Chapter 16

Fire management applications of wildland fire behaviour knowledge

16.1 Introduction

Wildland fire has been referred to as a 'two-edged sword' and as a 'good servant but a bad master' in recognition of the fact that, while there are many beneficial aspects, some wildland fires can turn out to be lethal and destructive (see also Part Three). In a guest editorial in the 1974 Summer issue of *Western Wildlands*, Jack S. Barrows expressed the opinion that 'there is one overriding challenge to fire management: that of maintaining full respect for the power of fire and the effects of this power on both wildland environments and the people who live and work in these environments'.

In this regard, the 1910 fires in the US Northern Rocky Mountains have come to be one of those defining moments in the history of wildland fires globally (Pyne, 2008). At least 87 firefighters and civilians met their deaths and several communities were completely destroyed, as some 1600 wildfires burned over 1.2 million hectares of forested land, most of it occurring on August 20–21.

The 1910 'big blow-up' forest fire event would have an indelible effect on those responsible for developing strategies to co-exist with wildland fires in the future. Both fire operations personnel and fire research staff alike considered it to be a moral obligation never to let it happen again. Harry T. Gisborne exemplified the attitude well in stating his view of wildland fire research's *raison d'être* (i.e. reason or justification for existence), even though at the time of the 1910 fires he was but a 16-year-old boy (from Gisborne, 1942):

> 'We are not doing research for research's sake. We have a definite, decidedly practical goal, and it is still the basic, over-all goal ... stated in 1910: The first measure necessary for the successful practice of forestry is protection from forest fires. Fire research is intended to serve as directly as possible the fire-control men who must first be successful before any of the others arts or artists of forestry can function with safety.'

While there were a few initiatives following the 1910 fires, fire behaviour did not catch on as a field of forestry research until the 1930s (Figure 16.1). Interesting, while the importance of fire behaviour information in the field of forest fire protection and the associated need for research was well recognized, the term 'fire behaviour' was not included in the first

Fire on Earth: An Introduction, First Edition. Andrew C. Scott, David M.J.S. Bowman, William J. Bond, Stephen J. Pyne and Martin E. Alexander.

