FIRE ECOLOGY AND MANAGEMENT

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The value and importance of the forest and range resources and related industries to British Columbia resulted in fire prevention laws which are now over 125 years old. The organized suppression of wildfires began in 1905 and over the decades has experienced vast technological and methodological improvements. Our knowledge of the natural role of fire and its beneficial and deleterious effects has improved markedly since 1905, and primarily during the past 40 years.

Fire ecology is more of a science, while fire management is both a science and an art. It does not take place in isolation of society, society's values or resource management objectives. As it has for the past few decades, fire management includes both appropriate fire control and appropriate fire use.

Fire Ecology and Types of Fire

Fire ecology is "the study of fire as it affects and relates to the natural environment and the interrelationships of the plants and animals therein" (CIFFC, 2003). Fire takes several forms and results in a wide range of ecological effects in space and time. Forest fires are classified as ground, surface or crown fires. Ground fires slowly consume the organic soil layers and, because oxygen is in short supply, combustion is slow and flames are absent or small. Surface fires burn the combustible material lying above the duff layer, between the ground and ladder fuels (CIFFC, 2003). These fires consume twigs, branches and coarse woody debris on the forest floor as well as herbaceous plants, shrubs and small trees. Flame lengths vary from about 30 cm to several metres and may reach into the overstorey tree canopy.

Crown fires advance through the crown fuel layer, usually in union with a surface fire, and are the most impressive of all forest fires, especially when aided by strong winds, steep topography, or both. Crown fires can be described in terms of their dependence on the surface fire. An intermittent crown fire is one in which trees torch sporadically, with the rate of fire spread determined by the surface fire. Active crown fires propagate as an established wall of flame that extends from the forest floor to above the crown fuels. An independent crown fire advances in the crown fuel layer only. Crown fires may travel as quickly as 200 m per minute and have flame lengths up to 200 m.

The behaviour of a fire can be described as smouldering, creeping, running, torching, spotting or crowning (CIFFC, 2003). Variations in type of fire (ground, surface or crown) and behaviour make each fire a unique event. The combination of frontal fire intensity (Byram, 1959; Alexander, 1982) and residence time, which is the length of time required for the flaming zone to pass a given point, determines

a fire's ecological effects. At a broader scale the ecological effects, fire sizes and fire frequencies determine the landscape patterns – from a mosaic of small patches of different ages resulting from frequent fires to large patches representing a few significant fire events.

Fire History

Evidence of historic forest fires exists as fossil charcoal, charcoal layers in aquatic sediments and soil horizons, unique stand age structures, burned standing dead trees and downed coarse woody debris, charred live trees, fire-scarred live and dead trees and historical records and photographs. Fire history studies in British Columbia have determined that fire has influenced most of our forests and grasslands over millennia.

The fire history of a particular area is related to a number of environmental factors such as climate (general and drought periodicity), aspect (warm versus cool), elevation (related to microclimatic variations and lightning incidence), topography (fire behaviour and burn patterns), fuel types (rate of spread and fire intensity) and ignition probability (lightning and human).

Wildfire size is determined by fire behaviour, which is a function of the number of ignition points, fuel quantities, fuel arrangements and availability for burning (due to moisture content) as well as terrain features (e.g. natural firebreaks or barriers to fire spread), topography, wind speed and wind directions (determinants of a fire's rate of spread and direction of travel). A fire event creates a unique pattern, ranging from a burned patch within an unburned landscape to a burned landscape containing unburned patches. Recurring fires modify these patterns.

Fire reports maintained by the BC Forest Service estimate that 11,207,000 hectares were burned by 181,000 fires from 1912 to 2004. This is an underestimate because many large fires of the early 1900s were not detected or recorded. However, other areas burned more than once during the period of record, especially in the grasslands and dry interior forests. Wildfire sizes have ranged from small spots to 100,000 to 200,000 hectares, or more, and have a size-class distribution with a large number of very small events (< 1 ha in size), a small number of very large events (> 100,000 ha) and a continuous size distribution in between. The largest fires often result from a combination of multiple ignitions, extensive and dry forests, gentle to moderate topography and strong winds.

Of the 20 largest wildfires known to have occurred since 1920, nine burned exclusively in the Boreal White and Black Spruce (BWBS) biogeoclimatic zone and five burned primarily in the BWBS but also into the zone above it, the Spruce – Willow – Birch (SWB). These 14 fires account for 1,280,700 hectares of the estimated total of 1,556,300 hectares represented by the largest 20 wildfires for the province (or 83% of that area). The largest fire on record occurred in 1958 and covered 285,900 hectares, mostly in the BWBS zone. Other large fires, ranging in size from 35,800 to 68,700 hectares, occurred in the Montane Spruce (MS), Interior Cedar - Hemlock (ICH), Engelmann Spruce - Subalpine Fir (ESSF) and Interior Douglas-fir (IDF) biogeoclimatic zones, almost exclusively in the early 1930s.

Fire Regimes and Ecosystem Groups

Fire regimes are defined by the type, frequency, intensity and size of fires which affect particular ecosystems (Pyne *et al.* 1996). Fire regimes range from no or rare natural fires, to surface fires of varying frequencies and intensities, to crown fires of varying frequencies. Mixed fire regimes, with both surface and crown fires, occur in forests where some stands experience surface fires and others experience crown fires during the same fire event. Knowledge of the fire regime is important at both the stand and landscape levels.

Ecosystems form four broad groups with respect to the role of fire (Vogl, 1977):

1. Fire-independent ecosystems: are usually fire-free and the plant species possess no or few fire adaptations. Fire effects are dramatic, long-lasting and post-fire recovery is slow. Examples include some floodplain forests, wetlands and alpine ecosystems.
2. Fire-dependent ecosystems: fire is common and fuel conditions are conducive to fire spread. The plant species are adapted to fire and require it for their existence. Post-fire recovery is immediate and fire exclusion is unnatural. Examples include grasslands, oak savannahs, and lodgepole pine, trembling aspen and black spruce forests (Vogl, 1977).
3. Fire-initiated ecosystems: fire is infrequent and “catastrophic” as it terminates, but also initiates, long-lived plants. Initial revegetation is rapid but the post-fire recovery period can be lengthy – up to hundreds of years. These ecosystems are common in temperate regions and include the western white pine, western larch, coastal Douglas-fir, western hemlock and western redcedar types.
4. Fire-maintained ecosystems: light-intensity surface fires are frequent and crown fires are uncommon. Individual plants usually survive fires, which thin the stand, decrease fuel loads and select against fire-susceptible species, maintaining the community at an early- or mid-successional stage. The prolonged absence of fire is unnatural and results in fuel build-ups, increased stand density, forest health problems, invasion by late-successional species and greater susceptibility to crown fires (Vogl, 1977). Ecosystems primarily include the interior Douglas-fir and ponderosa pine types.

Natural Disturbance Types

While there are many subtle variations in the type, spatial distribution, temporal occurrence and effects of natural disturbance agents, British Columbia’s ecosystems have been placed into five general Natural Disturbance Types (NDT) for planning and resource management purposes (Ministry of Forests and BC Environment, 1995):

NDT 1	ecosystems with rare stand-initiating events
NDT 2	ecosystems with infrequent stand-initiating events
NDT 3	ecosystems with frequent stand-initiating events
NDT 4	ecosystems with frequent stand-maintaining fires
NDT 5	alpine tundra and subalpine parkland ecosystems

Frequency varies according to the disturbance agent and geographic area, or biogeoclimatic zone. Knowledge of the effects of historic natural disturbances is used as a guide when considering biodiversity management objectives – specifically for seral stage distribution, patch size, old seral stage retention and representativeness, landscape connectivity, stand structure and species composition (Ministry of Forests and BC Environment, 1995; Ministry of Forests and Ministry of Environment, Lands and Parks, 1999).

Post-fire Succession

Post-fire vegetation succession varies with the pre-fire vegetation species and their state of development, the season of the burn, fire behaviour, fire intensity (heat output), fire severity (effects on the ecosystem), fire size, off-site vegetation, physical site characteristics and post-fire environmental conditions. There can be a wide range of fire effects in a large wildfire. Fire effects especially vary between fires in response to variations in fire size, topography, vegetative cover, soil characteristics and fire behaviour. The diversity of fire effects leads to a diversity of ecosystem responses.

In fire-initiated ecosystems, where the tree canopy can be entirely burned, vegetation recovery will depend on on-site or off-site adaptations. On-site adaptations include serotinous cones (lodgepole pine), root suckering (trembling aspen), root collar sprouting (birches), redevelopment from specialised rooting structures (rhizomatous shrubs and herbs) and seed stored in the soil which germinates following heat treatment (snowbrush and other shrub species). Off-site adaptations are exhibited by different herbs, shrubs and trees in the form of many light seeds which colonise the burned area.

Stand-maintaining fires suspend forest succession, preventing conversion to later-successional communities. The thick bark of older ponderosa pine, Douglas-fir and western larch enable them to survive surface fires. Large and open-grown ponderosa pine have their lower trunks clear of branches, thus lessening the chance that fire will move into the crowns. Most native herb and shrub species in these types are also fire-adapted by virtue of protected buds or the ability to regrow following fire.

Fire also affects soil processes, nutrient cycles, stream water chemistry, hydrological and geomorphological processes, various aspects of plant and animal habitat and air quality. Knowledge of the relationships between fire behaviour, fire effects and ecosystem response is required to predict the impacts of wildfires or when planning and executing prescribed burns.

Aboriginal Burning

Aboriginal peoples used prescribed fire to manage food and medicinal plants, wildlife habitat, and domestic range. Fire was also used to reduce fuel loadings around habitations. Burning was done at specific times of the year, under certain weather conditions and required special knowledge of fire behaviour and vegetation response.

At least 18 species of plants, including 12 fruiting shrubs and 6 plants with edible roots have been consistently identified by the First Nations peoples of BC as being purposefully encouraged by traditional burning practices. The major target plants were berry producers such as *Vaccinium* and *Rubus* species, nodding wild onion, several lilies, salal and soopolallie. Burning for berry production also took place on the west coast of Vancouver Island and on Haida Gwaii.

In some cases, individual plants such as hazelnut were burned, but primarily specific patches were treated with fire on perhaps a four- or five-year cycle. Such rotational burning kept a larger landscape area in constant production. The favourite locations for prescribed burning might have been close to a village or seasonal camp, or far enough away to require a special trip to harvest the current year's crop and carry out a prescribed burn (Gottesfeld, 1994).

