (C-6) Rate of Spread

$$T = 1500 - 2.75 \times \mathrm{FMC} \tag{59}$$

$$h = 460 + 25.9 \times \mathrm{FMC} \tag{60}$$

$$\mathrm{FME} = \frac{(1.5 - 0.00275 \times \mathrm{FMC})^{4.0}}{460 + (25.9 \times \mathrm{FMC})} \times 1000 \tag{61}$$

$$\text{RSI} = 30 \times \left(1 - e^{-0.08 \times \text{ISI}}\right)^{3.0} \tag{62}$$

$$\text{RSS} = \text{RSI} \times \text{BE} \tag{63}$$

$$\text{RSC} = 60 \times \left(1 - e^{-0.0497 \times \text{ISI}}\right)^{1.00} \times \frac{\text{FME}}{\text{FME}_{\text{avg}}} \tag{64}$$

$$\text{ROS} = \text{RSS} + \text{CFB} \times (\text{RSC} - \text{RSS}) \tag{65}$$

Total Fuel Consumption

$$\text{CFC} = \text{CFL} \times \text{CFB} \tag{66}$$

$$\text{TFC} = \text{SFC} + \text{CFC} \tag{67}$$

Fire Intensity

$$I = HwR \tag{68}$$

$$\text{FI} = 300 \times \text{FC} \times \text{ROS} \tag{69}$$

SECONDARY COMPONENTS

Acceleration to Equilibrium Spread

$$\text{ROS}_t = \text{ROS}_{\text{eq}} \times \left(1 - e^{-\alpha t}\right) \tag{70}$$

$$D = \text{ROS}_{\text{eq}} \times \left(t + \frac{e^{-\alpha t}}{\alpha} - \frac{1}{\alpha}\right) \tag{71}$$

$$\alpha = 0.115 - 18.8 \times \text{CFB}^{2.5} \times e^{(-8 \times \text{CFB})} \tag{72}$$

$$ti = \frac{\ln\left(1 - \frac{\text{RSO}}{\text{ROS}}\right)}{-\alpha} \tag{73}$$

Head Fire – Back Fire Spread Distance

$$\text{DH} = \text{ROS} \times \text{ET} \tag{74}$$

$$\text{B}f(W) = e^{-0.05039 \times \text{WSV}} \tag{75}$$

$$\text{BISI} = \text{B}f(W) \times f(F) \times 0.208 \tag{76}$$

$$\text{BROS} = a \times \left(1 - e^{-b \times \text{BISI}}\right)^{c} \times \text{BE} \tag{77}$$

$$\text{DB} = \text{BROS} \times \text{ET} \tag{78}$$

Length-to-Breadth Ratio

All fuel types except O-1

$$\text{LB} = 1.0 + 8.729 \times \left[1 - e^{-0.030 \times \text{WSV}}\right]^{2.155} \tag{79}$$

Open fuel types (O-1)

$$\text{LB} = 1.1 + \text{WSV}^{0.464} \qquad \text{WSV} \geq 1.0 \tag{80}$$

$$\text{LB} = 1.0 \qquad \text{WSV} < 1.0 \tag{81}$$

Fire Area and Perimeter Determination

$$a = \frac{(v + w) \times t}{2} \tag{82}$$

$$b = \frac{2 \times u \times t}{2} = u \times t \tag{83}$$

$$A = \frac{\pi}{2} \times (v + w) \times u \times t^2 \tag{84}$$

$$P = \pi \times t \times \left(\frac{v + w}{2} + u \right) \times \left(1 + \frac{M^2}{4} \right) \tag{85}$$

$$A = \frac{\frac{\pi}{4 \times \mathrm{LB}} \times D_T^2}{10\,000} \tag{86}$$

$$P = \pi \times \frac{D_T}{2} \times \left(1 + \frac{1}{\mathrm{LB}} \right) \times \left[1 + \left(\frac{\mathrm{LB} - 1}{2(\mathrm{LB} + 1)} \right)^2 \right] \tag{87}$$

$$PGR = \pi \times \frac{\mathrm{ROS} + \mathrm{BROS}}{2} \times \left(1 + \frac{1}{\mathrm{LB}} \right) \times \left[1 + \left(\frac{\mathrm{LB} - 1}{2(\mathrm{LB} + 1)} \right)^2 \right] \tag{88}$$