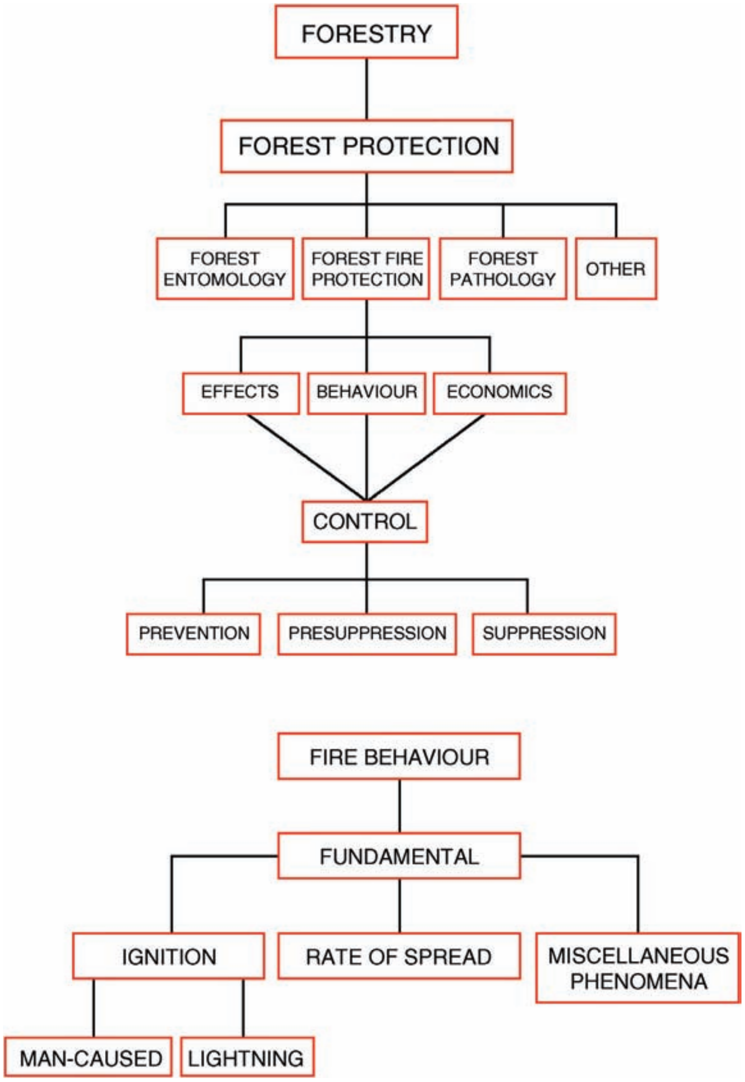

Figure 16.1 Flow charts illustrating the four main phases associated with forest fire protection (top) and four groups of studies associated with scientific study of forest fire behaviour research (bottom) as envisioned by Curry (1938). Miscellaneous phenomena include crowning and spotting, for example. Because some studies in fire behaviour apply to the whole field rather than to any particular phase, the fundamental section includes, for example, studies of the chemical and physical properties of forest fuels, classification of fuels, fuel moisture and weather relationships (after Curry, 1938).

formally published glossary of fire control terms (USDA Forest Service, 1930).

It is generally considered that nearly every aspect of wildland fire control and use requires some knowledge of fire behaviour (Figure 16.2). Operationally, this would include the following areas:

- Prevention planning (e.g. informing the public of impending fire danger, regulating access and risk associated with public and industrial use of forest and rural areas).
- Preparedness planning (i.e. level of readiness and pre-positioning of suppression resources).
- Detection planning (e.g. lookout staffing and aircraft scheduling and routing).
- Initial attack dispatching (e.g. prioritizing of targets for air tankers and ground crews).