A special case is the edible blue camas, whose bulbs provided a source of carbohydrates for the aboriginal peoples of southern Vancouver Island and nearby Washington state. Growing in prairies and Garry oak woodlands, this plant was harvested in the late spring and early summer and then the area was burned over later in the summer or in the early fall (Turner, 1991; Beckwith, 2002).

In general, the native peoples were adept at prescribed burning and used low intensity fires to create and maintain fine-scaled mosaics of communities of preferred plant species. In addition, their role in affecting the landscape as a result of carelessness leading to large-scale wildfires cannot be overlooked. While prescribed burning by native peoples was likely reasonably constant and sometimes quite local, the impact of non-natives in their use of fire was more abrupt and widespread.

The Settlement Era

Beginning with the settlement era of the late 1800s, exploration, industrial activity and land clearing resulted in many accidental and serious wildfires. In response to an increasingly-blackened landscape, the *Bush Fire Act* was passed by the Legislative Assembly in 1874 (SBC, 1874). This act provided for fines up to $100 or three months imprisonment for allowing unextinguished fires to escape and damage private or Crown land. However, the first Fire Wardens and fire-fighting crews were not hired until 1905 and so the law was of limited use and rarely enforced.

Controlled burning was used by settlers to clear forest land and permit agricultural development as well as to dispose of hazardous slash on logging operations, all with the encouragement of provincial government agencies. Nevertheless, escaped fires were common and between 1910 and 1916 the majority of wildfires resulted from campers, railways and land clearing operations. Two major concerns at this time were the prevention of wildfires on harvested areas regenerating naturally to new forests and the use of appropriate methods to reduce fires caused by railway and logging locomotives.

Fire Control and Fire Management

The first provincial *Forest Act*, passed in 1912, addressed fire prevention, established a fire season, required permits for the use of fire, directed that slash and other flammable debris be disposed of, and required fire patrols along railways (also subject to federal law and regulations) and at logging operations (SBC, 1912). The act also created the Forest Protection Fund, maintained by owners of timber land and the Crown to man and equip an expanding provincial fire-fighting force and construct trails, lookouts and communication lines.

Over the ensuing decades, technological improvements were made in fire detection and suppression. More and more lookouts were built and manned; fire roads and access trails were constructed; fire pumps and hose became lighter and more effective; aircraft were used to detect fires, deliver equipment and crews and finally were employed as air tankers in a direct fire suppression role. Land-based communication lines gave way to sophisticated radio and data transmission networks. Helicopters are now used to deliver Helitack and Rapattack fire suppression crews as well as act as helitankers to carry water or foam mixtures that are dropped or off-loaded to a portable reservoir near a wildfire. Electronic and computer technology in the 1970s and 1980s brought in remote automated weather stations, lightning detection and location networks and real-time data management and decision support systems.

Fire and Resource Management

Technology allows us to choose to influence natural wildfires and employ prescribed fire, but the role that fire plays in resource management is determined by the specific objectives for particular landscapes and ecosystems. The ecological outcome of any fire can be known or estimated in advance and the fire then judged to be negative, neutral or beneficial. Fires must be evaluated in light of both long-term fire regimes and human activities.

Consideration of the environmental and social implications of a particular fire event determines the appropriate response – whether or not to suppress a wildfire or whether or not to apply prescribed fire. In most cases, protection of life and limb, property values, timber resources and transportation and utility corridors demand fire suppression actions. Resource management plans for ecological reserves and protected areas include consideration of the natural role of fire and provide details as to when and where fire, natural or prescribed, is desired.

Prescribed Burning

In contrast to controlled burning, prescribed burning is more sophisticated and defined as "the knowledgeable application of fire to a specific land area to accomplish predetermined forest management or other land use objectives" (CIFFC, 2003). As knowledge of fire behaviour and fire effects improved, along with technological innovations such as ignition systems and suppression equipment, controlled burning evolved into more sophisticated prescribed burning.

Prescribed burning has been carried out to abate the fire hazard by reducing fuels resulting from harvesting operations and to meet silvicultural objectives – prepare a seedbed, enable access by tree planters, create plantable spots, bring about tree species conversion or site sanitation against certain insects or diseases, maintain stocking control and reduce levels of competing vegetation.

Prescribed burning for wildlife habitat and domestic range improvement has been carried out to manipulate species composition (remove unwanted vegetation and encourage wanted vegetation), improve the quantity and/or quality of forage and browse, create or improve access and change vegetative cover characteristics.

Ecosystem restoration treatments may be required where decades of fire exclusion have resulted in unacceptable changes, especially in the case of fire-maintained ecosystems. Resource and fire managers must recognize the need to restore and/or sustain ecosystems, by various means, and yet fire cannot always be easily or safely reintroduced. Major challenges are the choice of appropriate treatment and the ability to treat large enough areas to effect significant ecosystem restoration at the landscape level.

Combustion

What makes a fire burn? Why does one fire barely creep along while another becomes a roaring inferno? When forest fuels burn, oxygen in the air combines chemically with woody material, pitch and other burnable elements found in the forest environment in a process known as combustion.

Combustion is a chain reaction chemically similar to photosynthesis, but in reverse. Photosynthesis requires a large amount of heat that is furnished by the sun. The combustion process releases this heat in a process sometimes called “rapid oxidation.” Combustion is similar to the formation of rust on iron or the decay of dead wood in the forest, except that the process is very much speeded up.

During combustion, oxygen rapidly combines with the fuel and converts it into gases, primarily water (H_2O) and carbon dioxide (CO_2), as well as various residual by-products. The reaction produces significant thermal energy (heat) and light, and is generally self-sustaining in that no external heat source is required to maintain fuel combustion.

Fuel Chemistry

There are three phases to the combustion process: preheating, flaming combustion and glowing combustion. During preheating, the moisture in the fuel is first evaporated at temperatures > 100°C, then the cellulose is thermally broken down and those breakdown products are then volatilized (at > 200°C). This partial breakdown of cellulose molecules produces flammable hydrocarbon gases which ignite (at from 300–400°C), combining with oxygen to produce flaming combustion. The reaction for the flaming combustion of cellulose is written as:

$$C_6H_{10}O_5 + 6O_2 \overset{h}{\Rightarrow} 6CO_2 + 5H_2O + \text{Heat Energy}$$

Flaming combustion requires ignition energy, which can be represented by the simple relation (Van Wagner, 1977):

$$h = 460 + 26m$$

where: h = ignition energy in kJ/kg, and
m = moisture content (%) of the fuel expressed as a percentage of its oven dry weight

Ignition energy requirements increase sharply with increasing fuel moisture content. The moisture content of extinction – the maximum moisture content at which a fire will be self-sustaining and still spread – is hard to specify. Fire spreads poorly in surface litter with moisture contents greater than 30%, while conifer foliage can support fast-spreading crown fires at moisture contents of 100% or more.

After flaming combustion has ignited and burned off most of the volatile elements, the remaining carbon may burn as a solid by a surface oxidation process called glowing combustion. Flaming and glowing combustion are not discrete temporal events due to the complex mixture of wildland fuel sizes, moisture contents and arrangements but rather occur at the same time within an individual fire.

Heat Transfer

Heat transfer is the process by which heat is imparted from one body or object to another. Heat energy is transferred from burning to unburned fuels by conduction, convection, radiation and solid mass or ember transport (spotting) although conduction plays a relatively minor role in the spread of wildland fires.

Convective heat transfer through the movement of hot air usually occurs upwards in the absence of significant winds or slope (CIFFC, 2003). As a result of pressure gradients, the heated and therefore expanded parcel of air becomes buoyant and displaces, transporting heat by convection, in addition to some conduction. Such heat-induced motion in initially static fluids is called “free convection.”

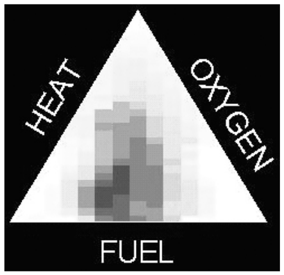
When the air mass is already in motion, conducted heat will be transported away – chiefly by fluid convection. These cases, known as “forced convection,” require a pressure gradient to drive the motion, as opposed to the gravity gradient that induces motion through buoyancy.

Radiation transfers heat in straight lines from warm surfaces to cooler surroundings (CIFFC, 2003). All materials radiate thermal energy (as a function of their temperature), which is carried by photons of light in the infrared and visible portions of the spectrum. When temperatures are uniform, the radiative flux between objects is in equilibrium and no net thermal energy is exchanged. The balance is upset when temperatures are not uniform, and thermal energy is transported from surfaces of higher to surfaces of lower temperature.

Conduction is the transfer of heat through solid matter (CIFFC, 2003). Regions with greater molecular kinetic energy pass their thermal energy to regions with less molecular kinetic energy through direct molecular collisions. Grasses, herbaceous plants and wood are poor conductors of heat and therefore this heat transfer mechanism is of nominal importance to the propagation of wildland fire.

Fire Spread

Three elements must be present and in a satisfactory combination before ignition and combustion can occur and continue. For the sake of simplicity we combine these elements into the fire triangle:



1. there must be fuel to burn,
2. there must be oxygen, and
3. there must be heat (ignition temperature) to start and maintain the combustion process. The sun is the primary source of heat in our environment and heat from the sun drives our weather.

When any one of these three factors is removed, flame production is impossible or ceases.

The three distinct yet simultaneous phases of preheating, flaming combustion and glowing combustion can be plainly seen in a spreading fire (Figure 1).

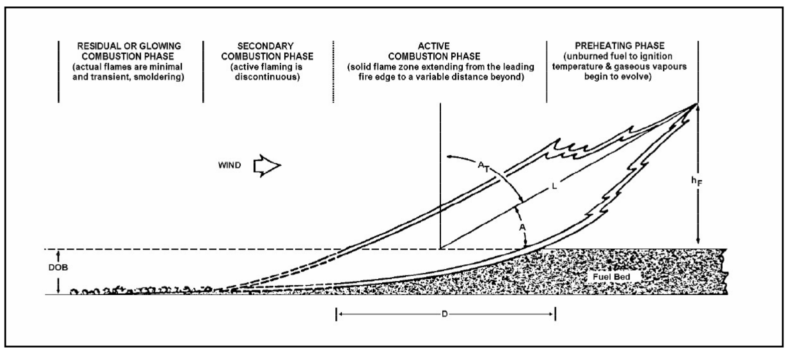


Figure 1: Cross-section of a spreading fire, where h_F = flame height, L = flame length, A = flame angle, A_T = flame tilt angle, D = flame depth and DOB = depth of burn (from Alexander, 1982).