Flank Fire Rate of Spread

$$\mathrm{FRS} = \frac{\mathrm{ROS} + \mathrm{BROS}}{\mathrm{LB} \times 2} \tag{89}$$

Rate of Spread Parameter Values for Each Fuel Type

Fuel type	*a*	*b*	*c*	*q*	BUI_0	CBH (m)	CFL (kg/m^2)
C-1	90	0.0649	4.5	0.90	72	2	0.75
C-2	110	0.0282	1.5	0.70	64	3	0.80
C-3	110	0.0444	3.0	0.75	62	8	1.15
C-4	110	0.0293	1.5	0.80	66	4	1.20
C-5	30	0.0697	4.0	0.80	56	18	1.20
C-6	30	0.0800	3.0	0.80	62	7	1.80
C-7	45	0.0305	2.0	0.85	106	10	0.50
D-1	30	0.0232	1.6	0.90	32	*	*
M-1	*	*	*	0.80	50	6	0.80
M-2	*	*	*	0.80	50	6	0.80
M-3	*	*	*	0.80	50	6	0.80
M-4	*	*	*	0.80	50	6	0.80
S-1	75	0.0297	1.3	0.75	38	*	*
S-2	40	0.0438	1.7	0.75	63	*	*
S-3	55	0.0829	3.2	0.75	31	*	*
O-1a	190	0.0310	1.4	1.00	01	*	*
O-1b	250	0.0350	1.7	1.00	01	*	*

CBH = height to live crown base; CFL = crown fuel load.
* Values not applicable.

Appendix II List of Symbols

PRIMARY COMPONENTS

Slope:

GS	Percent ground slope
SAZ	Slope azimuth, upslope
SF	Slope factor, upslope

Wind Speed (km/h):

WAZ	Wind azimuth, degrees
WS	Observed wind speed
WSE	Slope equivalent wind speed
WSV	Net vectored wind speed
WSX	Net vectored wind speed in the x-direction
WSY	Net vectored wind speed in the y-direction

Initial Spread Index (ISI):

B*f*(*W*)	Back fire wind function
BISI	ISI used to compute the back fire rate of spread
f(*F*)	Fine fuel moisture function in the ISI
f(*W*)	Wind function in the ISI
ISF	ISI, with zero wind upslope
ISI	final ISI, accounting for wind and slope
ISZ	ISI, with zero wind on level ground

Spread Rate (m/min):

a,*b*,*c*	Rate of spread equation coefficients
BROS	Back (or rear) fire spread rate
CF	Curing function for grass fuel types
FRS	Flank fire spread rate
RAZ	Spread direction azimuth
ROS	Final spread rate, surface or crown fire
RSC	Crown fire spread rate (C-6)
RSF	Surface spread rate with zero wind, upslope
RSI	Initial spread rate without BUI effect
RSO	Critical spread rate for crowning
RSS	Surface fire spread rate (C-6)
RSZ	Surface spread rate with zero wind on level terrain

Fuel Consumption (kg/m^2):

CFC	Crown fuel consumption
FFC	Forest floor consumption
SFC	Total surface fuel consumption
TFC	Total fuel consumption
WFC	Woody fuel consumption

Fire Intensity (kW/m):

CSI	Critical surface intensity for crowning
FFI	Flank fire intensity (elliptical fire model)
HFI	Head fire intensity
RFI	Back (or rear) fire intensity (elliptical fire model)
SFI	Surface fire intensity

Foliar Moisture Content:

D_j	Julian date
D_0	Julian date of minimum FMC
ELV	Elevation above sea level (m)
FMC	Foliar moisture content (%)
LAT	Latitude (degrees)
LATN	Normalized latitude (degrees)
LON	Longitude (degrees)
ND	Number of days between the current date and D_0