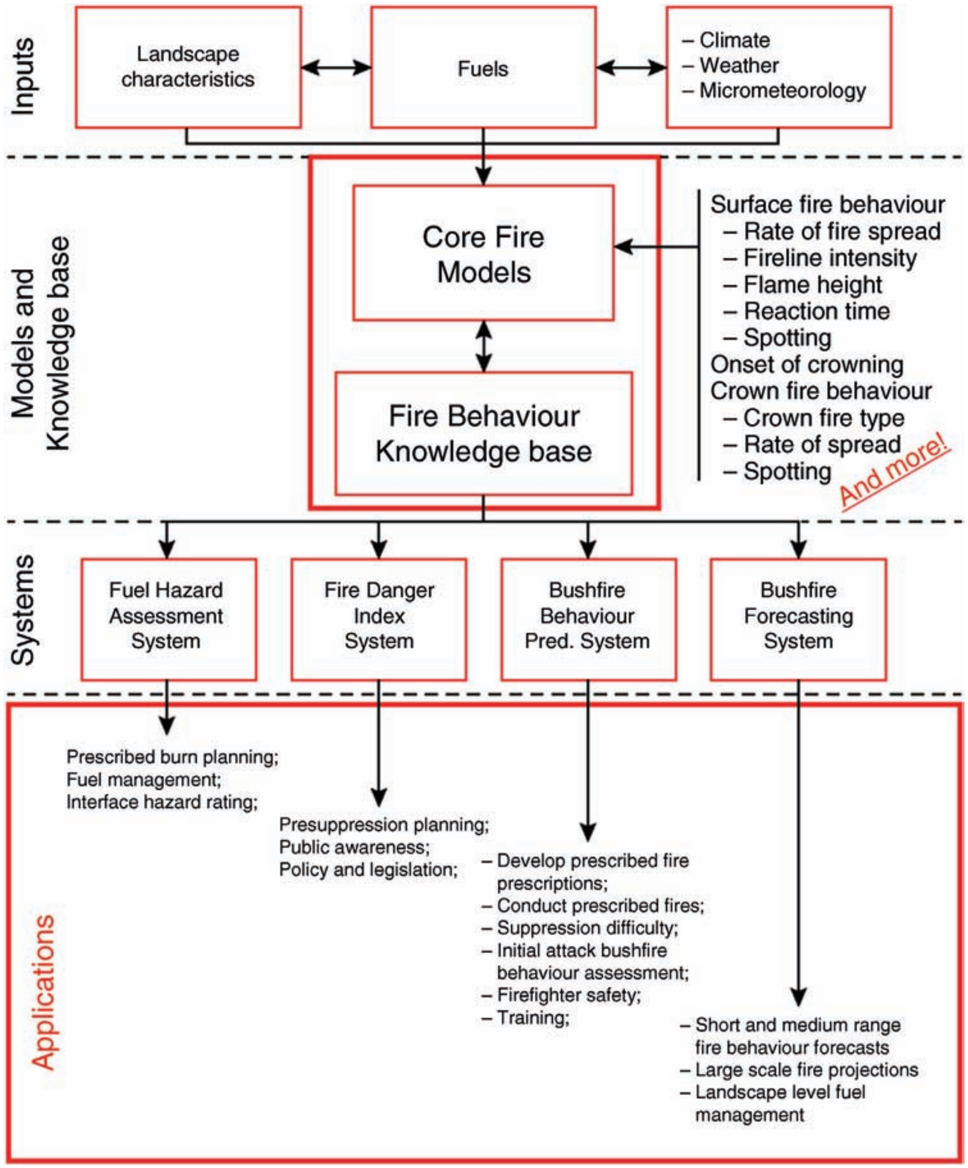

Figure 16.2 Flow chart illustrating the linkages between fire environment inputs, fire behaviour models and systems, and applications to fire and fuel management, as envisioned by Cruz and Gould (2009) in a national fire behaviour predictions system for Australia (from Cruz and Gould, 2009). Reproduced by permission of Taylor & Francis.

- Formulating suppression plans on active wildfires (including short-range predictions of fire behaviour and growth).
- Evaluating fire behaviour potential and guidelines for safe work practices for firefighters.
- Escaped fire situation analysis (including long-range projections of fire growth and behaviour).
- Prescribed fire planning and execution, including smoke management, fire and fuel management modelling and planning.
- Appraisal of impacts and effects of wildfires and prescribed fires.
- Wildland fire training.
- Wildfire fire accident investigations and reviews.
- Wildfire causal investigations.

However, since the early 1970s, the complexity of the issues requiring attention by wildland fire behaviour research has dramatically increased. For example, in Canada there is, paradoxically, a greater need for improved fire behaviour knowledge in order to manage wildfire more intelligently (e.g. no active fire suppression) in areas of low commercial timber value, or to apply prescribed fire safely in a critical habitat, than to dispatch an air tanker to a newly reported fire in an area with high values at risk. Research into the potential impacts of climatic change on fire activity and in turn fire management has steadily increased in recent years (e.g. Nitschke and Innes, 2008; Sullivan, 2010).

In this chapter, we touch on recent developments in the application of fire behaviour research and the practical knowledge gained from working on or with wildfires and prescribed fires. At the same time, though, some a historical context is provided, as well as how fire behaviour knowledge contributes to the on-the-ground application in wildland fire management.

16.2 Wildfire suppression

Fire suppression involves all the activities concerned with controlling and finally extinguishing a wildfire following its ignition (Box 16.1).

The fire triangle is commonly used to illustrate the basic principles of fire suppression (Figure 14.2a). To stop a free-burning fire, it is necessary either to:

1 remove the fuels ahead of the spreading combustion zone;
2 reduce the temperature of the burning fuels; or
3 exclude oxygen from reaching the combustion zone by smothering.

In practical terms, this means creating a physical barrier in front of the fire by removing the fuels or cooling/smothering the flames with water, covering them with mineral soil, suppressants (e.g. foam) or chemical fire retardants by various means from either the ground or the air (Alexander, 2000). If the fuel type(s) involves deep organic matter, smouldering combustion may still occur following initial containment, depending on the fuel moisture content, in which case extensive mop-up and patrol will be required before full extinguishment is achieved.

Box 16.1 Wildland fire suppression related terminology (adapted from Merrill, D.F., Alexander, M.E. (eds), 1987). Glossary of forest fire management terms. 4th edition. National Research Council of Canada, Canadian Committee Forest Fire Management, Ottawa, Ontario. Publication NRCC No. 26516. 91 p. Canadian Science Publishing or its licensors.

Difficulty of Control: the amount of effort required to contain and mop-up a fire based on its fire behaviour and persistence, as determined by the fire environment.

Resistance to Control: the relative ease of establishing and holding a fireguard and/or securing a control line, as determined by the difficulty of control and resistance to fireline or fireguard construction.

Resistance to Fireline or Fireguard Construction: the relative difficulty of constructing fireguards, as determined by fuel type characteristics (e.g., forest floor depth), effects of topography on access (e.g. slope steepness) and mineral soil type.

The forest fire behaviour research effort in the 1930s focused on estimating the rate of perimeter increase in relation to the production rates of various firefighting resources, such as ground crews, bulldozers and tractor-plough units for rapid initial attack in order to achieve containment as quickly as possible. Coupled with this emphasis was research on the early detection of initiating fires. Elapsed time since ignition, as a factor influencing fire behaviour, does not appear to have been fully appreciated in wildfire fire training, planning or operations (Box 14.2). As Alan McArthur (1968) states in his essay *The Effect of Time on Fire Behaviour and Fire Suppression Problems* (a landmark document in the field wildland fire management that should be required reading for all wildland firefighters), it is 'during the first 30 minutes

Box 16.2 Common denominators of wildland fire behaviour on firefighter fatality fires.