In the initial stages of fire development, under calm conditions on level terrain, the flames draw into the centre of the flaming zone (Figure 2). After 10–15 minutes the fire develops a doughnut shape, with the flames leaning inwards. Under windy conditions, flames can lean with the wind shortly after ignition. They will also develop a lean upslope on sloping ground. After the centre area begins to burn-out the rear of the fire will spread slowly against the wind as a backing fire with low flame heights, while the front or head of the fire with the highest flame heights will run upslope or with the wind. The portion of the fire that spreads at roughly right angles to the prevailing wind or slope is known as a flank fire.

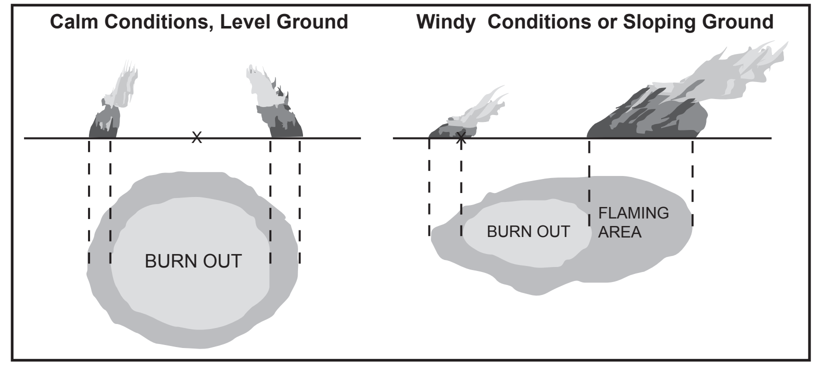


Figure 2: Initial fire spread (after Luke and McArthur, 1978).

Fire Acceleration

Fires can originate as a point or a line source. Fires originating from a point source (such as a match, campfire or lightning strike) accelerate through time until they reach a pseudo steady-state rate of spread or equilibrium rate of spread. In reality the acceleration pattern may be stepped, and this can be attributed to the progressive consumption of various fuel layers, the formation of a convection column and ultimately solid mass transport or spotting (Figure 3). Nonetheless, a more simple mathematical relationship is assumed to calculate a theoretical rate of spread with time since ignition (Figure 4). The time to reach an equilibrium rate of spread is dependent on fuel type, but in timbered fuels it takes about 30 minutes for a fire to reach its equilibrium rate of spread.

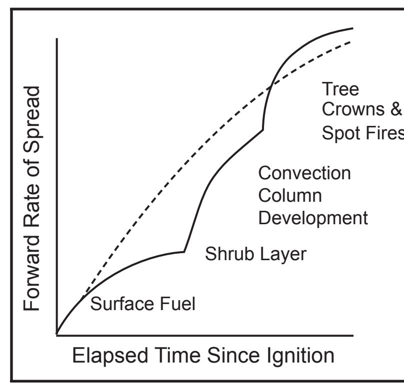


Figure 3:
Acceleration pattern of forest fires.

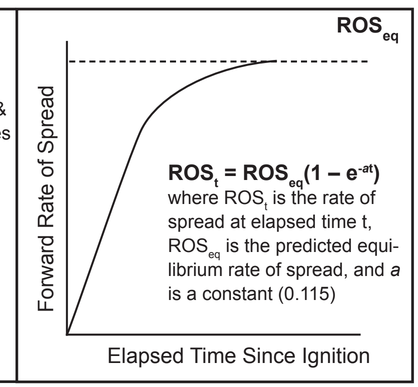


Figure 4:
Theoretical rates of spread with time.

With a reasonably constant time to reach equilibrium, it follows that the rate of acceleration will vary greatly depending on the equilibrium rate of spread, which in turn is a function of a number of factors in the fire environment such as fuel moisture, terrain and wind exposure. Fire shape and size characteristics, such as total length, maximum breadth and length-to-breadth ratio also vary with time since ignition. It is important to realize that the application of equilibrium rate of spread models during the incipient stages of a fire will over-predict spread rates, area burned and perimeter lengths.

Fires originating from line source ignitions, such as when an established flank fire becomes a head fire in response to a wind shift, are considered to reach an equilibrium rate of spread almost immediately. Therefore, a line source fire will travel further than a point source fire after the same elapsed time (Figure 5).

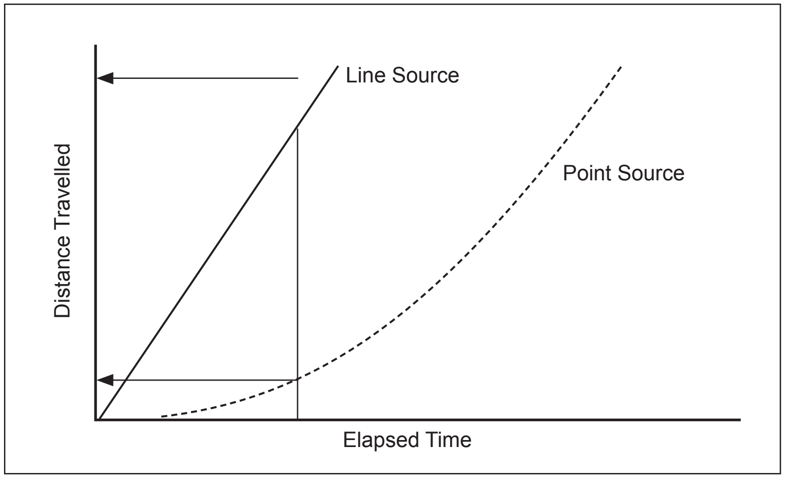


Figure 5: Point source vs. line source fire spread.

Fire Growth

Although a fire originating as a point source assumes a circular shape immediately after ignition, under the influence of a wind or slope it becomes roughly elliptical in shape (Figure 6). This feature allows the determination of fire perimeter length and fire area from simple mathematical formulas (Van Wagner, 1969).

The area of a simple ellipse is represented by πab, while the perimeter or circumference is represented by $2\pi \sqrt{(a^2 + b^2) / 2}$

Several assumptions are made in the application of simple mathematical models to predict fire growth. For example, the following apply for a wind-driven fire:

- the fire was lit at a single point source,
- the linear rate of spread at each point on the fire remains constant,
- the wind speed and direction are constant,
- the terrain is flat or its influence is negligible,
- the fuels are continuous and homogeneous, and
- man-made or natural barriers do not impede fire growth.

The relationship between the length and breadth of the ellipse is a function of

wind or slope (Figure 7). The stronger the wind or slope, the greater the length-to-breadth (L/B) ratio. To arrive at an L/B ratio for slope-driven fires, slope is converted into a wind speed equivalent. In the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group, 1992), an empirical relationship was developed to describe how L/B ratios of fires in standing timber fuel types vary with wind (Alexander, 1985). The L/B relationship for grass fuel types is based on the analysis of experimental and wildfires in Australian grasslands (Cheney, 1981).

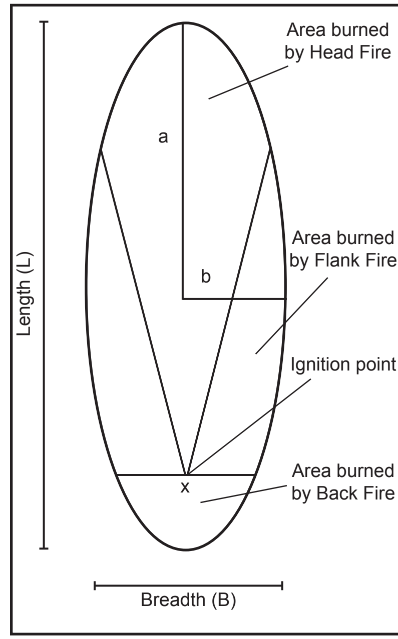


Figure 6: Simple elliptical fire growth model.

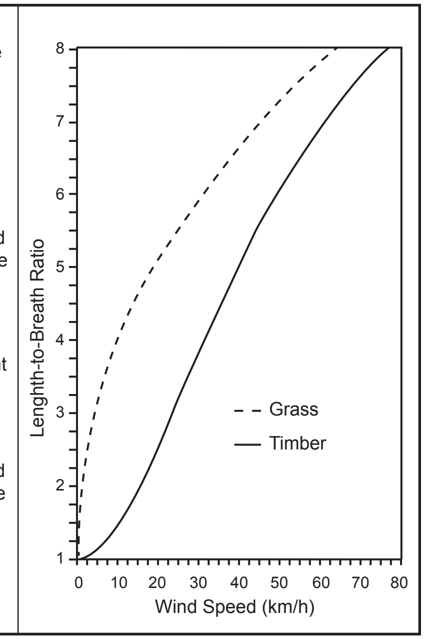


Figure 7: L/B ratio vs. wind speed.

Frontal Fire Intensity

The active front of a forest fire has three basic characteristics: 1) it spreads, 2) it consumes fuel and 3) it produces heat energy in a visible flaming combustion reaction. Fire intensity is the rate of heat energy release per unit time per unit of fire front (Byram, 1959). Intensity is calculated accordingly:

$$I = Hwr$$

where:
I = fire intensity (kW/m),
H = fuel low heat of combustion (kJ/kg),
w = weight of fuel consumed per unit area (kg/m^2) in the active flaming zone, and
r = linear rate of fire spread (m/s)

The amount of heat released per unit mass is called the heat of combustion. The high heat of combustion is the maximum heat release of dry fuel completely combusted (both flaming and glowing) to water and CO_2. The low heat of combustion (also known as the heat yield) adjusts the high heat of combustion downward to account for heat losses resulting from incomplete combustion and the presence of fuel moisture. The low heat of combustion is associated with the volatiles given off when the fuel is heated. For forest fuels, the low heat of combustion varies so little that it is usually thought of as a constant value. In Canada, 18,000 kJ/kg is commonly assumed.