Crown Fire Parameters:

CBH	Height to live crown base (m)
CFB	Crown fraction burned
CFL	Crown fuel load (kg/m^2)
FME	Foliar moisture effect

Buildup Index (BUI) Effect:

BE	Buildup effect on spread rate
BUI	Buildup Index
q	Proportion of maximum rate of spread at BUI equal to 50

Fuel Type and Fuel Moisture Inputs:

C	Degree of curing (%)
FFMC	Fine Fuel Moisture Code
GFL	Grass fuel load (kg/m^2)
M	Moisture content equivalent of the FFMC (%)
PC	Percent conifer (mixedwood fuel types; M-1, M-2)
PDF	Percent dead fir (mixedwood fuel types; M-3, M-4)
PH	Percent hardwood (mixedwood fuel types; M-1, M-2)

SECONDARY COMPONENTS

Point Source Fire:

α	Alpha function controlling the acceleration function
ROS_{eq}	Equilibrium rate of spread
ROS_t	Rate of spread after elapsed time, t (m/min)
t	Elapsed time since ignition from a single point (min)
ti	Elapsed time to crown fire initiation (min)

Fire Shape:

LB	Length-to-breadth ratio

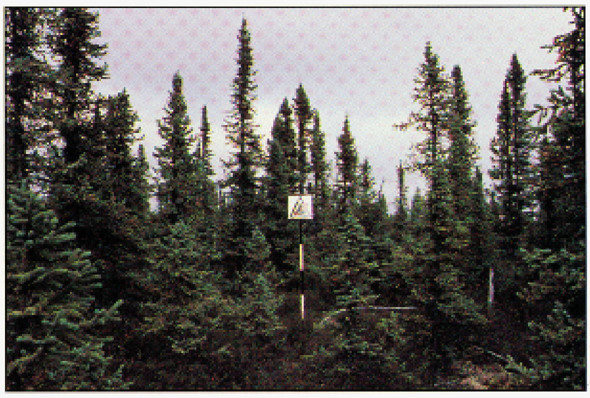
Spread Distances:

DB	Back fire spread distance (m)
DH	Head fire spread distance (m)
D_T	Total fire spread distance (DH + DR)
ET	Elapsed time since ignition (min)

Area and Perimeter:

A	Elliptical fire area (ha)
P	Elliptical fire perimeter (m)
PGR	Rate of perimeter growth (m/min)
π	Mathematical constant, 3.1415927


C-1


C-2


C-3


C-4


C-5


C-6


C-7


D-1


M-1


M-2


M-3


M-4


S-1


S-2


S-3


O-1

Forestry Canada

Forestry Canada is the main focus for forestry matters in the federal government. It provides national leadership through the development, coordination, and implementation of federal policies and programs to enhance long-term economic, social, and environmental benefits from the forest sector for Canadians.

Forestry Canada is a decentralized organization with six regions, two national research institutes, and seven regional sub-offices located across Canada. Headquarters is located in the National Capital Region in Hull, Quebec.

In support of its mandate, Forestry Canada carries out the following activities:

- administers forest development agreements negotiated with the provinces
- undertakes and supports research, development, and technology transfer in forest management, utilization, and environment
- compiles, analyzes, and disseminates information about national and international forest resources and related matters
- monitors disease and insect pests in Canada's forests
- provides information, analyses, and policy advice on economics, industry, markets, and trade related to the forest sector
- promotes employment, education, and training opportunities in the forest sector
- promotes public awareness of all aspects of the forest sector

Forestry Canada interacts regularly with provincial and territorial governments, industry, labor, universities, conservationists, and the public through such bodies as the Canadian Council of Forest Ministers, the Forest Sector Advisory Council, the Forestry Research Advisory Council of Canada, the Canadian Forest Inventory Committee, the Canadian Committee on Forest Fire Management, the Canadian Interagency Forest Fire Centre, and regional consultative committees. Forestry Canada is also active in international forestry agencies such as the International Union of Forestry Research Organizations and the Food and Agriculture Organization, as well as in technical and trade missions.