Based on an analysis of 67 fatal fires involving 222 wildland firefighter deaths in the US over a 61-year period (1926-1976), Carl Wilson (1977) identified some common features connecting these incidents. The five common denominators of fire behaviour associated with these fatal fires were:

1. Most of the incidents occurred on relatively small fires or isolated sectors of larger fires.
2. Most of the fires were innocent in appearance prior to the 'flare-ups' or 'blow-ups'. In some cases, the fatalities occurred in the mop-up stage.
3. Flare-ups occurred in deceptively light fuels.
4. Fires ran uphill in chimneys, gullies, or on steep slopes.
5. Suppression tools, such as helicopters or air tankers, can adversely modify fire behaviour (helicopter and air tanker vortices have been known to cause flare-ups).

or so of a fire's life history, suppression forces have their greatest chance of success purely because the fire is still accelerating and has not reached its maximum rate of spread'.

The inclusion of assessments of resistance to fireline or fireguard construction (e.g. Valachovic *et al.*, 2011) has tended to be an under-appreciated aspect of gauging fire behaviour potential. Research on fireline production rates has endeavoured to keep pace with changes in crew types and machinery over the years. Still, much of the existing information is in need of updating (Broyles, 2011). Fireline intensity and, in turn, flame length is a major determinant of the limit of effectiveness or minimum requirement for the different types of firefighting resources relative to the difficulty of control (Table 16.1).

The probability of containment will depend on sending enough resources of the right type relative to the expected fire behaviour at the time of initial attack (Figure 16.3). In order to achieve successful fire containment, the fireline production rate of the appropriate suppression resource(s) must exceed the fire's rate of perimeter increase over some specified period of time after their arrival on scene (Plucinski, 2012). Generally, there is a final target fire size in mind.

Flame length has been related directly to various measures of fire suppression over the years. Byram (1959a) recommended that, in the absence of severe spotting, the minimum width of a constructed fireline or fireguard should be 1.5 times the expected flame length. The amount of water required to extinguish wildfires has also recently been related to fireline intensity and also to flame length.

Forecasts or predictions of fire behaviour and fire growth are also needed in order to develop plans for

Table 16.1 The six distinct fireline intensity classes given in the Canadian Forest Fire Behaviour Prediction System field guide Taylor, S.W., Pike, R.G., Alexander, M.E., 1997. A field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Special Report 11. 60 p. © Canadian Science Publishing or its licensors.

Fireline intensity class	Fireline intensity (kW/m)	Flame length (m)[1]	Generalized fire potential and implications for fire suppression[2]
1	<10	<0.2	New ignitions and surface fire spread unlikely. No control problems.[3]
2	10–500	0.2–1.3	Surface fires with flame heights of ≈1.0 m. Limit of control with hand tools.
3	500–2000	1.3–2.6	Vigorous surface fires with short-range spotting. Water under pressure needed.
4	2000–4000	2.6–3.5	Intermittent crowning in forests. Heavy equipment required for fireline operations.
5	4000–10 000	3.5–5.4	Onset of 'blow-ups'. Fires escape initial attack leading to major campaign incidents.
6	>10 000	>5.4	Conflagrations. A change in fuels and/or weather is needed to affect containment of the head fire.

[1]According to Byram (1959a).
[2]See Alexander and Cole (1995).
[3]Ongoing fires could still require mop-up if ground fuels are dry and plentiful.

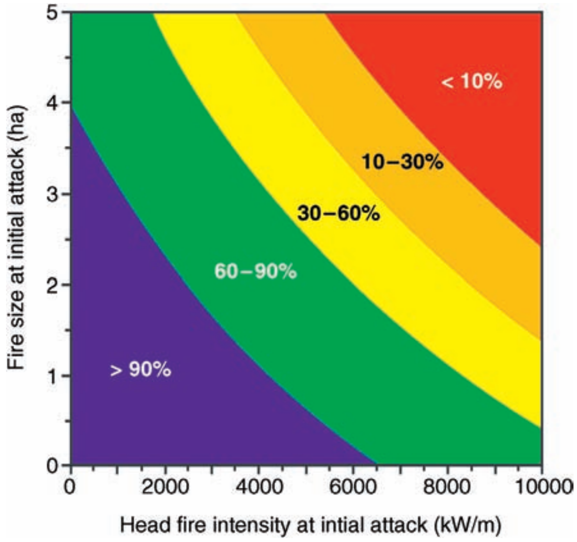

Figure 16.3 Probability of containment by a medium-sized initial attack crew (5–7 members) in the boreal spruce type of western Canada with support of water bucketing from a helicopter. This chart is based on interviews with initial attack crew leaders (from Hirsch *et al.*, 2000). Canadian Forest Service Publications (Natural Resources Canada). Reproduced with permission.