If 18,000 kJ/kg is used as a standard value for the heat of combustion (H), a value of 300 allows us to use m/min rather than m/sec as the spread rate unit (since 18,000/60 = 300):

$$I \text{ (kW/m)} = 300\ w(\text{kg/m}^2)\ r \text{ (m/min)}$$

All fuel consumption is assumed to occur in the active flaming zone rather than via smouldering combustion.

Fire effects can be related to fire intensity. For example the height of lethal crown scorch (h_s), which is the browning of foliage in a tree crown caused by the heat rising above a surface fire (as a result of convection) can be related to Byram's fire intensity:

$$h_s = 0.1483\ (I)^{2/3}$$

where: h_s = lethal scorch height (m), and
I = fire intensity (kW/m)

Fire intensity is directly related to many aspects of the flame geometry of the fire front (Alexander, 1982). For instance, flame length (refer back to Figure 1) has been empirically related to fire intensity (Figure 8):

$$I = 259.833(L)^{2.174}$$

where: I = fire intensity (kW/m), and
L = flame length (m)

However, the following rule of thumb is regarded as adequate for field use:

$$I = 300(L)^2$$

Fire intensity influences the distance spot fires will be thrown and whether or not existing or prepared barriers to fire spread will be breached. Thus, fire intensity is one of the major determinants associated with the likelihood of controlling or containing a free-burning wildland fire (Hirsch *et al*. 1998) and in turn the strategy and tactics to be adopted for safe and effective fire suppression.

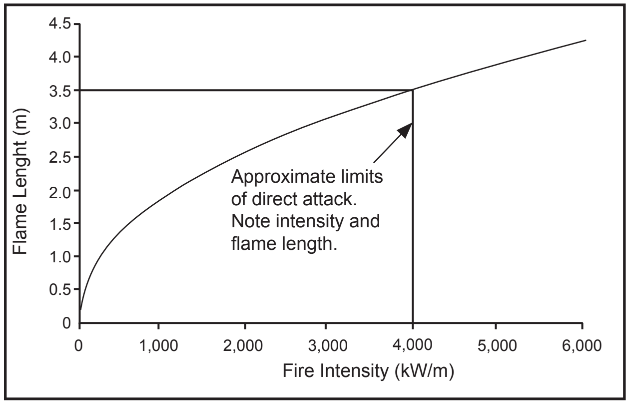


Figure 8: Flame length vs. fire intensity.

Crown Fires

The transition from a two-dimensional to a three-dimensional fire is achieved through crowning. There are three classes of crown fires according to Van Wagner (1977) and CIFFC (2003):

1. intermittent or passive crown fires are those in which trees torch sporadically as individuals, reinforcing the spread rate, but are not basically different from surface fires.
2. active crown fires are those in which a solid flame develops in the crowns, but the surface and crown phases advance as a linked unit, dependent on each other.
3. independent crown fires advance in the crowns alone.

Passive crown fires are common in open-canopied forests. Active crown fires are common in closed-canopied forests, where the fire crowns after a substantial surface fire develops and then they spread as a linked unit. A strong wind is first required to intensify the surface fire until crowning occurs – otherwise the fire will fall back to the surface if the wind subsides. Independent crown fires are rare and can only exist for short periods of time during extreme wind events and/or on very steep slopes.

The class of crown fire to be expected in a conifer stand on any given day depends on three simple properties of the crown fuel layer and two basic fire behaviour characteristics:

- initial surface fire intensity,
- foliar moisture content,
- live crown base height,
- crown bulk density, and
- rate of fire spread after crowning

Van Wagner (1977) theorised that vertical fire spread will occur in coniferous stands when the surface fire intensity (I_s) attains or exceeds a certain critical surface intensity (I_o) value (i.e. $I_s \geq I_o$):

$$I_o = [0.01 \times z \times h]^{1.5}$$

where: I_o = critical surface intensity for crown combustion (kW/m),
z = height to live crown base (m), and
h = ignition energy (kJ/kg) = 460 + 26m, where m = moisture content (%)

The critical surface fire intensity can also be derived from look-up tables. 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 ($I_s < I_o$) the fire is classified as a surface fire; if the predicted surface fire intensity is the greater ($I_s \geq I_o$), then crowning is assumed to occur.

Wildfires and suppression operations, particularly in the wildland-urban interface will generate great public impact, disruption and concern. Fire behaviour analyses are fundamental to safe and effective fire suppression efforts. It is equally important to identify situations that are not likely to experience suppression success. Through advanced notification of wildfire and suppression realities, much can be done to prepare for and mitigate some of the negative reactions that accompany fire suppression operations in settled areas.

Fire Control Strategies

With a continuous supply of heat (furnished by the combustion process itself), the ignition of additional fuel will continue as long as enough oxygen is present. Therefore, when you tackle a going fire, you should consider how best to use personnel and equipment to remove one or all of the sides of the fire triangle. Remove any one of the three sides or elements and the fire will cease to burn. Weaken any one, and the fire will weaken. Increase any one or more of the elements, and the fire will increase in intensity. Armed with this knowledge the fire fighter or prescribed burner can do much to manage a fire.

Fire Control Tactics

Good fire-fighting is therefore often a skilful combination of removing fuel, heat and oxygen. Fire control is achieved by breaking the fire triangle, in one or more ways.

Reducing heat

This may be accomplished by cooling fuels with water, fire-fighting foam, or dirt or scattering the available fuels to reduce the effects of radiant heat. Water or dirt should be applied directly to fuels in order to reduce fuel temperature. As flames are actually the burning gases liberated by heated fuels, cooler fuels release less gases and therefore have a lower probability of ignition and combustion.

Reducing air and oxygen

Water, foam, dirt and fire retardants will reduce the supply of oxygen for the combustion process. Artificial fog can be created with a special hose nozzle to smother the flaming gases by occupying the air space with millions of fine particles of water. This can also be accomplished with chemical retardants dropped from fixed-wing aircraft or helicopters or applied from the ground.

Fires burning in forest fuels are difficult to completely smother with dirt, even when it's damp, because of the porous nature of most soils. Soil can be applied to slow down a fire by reducing its intensity. Plain water is more effective but the excess quickly runs off.

Foams and fire retardants are most effective because they are long-lasting – the former is applied to the flames as a suppressant, the latter is applied adjacent to the flames to coat the unburned fuels and act as a fire barrier.

Fire-fighting foam reduces the supply of oxygen more effectively than does plain water by completely coating the fuel. The majority stays on the surface and evaporates very slowly, protecting the fuel from heat and reducing the supply of oxygen. As the surface tension of water is reduced, more water is absorbed into the fuel. This additional fuel moisture absorbs heat as it is changed to steam and driven off. Consequently, more heat is required to bring the fuel to ignition temperature and therefore the fire's effectiveness is reduced. Foam can also be used very effectively in prescribed burning operations.

Removing fuel

Removing fuel is the most common method of attacking wildfires. This method does not extinguish the fire, which continues to burn until the available fuel is consumed. Rather, the physical removal of fuel from the path of a fire prevents it from spreading past that fireline. A slow-moving ground or surface fire may be checked by a fireline constructed down to mineral soil. Several firelines and/or "burning out" of the remaining fuel between a fireline and a hot, fast-moving surface and/or crown fire may be required in order to bring it under control. By burning the available fuel in advance of the fire front, the fuel is effectively removed and therefore unavailable to the oncoming fire.

Chemical fire retardants (applied from the ground or by air) "remove" the fuel by coating it with a barrier that protects the fuel from preheating and cuts off the supply of oxygen. The available fuel thus becomes unavailable fuel, incapable of burning. Retardants are long-lasting, continuing to be effective after the water that was used as a carrier has evaporated.

The Fire Environment

Placing fire in a broader context, the fire environment is defined as "the surrounding conditions, influences and modifying forces of topography, fuel and weather that determine fire behaviour." Fire behaviour is "the manner in which fuels ignite, flame develops, and fire spreads as determined by the interaction of fuels, weather and topography" (CIFFC, 2003). The primary factors that influence fire behaviour are known as the fire behaviour triangle: fuel, weather and topography. How a given fire behaves is determined by the state of these three factors (Countryman, 1972). A change in any one will change the characteristics of the fire.

Fuel

Fuel properties such as type, arrangement, quantity or load, size distribution, continuity and moisture content are important for assessing potential fire behaviour. Forest fuels are either live or dead and with wildland fire we are primarily concerned with the dead fuels on the forest floor. Fuels are classified as

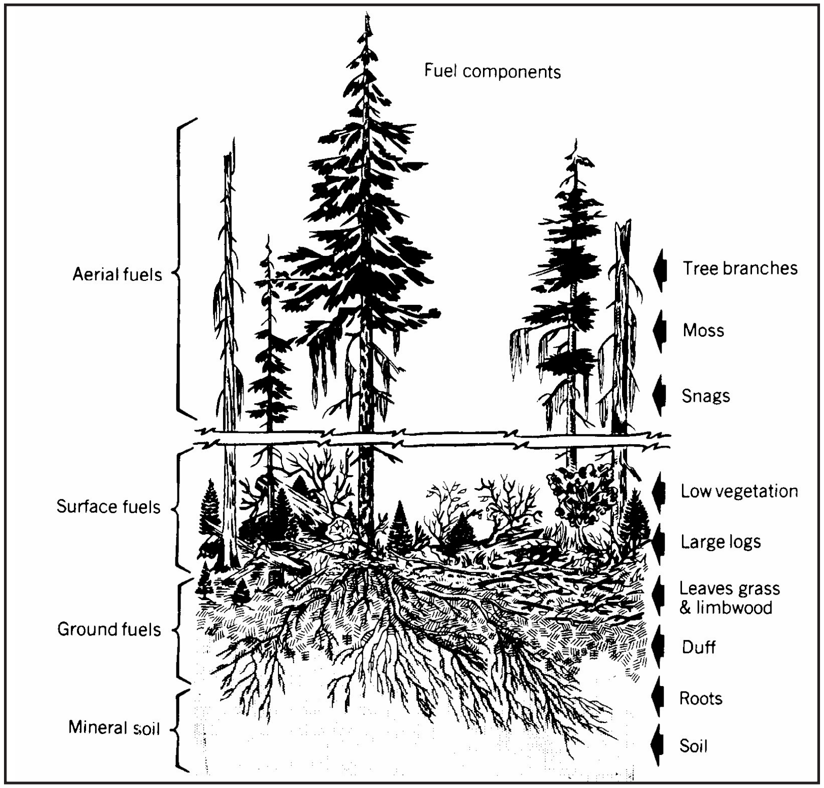


Figure 9:
Components of a forest fuel complex (from Pyne *et al.* 1996).

aerial, surface or ground fuels (see Figure 9).