undertaking suppression activities on large wildfires (Teie, 2005). This will take into account the method of fireline construction or attack (i.e. direct, parallel or indirect), based on safety and tactical considerations as dictated by fuel continuity and probable fire behaviour. Fire behaviour considerations have been incorporated into guides for suppression firing using ground and aerial ignition (Cooper, 1969; Burrows, 1986).

16.3 Wildland firefighter safety

Wildland fire suppression can be an especially dangerous activity (Figure 16.4). Wildland firefighter fatalities have, unfortunately, occurred from time to time, due to entrapments or burn-overs, falling trees and snags, rolling rocks, vehicle and aircraft crashes, and even heart attacks. They have occurred on both wildfires and prescribed fires.

At least 443 wildland firefighters have died as a result of being overrun or entrapped by wildfires since 1910 in the United States, up to and including the 2011 fire season (Figure 16.5). Some of these tragedies have been chronicled in book form, in addition to the official accident investigation reports. The most notable of these is Norman Maclean's (1992) epic accounting of the 1949 Mann Gulch Fire in north-western Montana, in which 12 smokejumpers and one fire guard perished. His son John Maclean has since written four similar-type books, the most recent being an account of the 2006 Esperanza Fire in southern California, where a five-person engine crew died as a result of being overrun by the fire (Maclean, 2013). This incident occurred virtually on the steps of the Riverside Forest Fire Laboratory.

Current guidelines and advice on wildland firefighter safety can be traced to fire behaviour-related fatalities (e.g. Cook, 1995; Braun *et al.*, 2001; Cheney *et al.*, 2001). These include, but are not limited to, the *10 Standard Fire Orders*, *18 Watch Out Situations*, *LCES: Lookouts – Communications – Escape routes – Safety zones* (or *LACES*, with the 'A' denoting anchor point or awareness), and the *Common Denominators of Fire Behavior on Tragedy Fires* (see Box 16.2). Aggressive initial attack on wildfires can, in fact, serve as a means of increasing wildland firefighter safety.

It is worth noting that, in discussing the findings and observation from their study of the 1994 South Canyon Fire, Butler *et al.* (1998) pointed out that no new breakthroughs in the understanding of wildland fire behaviour had occurred, but rather that *their findings support the continued need for increased understanding of the relations between the fire environment and fire behaviour* (Box 16.3). 'We can also conclude that fire managers must continue to monitor and assess both present fire behaviour and

Figure 16.4 The photo memorial of the 'faces' of fallen wildland firefighters located in the lobby of the national fire control centre of the Ministry of Environment and Forestry in Ankara, Turkey (translation of the inscription at the bottom: 'We remember with gratitude those who have lost their lives fighting forest fires') (photo Ertuğrul Bilgili, Faculty of Forestry, Karadeniz Technical University, Trabzon, Turkey).

potential future fire behaviour given the possible range of environmental factors' (Butler *et al.*, 1998).

When fire behaviour becomes threatening, wildland firefighters disengage from the fire and travel along escape routes to reach safety zones to avoid being entrapped or burnt over (Figure 16.6). In spite of the fact that the concept of escape routes and safety zones has been a formally recognized element of wildland firefighter safety since 1957, when the *10 Standard Fire Orders* first appeared, until the 1994 South Canyon Fire tragedy in Colorado, involving the deaths of 14 firefighters, there was a surprisingly paucity either of quantitative information available on firefighter travel rates using escape routes, or of scientific data describing what made for an adequate safety zone.

An extensive study of wildland firefighter travel rates carried out in west-central Alberta, Canada involving

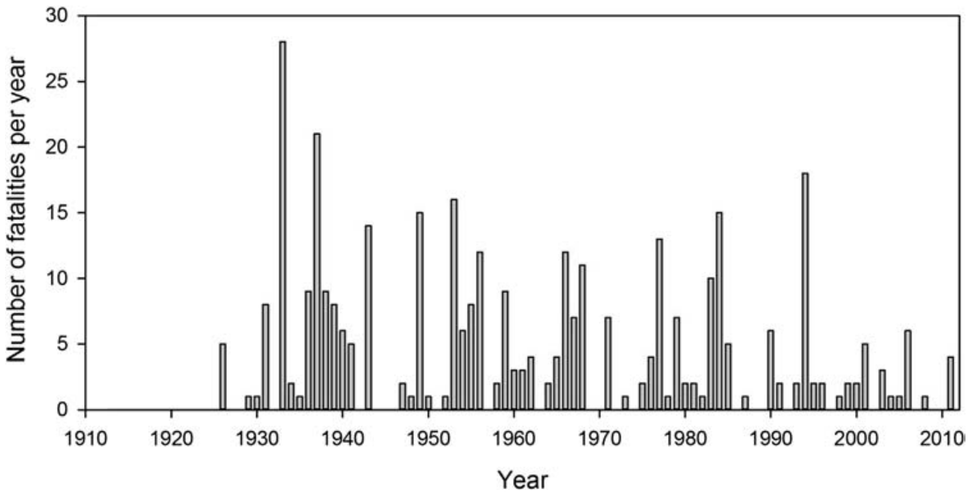

Figure 16.5 The number of reported wildland firefighter fatalities associated with burn-overs and entrapments, including heavy equipment and vehicle entrapments, by year in the United States for the years 1911–2011. A total of 78 firefighters also died as a result of the same causes during the 1910 fire season. The reporting from 1911 to the mid-1920s is undoubtedly incomplete (source: http://www.nifc.gov/safety/safety_HistFatality_report.html).

Type I, II and III wildland firefighters (Alexander *et al.*, 2005). This involved simulated runs over 250 m courses in six different fuel types/slope situations involving both 'natural' or unimproved and 'improved' routes (i.e. cleared trail and flagged), made with and without a pack (6.8 kg) and tool (fire shovel). On the basis of 360 timed runs, the following conclusions were reached:

- The fastest overall times occurred in the improved no pack/tool courses, followed by the improved pack/tool, natural no pack/tool, and then the natural pack/tool.
- The two open fuel types (i.e. grass and slash) were the easiest to travel across and the dense spruce stand was the hardest, while the mature pine stand was of intermediate difficulty.
- There was less variation in travel rates among individual crew members on improved routes.
- Trying to move upslope (a highly questionable action unless a safety zone is close by) dramatically decreases the pace a firefighter is able to attain.
- Carrying a pack and tool slows down a firefighter's rate of travel, regardless of whether they are on an

Box 16.3 Discussion points emanating from the fire behaviour analysis undertaken by Butler *et al.* (1998) into the 1994 South Canyon Fire, Colorado. Fourteen firefighters died as a result of being overrun by the fire. USDA Forest Service.

1. Topography can dramatically influence local wind patterns.
2. Vegetation and topography can reduce a firefighter's ability to see a fire or other influencing factors.
3. Current and past fire behaviour often does not indicate the potential fire behaviour that could occur.
4. The longer a fire burns and the larger it gets, the greater the likelihood of high-intensity fire behaviour at some location around the perimeter.
5. The transition from a slow-spreading, low-intensity fire to a fast-moving, high-intensity fire often occurs rapidly. This seems to surprise firefighters most often in live fuels.
6. Escape route effectiveness should be considered in relation to potential maximum intensity fire behaviour, rather than past or present fire behaviour.
7. The under-burnt Gambel oak did not contribute to the blow-up. It was significant in that it did not provide a safety zone.
8. Smoke can significantly reduce a firefighter's abilities to sense changes in fire behaviour.

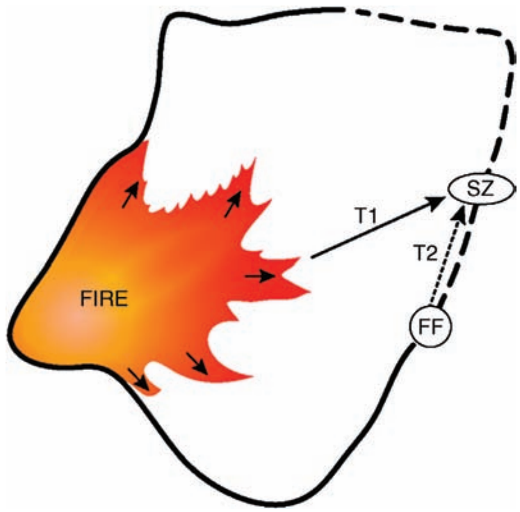

Figure 16.6 An illustration of the 'margin of safety' concept involved in wildland fire suppression (adapted from Beighely, 1995). The safety margin is a measure of the ability of wildland firefighter(s) (FF) to travel along an escape route and reach a safety zone (SZ). Mathematically, the safety margin ($\pm$) equals T1–T2, where T1 is the time for a fire to reach the SZ and T2 is the time for FF to reach the SZ. T2 depends not only on FF's rate of travel but also on their reaction time. USDA Forest Service.