A fuel complex or type is an identifiable association of fuel elements of distinctive species, form, size, arrangement and continuity that will exhibit characteristic fire behaviour under defined burning conditions. Fuel continuity describes the distribution of fuels. Uniform fuels have a contiguous distribution, whereas patchy fuels are distributed unevenly with distinct inclusions of fuels of a much lower flammability. Continuity is an important factor in fire behaviour since the distribution of fuels may enhance or limit fire spread. If fuels are uniformly distributed throughout an area, there is a high potential for a complete, rapid burn and the fire may be difficult to control.

Fuel load is the oven dry weight of combustible materials per unit area, and is usually expressed in kilograms per square metre (kg/m^2) or tonnes per hectare (t/ha). As the amount of fuel available for combustion increases, the heat produced by the fire increases. When both small and large fuel size classes are present, small fuels act as kindling for larger fuels.

Fire burns rapidly in loosely compacted fuels because individual fuel particles are readily exposed to oxygen. Compacted fuels such as piled logging debris and duff burn more slowly because of the lack of space for oxygen between fuel particles.

Moisture content is a critical factor in determining the flammability of a given fuel complex. When fuels are green or moist, fire will spread slowly if at all. When grasses are fully cured and dry, fire will spread at an extremely rapid rate. Dead fuels gain and lose moisture as they attempt to come into balance with the atmosphere that surrounds them, and the rate at which they do so depends on particle size, porosity and amount of exposed surface area.

Species, canopy cover, ecological moisture regime and exposure all influence the moisture characteristics of a given fuel complex. In North America at least, live deciduous leaves are less flammable than live conifer needles because of differences in the moisture content, surface area-to-volume ratio and chemical composition. The flammability of mixedwood forests varies with the proportion of conifer versus deciduous species, and whether or not the deciduous overstorey, grasses, herbaceous plants and shrubs in the understorey have flushed in the spring. Surface fuels beneath dense stands may dry out slowly due to less exposure to solar radiation and wind, but will also receive less precipitation than more open stands due to canopy interception.

Weather

At a more specific level than the large-scale general circulation of high and low pressure systems and the many complexities of regional weather, fire weather – the components of weather that determine fire incidence and behaviour – includes relative humidity, temperature, wind speed and direction and precipitation. Hourly, daily, weekly, monthly and yearly variations in weather conditions all exert some influence on how, when and where fires will start; how they will behave once ignited; and how difficult they will be to control.

Weather is of special importance because it may change quickly and hence fire behaviour characteristics may also change rapidly as a result. At low relative humidities, fuels dry out sooner and at higher temperatures less energy from a fire will be required to raise unburned fuels to their ignition points. Temperature and relative humidity are inversely related such that at higher temperatures, relative humidities are lower.

Wind speed and direction exert strong influences on fire behaviour, along with fuel moisture and slope. Wind supplies oxygen to the combustion process, physically moves heat and fire and increases evaporation rates. If fuel and topography remain constant, wind is the prime determinant of the direction of fire spread, rate of spread, fire size and fire shape. Large fires often create their own very strong local winds, which add more complexity to predicting fire behaviour.

General winds result from global-scale variations in temperature and air pressure, while local winds are a product of terrain and local differences in heating and cooling. In mountainous terrain, winds flow upslope during the day in response to heating and downslope at night in response to cooling. The speed and daily regime of these winds varies with aspect. Differential heating and cooling of the ocean and adjacent land masses give rise to sea breezes blowing onshore during the day and land breezes blowing offshore during the night. After the passage of a cold front, local winds will change direction and may increase in speed. These relationships can aid or hinder wildfire control and prescribed burning operations.

In addition to the effects of relative humidity and temperature, the moisture content of fuels is determined by precipitation, primarily as rainfall and dew. The timing, duration and amount of precipitation received during the fire season helps to determine fire incidence and on a shorter time frame influences fire behaviour and spread.

Historically, the largest forest fires in North America occurred under extreme burning conditions when extended fire season drought created very dry fuels and fires accompanied by high temperatures, low relative humidities and/or strong winds lead to rapid rates of spread. Fires have also occurred outside the usual fire season, notably after unusual winter drought and early spring drying. Some fires burning under extreme conditions do not moderate their behaviour at night, thus adding to fire control difficulties. Large wildfires burning under extreme conditions are virtually impossible to control, in which case specific resources or values at risk are defended until weather conditions change and rain and/or snow events extinguish the entire wildfire.

Topography

Elevation, slope, aspect and terrain are highly variable over the landscape, changing especially quickly in mountainous areas. Elevation influences climatic regimes and therefore the total annual precipitation, the proportion of precipitation falling as snow, snow melt rates, and vegetation greenup and curing dates. Elevation is directly linked to the fuel complex and length of the fire season.

Slope aspect and angle are large determinants of the amount of solar energy received by a site and, in combination with other factors, influence the vegetation type which is present, therefore the fuel complex, and ultimately the fire regime. For example, a south aspect can be covered with an open grass – shrub mixture while the north aspect at the same elevation of the same hill or mountain may support a closed coniferous forest. Each fuel complex has different ignition probabilities and fire behaviour potentials.

Because of the direction of travel of the sun through the sky, East-facing slopes heat up first, reaching their highest temperature before all other aspects. South-facing slopes reach their maximum temperature about two hours later and it can be higher than that experienced on an East-facing slope. West-facing slopes reach their maximum temperature still later, and it can be higher than those of both east- and south-facing slopes. North-facing slopes have a lower range of temperatures through the day and the peak daily temperature is lower than those for all other aspects. The specifics of these relationships vary with cloud cover, slope, time of day, time of year and latitude (Countryman, 1966; Pyne *et al.* 1996).

Because local air temperatures and relative humidities are affected by these aspect relationships, variations in fuel temperature and moisture content result. Slope position also affects the daily temperature and humidity regimes, thus adding another determinant of fuel condition and availability. As a wildfire burns through different elevations and different aspects, its behaviour varies as it encounters different fuel complexes in a variety of conditions. The behaviour of a fire at a particular location will change as solar insolation, air temperatures and relative humidities change through the day.

Slope angle affects the ability of a fire to heat adjacent unburned fuels. Fires spreading upslope are more effective at heating by radiation and convection and behave as if they are running with the wind. Fires backing down a slope behave as if they are burning into the wind, although burning woody debris rolling downslope can encourage more rapid fire spread at lower elevations.

Larger terrain features also affect fire behaviour and spread. Weather conditions may be more variable in mountainous terrain, especially with respect to wind speed and direction. Fires on one side of a steep ravine direct radiative heat to the opposite side and bring those fuels to ignition sooner. In a box canyon, or chimney, both radiative and upslope heating, aided by unstable air, can lead to extreme fire behaviour. On the other hand, terrain features such as bare rock, talus slopes, lakes and rivers, riparian areas, roads and trails can act as a barrier to fire spread and serve to moderate fire behaviour.

The Canadian Forest Fire Danger Rating System[1]

Forest fire danger rating research in Canada was initiated by the federal government in 1925. Five different fire danger rating systems have been developed since that time, each with increasing applicability across Canada. The approach built on previous danger rating systems and used field experiments and extensive empirical analysis.

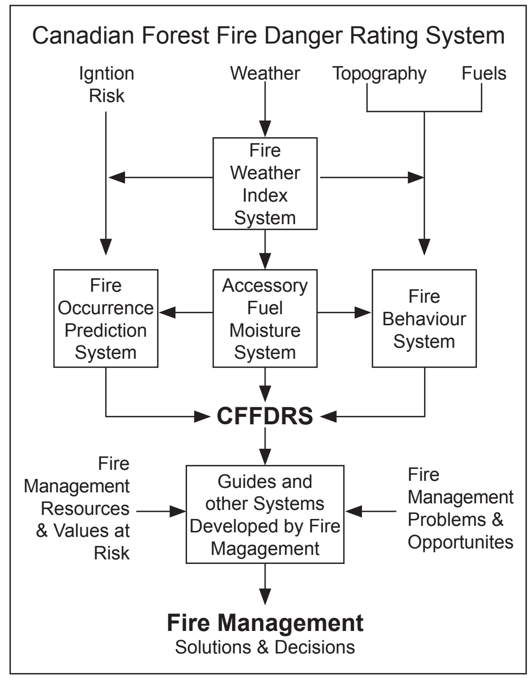


Figure 10:
Simplified CFFDRS structure diagram illustrating the linkage to fire management actions.

The current system, the Canadian Forest Fire Danger Rating System (CFFDRS), consists of two major subsystems (Figure 10). The Canadian Forest Fire Weather Index (FWI) System provides numerical ratings of relative fire potential for a standard fuel type on level terrain. The Canadian Forest Fire Behavior System accounts for variability in fire behaviour amongst fuel types for a given slope steepness based on certain FWI System components.

The Fire Weather Index System

The FWI System assesses relative fire potential based solely on weather observations. The six components individually and collectively account

[1] Much of the text in this section has been adapted from Van Nest and Alexander (1999) with kind permission of the authors.

for the effects of fuel moisture and wind on ignition potential and probable fire behaviour in the form of relative numerical ratings (Figure 11). Three fuel moisture codes reflect the fuel moisture content of fine surface litter (Fine Fuel Moisture Code, FFMC); loosely compacted duff of moderate depth (Duff Moisture Code, DMC); and deep compact organic matter (Drought Code, DC), respectively. The codes are dynamic bookkeeping systems that account for the effects of each day's precipitation and drying.

The fuel moisture codes plus wind are linked in pairs to form two intermediate and one final index of fire behaviour. The Initial Spread Index (ISI) combines the effects of wind and fine fuel moisture content (FFMC). It represents a numerical

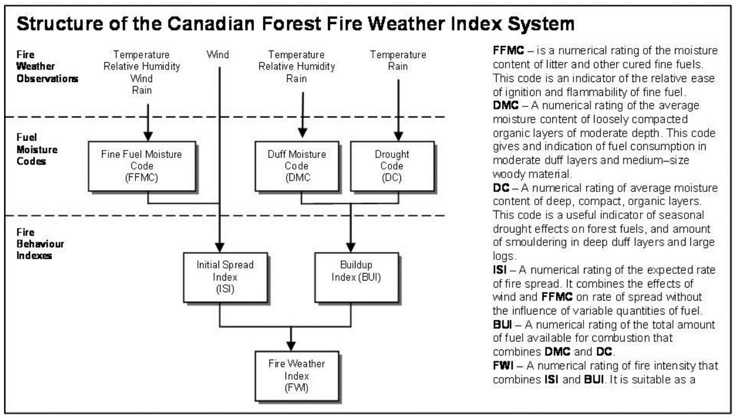


Figure 11:
Structure of the Canadian Forest Fire Weather Index System and component definitions.

rating of fire spread rate, without the influence of variable fuel quantity. The Buildup Index (BUI, based on the DMC and DC) represents a measure of the total fuel available for combustion.