open improved route or in a natural standing timber fuel type. Dropping the pack and tool could allow a firefighter to increase their travel rate by up to 20% (firefighters have to be trained to perform this action – it does not come naturally).

- Firefighters can be expected to move up to 40% faster on improved routes. Simply constructing a rudimentary trail (e.g. removing or cutting through large deadfall) and flagging or marking the route in some manner can decrease the overall time taken to reach a safety zone.

Thus, by using an improved escape route and dropping the pack and tool, firefighters can travel up to two times faster than if they had attempted to travel over an unmarked/unimproved route with their pack and tool. Precious seconds gained by these actions could mean the difference between life and death on the fireline. This study also found, from simulations of rate of fire spread in relation to firefighter travel rates, that while firefighters would be able to momentarily outpace the rate of advance that most wildland fires are capable of achieving, even the most fit individuals would not be able to sustain such a pace for more than a few minutes on a moderately steep slope.

A safety zone is an area that offers refuge from the dangers associated with an approaching wildland fire. What constitutes a safety zone varies considerably amongst individuals. Ideally, it is an area completely free of readily combustible fuels. The minimum size required is determined by the characteristics of the fire environment (e.g. fuels immediately adjacent to a clearing) and the ensuing fireline intensity. Based on theoretical considerations for radiation emitted from a 'wall of flame' under idealized conditions (e.g. level terrain, steady-state fire conditions), it has been suggested, from the standpoint of flame radiation, that a safety zone should be large enough so that the distance between the human occupants and flame front should be at least four times the maximum expected flame height at the edge of the safety zone (Table 16.2). This recommendation does not directly take into account the impacts of smoke inhalation on firefighter consciousness.

How does one go about gauging the maximum flame height to be expected? Based on general field observations and measurements made of wildfires, prescribed burns and experimental fires, one can say with some degree of certainty that the maximum

Table 16.2 Minimum safety zone separation distances and sizes (circular shape) in relation to flame height for a single person (adapted from Alexander *et al.*, 2012). As current proofs but add Reporduced with permission of Elsevier.

Safety zone size	Flame height (m)					
	2	5	10	20	40	60
Separation distance (m)[1]	8	20	40	80	160	240
Area (ha)[2]	0.02	0.13	0.5	2.0	8	18

[1]For flat topography based on the Butler and Cohen (1998) '4-times-flame-height' rule of thumb for radiant heat only (i.e. no allowance for convection, flame impingement, fire whirls or other fireline hazards (e.g. falling trees and snags, rolling rocks and logs). It is assumed that the person is standing upright and is properly clothed, including headgear and gloves.

[2]Assuming the area of a circle is equal to $(\pi \times (SD)^2) \div 10\,000$, where π equals $\approx$3.14159 and the separation distance (SD, m) is deemed to be radius of a circle. For perspective, a North American ice hockey rink is 0.16 ha in size and an American football field is 0.4 ha in size.

flame heights in grasslands, low- to medium-tall shrublands and boreal hardwood stands, for example, would range from 4–10 m, implying that a separation distance of at least 40 m should be adequate in fuel types that lack significant vertical fuel dimension. This is in contrast to crown fires in fuel complexes like mature chaparral, dry eucalypt forests and conifer stands, where flame heights in excess of 20 m and higher are commonly attained.

Past experience has shown that survival is possible in areas much smaller than that recommended for a safety zone (Alexander *et al.*, 2009). However, this is contingent on maintaining a prone position and using every means possible of protecting oneself against radiation and convective heat transfer, as the advancing flame front approaches and passes around the firefighter in the 'survival zone'.

There have been several direct applications of information from fire danger rating and fire behaviour prediction systems to enhancing situational awareness and entrapment avoidance amongst wildland firefighters. These include firefighter safety guidelines related to the real-time, diurnal and seasonal assessments of wildland fire behaviour potential (Andrews *et al.*, 1998; Beck *et al.*, 2002; Cheney *et al.*, 2001).