The Fire Weather Index (FWI) component itself combines the ISI and BUI to indicate the potential intensity of a fire on level terrain in a stand of mature pine. Because jack pine and lodgepole pine forests form a more or less continuous band across Canada, the concept of a standardised fuel type is reasonable.

FWI System components depend solely on daily measurements of dry-bulb temperature, relative humidity, a 10-metre height open wind speed and 24-hour accumulated precipitation, recorded at noon local standard time. Because calculation of the components depends solely on weather readings, they can be calculated from forecast weather to yield a fire danger forecast.

The FWI itself is a good indicator of several aspects of fire activity and is best used as a measure of general fire danger for administrative purposes. However, it is impossible to communicate a complete picture of daily fire potential in a single number. The subsidiary components also need to be examined for proper interpretation of past and current weather effects on fuel flammability.

Each component of the FWI System conveys direct information about certain

aspects of wildland fire potential. For example, the FFMC is a useful indicator of human-caused ignition probability, as is the DMC for lightning-caused ignitions. The DC and the BUI are excellent indicators of smouldering combustion or fire persistence in deep compact organic layers and hence of mop-up difficulty.

The Fire Behaviour Prediction System

The relative numerical values of the FWI System components have different meanings in different fuel types because the system was developed to rate relative fire potential in a generalised standard fuel type. The FBP System (Figure 12) addresses the variation in fire behaviour with fuel type, in quantitative terms.

The technical derivation of the FBP System rests on a sound scientific basis developed from real-world observation and measurement of numerous

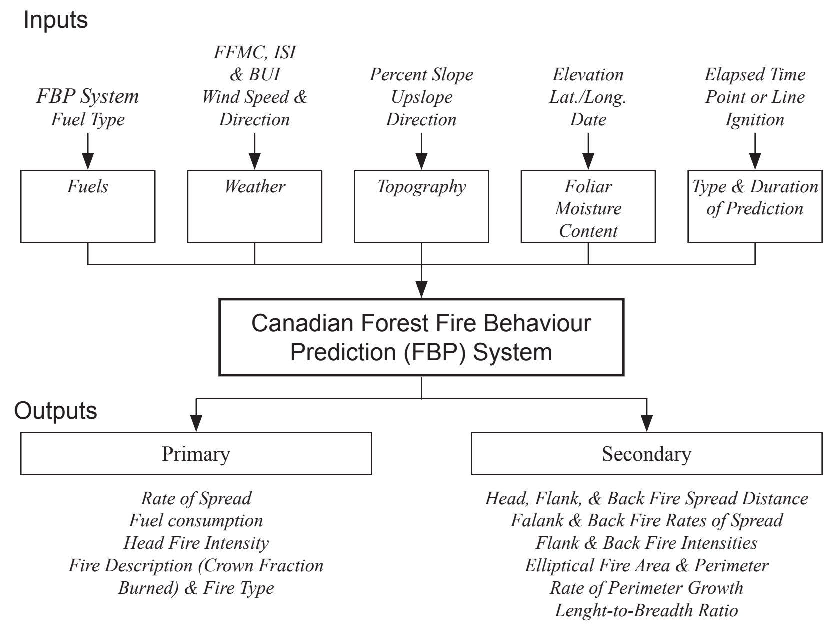


Figure 12:
Structure of the Canadian Forest Fire Behaviour Prediction System.

experimental fires, coupled with many well-documented wildfires and operational prescribed fires, correlated against the weather-based fire danger indices of the FWI System or weather parameters for discrete fuel types. The FBP System is unique in that it incorporates the most extensive crown fire data set available anywhere.

The FBP System allows the user to predict the rate of spread (m/min), fuel consumption (kg/m^2) and intensity (kW/m) at the head, back or flanks of fires that are still accelerating or which have reached a steady-state condition with their environment. These characteristics are determined by the prevailing fire weather severity (based on wind velocity and certain FWI System components), fuel type, slope steepness, geographical location, elevation and calendar date. A general description of the type of fire is also given (for instance, surface fire, intermittent crowning or continuous crowning). A simple elliptical fire growth model is employed in estimating the size and shape of fires originating from a single ignition source as opposed to an established line of fire.

The FBP System's operation is based on a small number of readily available inputs. At present, 16 major Canadian benchmark fuel types are recognised in the system, a reflection of the empirical fire behaviour data available in Canada (Table 1).

Table 1: List of Canadian Forest Fire Behaviour Prediction 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

Incorporation of the best available information on forest fire behaviour in Canada into the FBP System gives fire managers the ability to predict certain fire behaviour characteristics with reasonable assurance, for a wide range of burning conditions.

For field use in predicting fire behaviour, the FBP System is available as tables or a computer program. The table format (Taylor *et al.* 1997) provides a simplified method for assessing wildland fire behaviour potential and making first approximations of FBP System outputs. Quantitative estimates of head fire spread rate; fire intensity; type of fire; and elliptical fire area, perimeter, and perimeter growth rate are provided for sixteen discrete fuel types within five broad groupings (coniferous, deciduous and mixedwood forests; logging slash; and grass).

Computer-based programs which provide all the outputs available from the FBP System range from FBP calculators such as the RemSoft DOS-based FBP93, Windows based FBP97 and BEHAVE programs to more sophisticated systems linked to GIS systems. The choice of computer program depends on the fire prediction objectives, computing capability and ability to provide sufficient data to run the computer application.

Regardless of the application, operational experience has shown that the underlying FBP system will provide reasonable predictions provided that the user understands the assumptions associated with the FBP System and that reasonably reliable data are used as input for the fire behaviour evaluation process. As with all prediction systems, the FBP System is intended to assist in decision-making, and is not a substitute for experience, sound judgement or observation of actual fire behaviour.

Applications

The CFFDRS remains one of the few nationally implemented fire danger rating systems in the world. Daily calculations of system components are made from data recorded at more than one thousand weather stations across Canada. Some current uses of the danger rating system include:

- fire behaviour training,
- prevention planning (e.g. informing the public of impending fire danger, regulating access and risk associated with public and industrial forest use),
- preparedness planning (level of readiness and pre-positioning of suppression resources),
- detection planning (e.g. lookout manning and aircraft patrol routing),
- initial attack dispatching,
- suppression tactics and strategies on active wildfires,
- escaped fire situation analysis, and
- prescribed fire planning and execution.

The CFFDRS is also being used increasingly by other wildland fire researchers and environmental scientists for applications ranging from fire suppression effectiveness and fire growth modelling to analyses of fire regimes and potential impacts of climate change.

Decision Support Systems

Fire management information systems exploit advances in computerized information handling, automatic remote collection and transmission of fire weather data, and automatic lightning detection and location networks. The value of such technologies depends, in part, on the CFFDRS to integrate the information and provide fire managers with near-real-time fire occurrence and behaviour prediction capability.

Conceptually, the CFFDRS deals with the prediction of fire potential from point-source weather measurement (i.e. a single fire weather network station). The system deals primarily with day-to-day variations in the weather, but will accommodate variations through the day as well. The system does not account for spatial variation in weather elements between points of measurement; such interpolation must be handled by models and guidelines external to the CFFDRS.

In operational practice, fire weather and fire danger forecasting procedures have been devised to integrate point-source measurement of the system's components over time and space. Spatial variation in fuels and terrain is a fire management information problem not easily handled by a fire danger rating system unless it can be linked to a computer-based geographic information system which stores, updates and displays land base information in ways directly usable by the fire manager. Geographic information systems for fire management are in use in nearly all regions of Canada.

Further information on the CFFDRS is available on the Internet at:

http://fire.cfs.nrcan.gc.ca/research/environment/cffdrs/cffdrs_e.htm

Fire Growth

Forest fire spread is not a rectilinear phenomenon; rather a fire expands in all directions, but not necessarily at the same rate. Suppression strategies must consider the rate of advance of a fire in all directions, as well as the intensity at various locations on the front.

Estimates of the perimeter length of a fire are vital for planning and assessing containment objectives. Estimates of the perimeter length of a fire at regular time intervals are used in conjunction with the size of fire fighting resources, and fireline construction rates, to determine if containment objectives can be attained with the available suppression resources.

Fire appreciation must consider priorities for the protection of life, community, commercial and environmental values. To this end, the estimated position of a fire front at various time intervals is drawn or plotted on a map, using procedures to convert spread rates into travel distances at a given map scale.

If fuel, weather and terrain conditions are continuous and homogeneous, fire mapping is a reasonably straightforward exercise using the CFFDRS. This situation occurs rarely, if ever, and therefore projecting fire growth manually is a complicated and time-consuming process. Weather forecasts are amended or do not reflect the actual situation in the field, and projections must be revised. A fire that burns for a number of days is apt to undergo considerable changes in wind velocity and other weather conditions, travels through a variety of topographic and fuel conditions, and encounters a number of natural and constructed barriers (Alexander, 1985).

Fire Modelling

A computer-assisted model, or simulation, is used to translate fire growth under homogeneous conditions into fire growth given varying conditions of fuel and terrain, under weather that varies over both space and time. The output from computer-assisted fire growth models can be applied to optimise the deployment of suppression resources; help allocate initial attack priorities given multiple ignitions; support control strategies and fireline techniques; facilitate briefing the media and the general public; or improve prescribed burn planning (Beck, 1988; Andrews, 1989).

Most of the systems developed to predict and map fire growth are largely academic exercises of event reconstruction. Few have been used operationally during an emergency situation. Canada's operational fire growth model is known as Prometheus (Tymstra, 2002) (http://www.firegrowthmodel.com) and fire behaviour analysts in the United States use FARSITE (Finney, 2004) (http://farsite.org/). These are fairly complicated systems that require GIS support and their outputs are unlikely to be interpreted correctly without specialised training in fire behaviour prediction and operational experience in fire management.

Even with a comprehensive fire behaviour prediction system and valid models to predict fire growth, fire management agencies across Canada are just preparing to use these systems operationally. Most fire management organisations do not have ready access to the geographic information that is required to predict fire growth. Although terrain information is readily available, fire growth models require details on fuels (Hawkes *et al.* 1995) and weather, which are not obtained easily from typical forest inventories or existing fire weather systems. Detailed spatial and temporal data, particularly for wind speed and direction, must be generated from mesoscale weather models and applied to forecast fire growth if credible results are to be expected, especially in complex terrain.

Smoke Production

Smoke is a by-product of incomplete or inefficient combustion. The only way to eliminate smoke is quick and complete fire extinguishment, which is not always possible. While wildfire smoke cannot be eliminated, its production and dispersal can be predicted reasonably well.

The amount of smoke produced by a given fire is a function of the volume of available fuel and the efficiency of the combustion process. While a conflagration level wildfire produces large volumes of smoke as a result of the area and amount of fuel being consumed, flaming combustion is still more efficient than smouldering combustion. As such, the factors influencing fire intensity and fuel consumption also influence smoke production. These include the time of year, time of day, the nature of the fuel complex, fuel moisture status, relative humidity, wind, slope and aspect.

Smoke Dispersion

Accurate prediction of the when, where and extent of wildfire smoke permits fire managers to be proactive and furthers fire fighter confidence and public credibility in the fire management organization. The transfer of pollutants through the atmosphere depends almost entirely on the fire environment and concentrations decrease either by vertical removal processes (settling, deposition and scavenging) or dispersion. In the absence of precipitation, the influence of vertical processes is assumed to be negligible.

Pollutant and smoke concentrations are proportional to the product of the depth of the turbulently-mixed layer and the speed of the wind within that layer:

$$V\ (m^2/s) = \text{wind speed}\ (m/s) \times \text{mixing height}\ (m)$$

Where V, the product of the wind speed (m/s) and mixing height (m), is the computed Ventilation, which ranges from about 0 to 15,000 m^2/s. The depth of the mixing layer can be estimated from vertical temperature profiles observed at nearby upper air reporting stations and the values of surface temperatures in the area.

Next, the computed Ventilation (V) is scaled to produce a Ventilation Index (VI), which varies from 0 to 100. The higher the VI, the more effective the smoke dispersion:

$$VI = 9 + 0.02 \times V - 1.7 \times 10^{-6} \times V2 + 6.8 \times 10^{-11} \times V3$$

Environment Canada issues Smoke Control Forecasts, which provide Ventilation Indices, temperatures, mixing heights and wind speeds for both upcoming mornings and afternoons. Spot indices are based on the aspect and elevations of the sites. Heights of inversions and breakthrough temperatures are also given, along

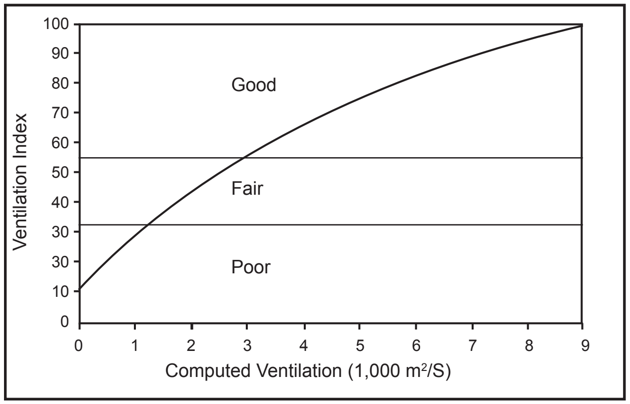


Figure 13: Ventilation Index versus Computed Ventilation.

with a four-day forecast of general venting conditions. These forecasts assist fire suppression and prescribed burning operations by indicating the extent to which smoke will or will not be dispersed. The factors that influence atmospheric stability also influence smoke dispersion. Smoke concentrations in a stable air mass will be higher than those in an unstable air mass due to differences in mixing depth (other conditions being equal). Items of special concern are diurnal variations, inversions, topography and fire intensity.

Health Effects

Carbon monoxide (CO) is given off during incomplete combustion. Unlike most by-products of smoke it is tasteless, invisible and odourless. Haemoglobin's affinity for CO is about 210 times what it is for oxygen and so CO blocks haemoglobin's ability to deliver oxygen throughout the body. As the level of CO in the bloodstream increases, the effects become more and more severe. Behaviour and performance are initially affected, followed by the central nervous system and vision. At higher CO concentrations, cardiac and pulmonary changes occur and eventually headaches and fatigue lead to coma, respiratory failure and death.

Wildland fire fighters should be aware of the hazards associated with working in heavy concentrations of smoke for extended periods. Investigations by the North Carolina Division of Forestry found that smouldering combustion produces high

levels of CO. Be alert for complaints of headaches, fatigue or vision problems while on extended fire attack duties.

In addition to CO emissions, wildfire smoke contains potentially hazardous concentrations of particulate matter. Wood smoke particulates are relatively small – 70% are less than 2.5 microns in diameter, 20% are between 2.5 and 10 microns and 10% are greater than 10 microns. Their size distribution varies greatly, depending on the fire's rate of energy release. For example, particulate emissions for high intensity fires have a bimodal size distribution with peaks near 0.3 microns and > 35 microns. For less intense fires, particulate emissions have a normal distribution with the peak near 0.3 microns. Larger particulates in the plumes of high intensity fires are not products of combustion, but rather products of mechanical mixing (turbulence).

The reduction of visibility due to wildfire smoke can have widespread impacts which not only affect the fire suppression operation but also those of other public service organisations, along with public safety. Visibility reduction reduces the effectiveness of fire detection, impairs intelligence gathering, disorients ground forces, compromises the safety and effectiveness of airtanker operations and eventually grounds fire suppression aircraft.

Public health and safety may be compromised by road and airport closures, as well as increased risk during evacuations. Road and airport closures have economic impacts, especially upon tourism. While it is not possible to prevent smoke from wildfires, advanced notice allows for implementation of contingency plans. In addition to concerns about the destructive aspects of wildfires there are potential health problems for people with respiratory conditions as small particulates are carried deep into the lungs.

Fire Prevention

The Ministry of Forests has recorded data about the cause, size and costs of wildfires almost since the inception of fire suppression in this province. These data are analyzed frequently to determine trends in fire causes and locations. Fire prevention strategies are based on these analyses and annual comparisons determine if fire prevention measures are effective.

The prevention of human-caused wildfires is an important function of fire management. Significant cost savings and reduction of undesirable environmental and social impacts result when unwanted wildfires are reduced or eliminated. Preventative measures are applied to the general public and various industrial activities carried out in the forest through legislation which identifies the authority and responsibility to address fire prevention, control and use.

Activity management modifies or restricts human activities in terms of functions, location and timing in relation to the degree of fire hazard and risk. A number of vehicles exist:

1. Fire season: the period from April 1st to October 31st is defined as the official fire season during which most preventative conditions apply.
2. Forest use restrictions: legislation provides for a designated Forest Official to restrict public access and various forest-based industrial activities when fire hazard conditions warrant.

3. Open burning: legislation recognizes the need for the use and application of fire but provisions are made for the restriction, prohibition or extinguishment of open burning when conditions warrant.

Open burning is broken into four broad sections: open fires for cooking, warmth and ceremony; small open fires; large open fires and resource management open fires. A burning reference number is required for larger burns throughout the year. The conditions under which each type of burning may be conducted are specified within the *Forest Fire Prevention and Suppression Regulation*. A number of precautions need to be taken and specific equipment and human resources are required to prevent fires from escaping. All open burns are subject to regulations governing smoke management.

More information on open burning is available at the MoF Protection web site at http://www.for.gov.bc.ca/protect/burning.

Fuel Management

Since 1825, devastating wildfires have taken many lives and destroyed entire communities all over North America as a consequence of failures to manage fuel. Fuel accumulations significantly impact the type and nature of wildfires which threaten settlements and improvements in what is termed the wildland-urban interface.

Controlled burning in BC to reduce fuel levels after forest harvesting dates from the early 1900s, especially on the south coast. In the past two decades, management for biodiversity values (including coarse woody debris retention), public opposition to wildland smoke, and improved harvesting and site preparation technologies have significantly reduced the amount of prescribed burning for silvicultural site preparation and hazard reduction. These have been the most common applications for prescribed fire in this province.

Piling and burning of waste wood, rather than broadcast burning, became more popular in the late 1980s. However, in recent years, roughly five times as much Crown land has been treated by mechanical silvicultural site preparation techniques than with prescribed fire. Prescribed burning is also used to improve wildlife habitat, safeguard communities in the wildland-urban interface and restore fire-maintained ecosystems.

Current legislation and regulations require an individual who engages in specified timber harvesting activities to assess the resulting fire hazard. They also enable a designated Forest Official to assess the fire hazard on Crown or private land and order disposal of the hazard if deemed necessary.

Future forest managers will face a number of problems if fuel accumulation continues in some ecosystems. Fires will be more intense and more difficult to manage, forest health problems will continue to escalate, and biodiversity will be reduced as fire-dependent species of plants and animals become scarcer. A lack of strategies to address the accumulation of forest fuels will result in a significant threat to forest resources and rural structures. Future land managers and planners must understand the natural role of fire in the ecosystem and find ways to mimic or apply fire in order to solve these problems.

Fire Detection

The goal of BC's wildfire detection program is to find fires when they are small enough to allow quick initial attack and effective control. Minimizing the lag time between ignition and detection, relative to fire spread rates, is crucial to achieving the current initial attack success rate – containment of 94% of all unwanted wildfires at less than 4 hectares.

There are a number of key components to wildfire detection:

1. Public detection: as the single largest detection group, the public is responsible for reporting approximately 46% of wildfires via a toll-free phone number.
2. Ground patrols: Ministry of Forests' Fire Wardens patrol high risk areas, such as forest recreation sites, during periods of high use and increased fire hazard. These patrols detect approximately 3% of all wildfires but also serve a prevention function by informing the public about the careful use of fire relative to the fire danger. Forest industry personnel may also inspect active forest harvesting areas for potential fire starts, primarily from operating machinery.
3. Aircraft patrols: fixed-wing aircraft were first used in 1921 and usually followed a set patrol route. Using information gathered by the lightning detection and location system, patrol routes now cover specific areas with increased effectiveness and efficiency. Aircraft consistently patrol areas prone to fire activity and detection problems. Aerial detection finds approximately 20% of all wildfires.
4. Lookouts: once considered the mainstay of the detection system, lookouts now play a minor role – detecting approximately 5% of wildfires. Lookouts are still utilized during periods of high hazard where no other detection mechanism is available. A number of lookouts, located in critical or isolated locations, continue to observe areas of high risk and/or high values.
5. Lightning location: the current lightning detection and location system was first used in 1980. Detectors at a number of sites discriminate between cloud-to-ground lightning, cloud-to-cloud lightning and electromagnetic noise. Data are transmitted to a central position analyzer, which calculates the time and location of each lightning strike for display on computer-generated maps at fire control centres throughout the province. The system cannot predict where specific lightning-caused fires will occur but contributes data to computer models that carry out that task.
6. Infrared scanning: hand-held and aerial devices are used extensively to detect heat sources and reduce the number of wildfires resulting from "hangover" landing and pile burns. These fires smoulder for long periods and are undetectable by other means. The result of this technology has been a significant reduction in the area burned, timber damage and fire suppression costs.

Fire Reporting

Reporting wildfires is a final crucial step in the fire detection process. A centralized fire reporting centre gathers information through the 1-800-663-5555 toll-free number and electronically transfers that information to the responding fire centre. Forest industry personnel and aircraft flight services also report wildfires through their respective communication networks.

It is important to collect and report accurate information about fire size, location and behaviour; weather conditions; fuel types; topography; access; and property and resource values. These data are entered into a computer and transferred to the appropriate fire centre, where personnel determine the appropriate response for each wildfire.

Fire Fighter Safety

Fighting fire is a dangerous occupation. The first responsibility of fire fighters is to prevent injury to themselves and others. Safety is of paramount importance, cannot be over-emphasized and must not be compromised – even if homes and commercial values are threatened. Homes should be insured and can be rebuilt. The natural environment is resilient and will recover from wildfire, people cannot.

The fire crew boss looks after the crew's safety and welfare 24 hours a day and ensures they are productive. The crew boss must be alert and know where the fire is at all times and what it is doing, as well as the location of all crew members. An up-to-the-minute escape route must be identified. Know what danger signs to look for, including crew fatigue, and know when to take a break. The crew boss must think before acting and then act decisively, assigning the most experienced crew members to key positions and keeping the crew informed of all activity and progress.

Fire fighters should always work by these rules: stay with the crew boss and follow all instructions; stay at least 3 metres apart while working or hiking; and watch where you're going. Never walk near, or work beneath, a burning dead tree or trees with fire-weakened root systems. Watch for rolling rocks or debris on steep slopes and never work below a bulldozer or another crew. If you see something dangerous, shout out and warn your crewmembers. Let everyone know if the fire jumps the fire guard. Follow the WATCH OUT guidelines:

Weather	dominates fire behaviour, so keep informed
Action	must be based on current and expected fire behaviour
Try out	at least two safe escape routes
Communications	should be maintained with crew, boss and adjoining forces
Hazards	watch for grass fuels, chimneys and snags
Observe	changes in wind direction, velocity, and clouds
Understand	your instructions and make sure yours are understood
Think	clearly, be alert, and act decisively before your situation becomes critical

The fire environment is such that some fires are impossible to control. Extreme fire behaviour may occur, for example, when a fire encounters plentiful and dry fuels or when wind speeds increase with the passage of a cold front. The safety of the crew is paramount, and the crew boss must expect the unexpected.

Two escape routes and a safety zone must be established before a fire is attacked. Provided that standing dead and burned trees do not present a hazard, a burned-over area free of other fuels can be used as a safety zone. Heavy equipment can construct safety zones at specified intervals along the fireguard. Escape routes and safety zones must be confirmed or re-established on a regular basis and all crew members kept informed.

Air support is a valuable tool for the fire fighter, but it brings dangers to the fireline. The bird-dog aircraft makes at least one pass before an air tanker drop to provide a warning. Fire fighters on the ground must keep out of the drop area and clear out any branches or dead trees that could be an overhead hazard.

Community Safety

BC has one of the fastest-growing rural populations in North America. Many people are leaving the city to live in forested areas. But living in the wildland-urban interface, the area where forests and communities meet, means living with fire and yet residents are rarely prepared for the serious wildfires that destroy homes, property and lives.

To mitigate the impacts of wildfire, action must be taken well in advance. A home's chances of survival are greatly improved through careful location, design and maintenance. Homes should be sited where potential fire behaviour is minimized and also be surrounded by a fuel-free zone. Appropriate landscaping reduces the fire hazard, with deciduous trees being better than conifers. The forest beyond the fuel-free zone, up to several hundred metres away, should be evaluated and treated if necessary. Fire intensity is reduced where less fuel is available.

Roofs can be made of fire-resistant material rather than highly-flammable shakes or shingles. Deck supports should be made of non-combustible materials or encased. Deck surfaces should also be non-combustible. Exterior siding, windows and vents are probably more vulnerable than the roof to intense heat. When a fire is close enough, its heat and flames directly threaten the home, causing combustible materials to ignite. The intense heat of a wildfire can also melt plastics, including vinyl siding, and break windows.

Burning embers or firebrands can be carried by the wind for several kilometres to land on roofs or collect in low points around a house. Embers can be drawn inside if there are open eaves or unscreened windows and vents. Firebrands can lodge in the exterior siding and structure loss is likely unless the siding is fire-resistant. Windows should be double-paned and be at least 10 metres away from trees or flammable shrubs

Every home should have a clearly-visible address sign, adequate road access for emergency response vehicles and provide for fire fighter safety zones and escape routes. Homeowners must ensure that the roof and gutters are free of leaves, needles and other debris; have fire-fighting tools on hand; have a water hose that is able to reach all exterior walls, and the roof; and have a home and area evacuation plan.

Rural developments often lack building restrictions, provisions for fire protection or roads suitable for the movement of heavy fire-fighting equipment. Residents of rural or forested areas play a key role in wildfire protection and are responsible for their buildings and property. The BC Forest Service is concerned about residents living in forested areas and will take action to prevent loss of life or the spread of fire to or from structures. However, Forest Service personnel are not equipped or trained to fight structure fires.

Effective wildfire prevention and control in the wildland-urban interface requires co-operation between municipal and rural fire departments, the Forest Service, developers and homeowners. The insurance industry is becoming more and more proactive due to multi-million dollar insurance claims resulting from fires in the wildland-urban interface.

Legislation, Policy and Procedures

The *Ministry of Forests Act*

The *Ministry of Forests Act* mandates the Ministry of Forests to "encourage maximum productivity of the forest and range resources in British Columbia" and to "manage, protect and conserve the forest and range resources of the government, having regard to the immediate and long term economic and social benefits they may confer on British Columbia" (RSBC, 1996). This act gives broad direction to the ministry's programs and forms the environmental and socio-economic bases for protection of the natural resources from the unwanted effects of wildfires.

The *Forest Practices Code of British Columbia Act*

The *Forest Practices Code of British Columbia Act* was passed in July 1994 and took effect on June 15, 1995 (SBC, 1994). The act is the legal umbrella that authorizes all of the components of the Forest Practices Code. It provides the mandatory requirements for forest practices, sets out enforcement and penalty provisions and outlines supporting procedures and administrative bodies such as the Forest Practices Board and the Forest Appeals Board.

The *Forest Practices Code of British Columbia Act* allows for standards which expand on regulatory requirements. Supporting the act, regulations and standards, but not embodied in legislation, are guidebooks. Their purpose is to help users exercise their professional judgement to develop site-specific strategies and prescriptions. They provide recommended procedures, processes and results for forest practices. These provisions become enforceable only when they are included in plans, prescriptions or contracts or when incorporated by reference in the regulations.

Part 5 of the *Forest Practices Code of British Columbia Act* outlines protection of forest resources. Sections 75 through 95 cover fire use, hazard assessment and responsibilities, fire suppression, duty to report a forest fire, government jurisdiction and compensation. Many or most of the fire-related provisions of this act and its regulations were formerly part of the *Forest Act* and its regulations.

Forest Fire Prevention and Suppression Regulation

The *Forest Fire Prevention and Suppression Regulation* is one of 20 regulations established under the *Forest Practices Code of British Columbia Act*. This regulation requires every person working in or within 1 kilometre of a forest to provide suitable fire-fighting equipment. The kind and amount of equipment varies with the type of activity being conducted, the time of year the activity is performed and the number of persons employed at the worksite of the activity.

Fire regulations have undergone a number of significant changes over the years. These changes have included combining the *Fire Precautions in Relation to Railways*, *Forest Fire Prevention Regulation, Snags and Slash Disposal and the Campfire Regulation*. The *Forest Fire Prevention and Suppression Regulation* was introduced in 1995. The elimination of both Class 'B' burning permits in 1994 - 1995 and Class 'A' burning permits in 1998 made way for a more efficient system for administration of open fires.

Other changes were made regarding the fire equipment required in helicopter logging operations and the submission of fire preparedness plans in order to ensure efficiencies and keep in step with changes in the forest industry.

For further information: http://www.for.gov.bc.ca/tasb/legsregs/comptoc.htm
http://www.for.gov.bc.ca/protect/burning

Integrating Fire and Land Management

Wildfires are the most prevalent natural disturbance in BC and demand both our understanding and our respect. Wildfires promote plant and animal diversity by maintaining structural complexity within stands and by influencing the composition, size, edge characteristics and distribution of stands across the landscape. Most grassland and forested ecosystems in BC are influenced by wildfire, which may select for or against particular plants and animals – within populations, among species, in ecosystems and on the landscape.

There are differences between natural fire regimes and those implemented by resource managers. A role for natural and/or prescribed fire may be possible in protected areas and ecological reserves, and in other forested areas under certain circumstances. The challenge to resource and fire managers is one of including and excluding the appropriate type, location and quantity of both natural and prescribed fires on the various landscapes of this province, in consideration of resource, community and wilderness values.

Technological improvements in fire detection and suppression have greatly enhanced our abilities to manage fire but attention must always be paid to the long-term environmental effects of fire inclusion or exclusion and the economic and social costs and benefits of fire management policies and practices.

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