16.4 Community wildland fire protection

While the use of the term 'wildland-urban interface' or WUI (pronounced 'woo-ee') can be traced back some 40 years or so, in actual fact the protection of settlements or communities against the adverse impacts of wildfires has a much longer history (Cohen, 2010). As mentioned earlier, as humans we tend to have short memories. The destructive power of wildfires in modern times was forcibly demonstrated during the 2009 Black Saturday fires in the State of Victoria in south-eastern Australia, where wind-driven fires, some ignited by arsonists, led to the deaths of 173 civilians and the devastation of numerous communities. The ever increasing incidence of major WUI fires in recent years has, to a large extent, blurred the distinction between urban and wildland fire behaviour.

Advances in the understanding and prediction of wildland fire behaviour will enable fire planners and community managers to tackle the WUI fire problem more effectively. Wildland fire growth simulation models like PROMETHEUS, for example, are now being used to test containment strategies for dealing with wildfires based on fuel treatments in the context of community wildfire protection planning (Walkinshaw, 2012).

Fire weather databases have combined with fire danger rating or fire behaviour predictions system to create fire danger and fire behaviour climatologies. This has allowed for the quantification of the potential wildfire threat in simple terms that can be readily understood by non-specialists, including the general public. For example, during a public information session associated with the presentation of the information contained in Table 16.3 in March 1997, the town's emergency planner was quite surprised to learn that, on average, a fifth of the days in a fire season were capable of wildfire behaviour that would likely not be controllable should an ignition take place. Similar analyses has been undertaken in the province of Saskatchewan, Canada (Johnson *et al.*, 2005) where wildfire risk profiles have been completed for over 100 northern communities there.

Table 16.3 Average number of days in various fireline intensity classes for the black spruce forests adjacent to the town of Hay River, Northwest Territories, Canada as derived by Alexander *et al.* (2001). This compilation is based on daily fire weather records for the period 1954–1996 and using fuel type C-2 (boreal spruce) of the Canadian Forest Fire Behavior Prediction System. © Scion, New Zealand. Reproduced with permission.

Fireline intensity class(es)[1]	Fireline intensity (kW/m)	Average number of days					
		May	June	July	August	September	Fire season
1 and 2	<500	14	8	10	10	16	58
3	500–2000	9	9	9	11	8	46
4	2000–4000	4	4	5	4	2	19
5 and 6	>4000	9	9	9	7	3	34

[1]The four fireline intensity class groups could be equated to low, moderate, high and extreme fire danger.

The requirement for WUI fire planners and consultants to be certified as operational fire behaviour analysts (i.e. FBANs) has not yet happened. However, FBANs assigned to incident management teams make recommendations regarding community evacuation alerts and warnings with increasing confidence, given the current state of fire behaviour science and technology (Beverly and Bothwell, 2011). For example, the second evacuation of the town of Swan Hills on May 13, 1998 during the 167 000 ha Virginia Hills Fire in central Alberta, Canada, was based on the fire's uncontrolled status in the north-eastern sector at the time, the forecasted weather, the fuel type mosaic and topography in the area between the fire and the town. This was also coupled with projections using the Canadian Forest Fire Behaviour Prediction System undertaken by the author of this chapter (MEA) while serving as the FBAN on the command team assigned to this incident. Based on interpretations of the predicted spread rate and fireline intensities, the decision was made to evacuate Swan Hills. While the forecasted weather conditions failed to materialize, the second evacuation was conducted in an orderly manner during daylight hours, in stark contrast to the haste involved in the first evacuation during the middle of the night.

Additional research and development aimed specifically at the application of fire behaviour knowledge to the WUI fire problem has been undertaken. These include the development of a model for calculating the probability of house survival that depends on estimates of fireline intensity (Wilson, 1988a), as well as the Wildland Urban Interface Evacuation (WUIVAC) Model, a spatial decision support system that can be used to evaluate public evacuation routes under emergency wildfire conditions (Cova *et al*., 2011).

16.5 Fuels management

From a wildfire suppression standpoint, fuels management involves planned changes to living or dead wildland fuels in order to lessen fire behaviour potential and resistance to fireline construction. This increases the probability of successful containment, while minimizing adverse impacts as well as increasing the safety of wildland firefighters and the public at large. More specifically, the purpose of modifying fuels in the fire environment is to decrease the rate of fire spread and/or available fuel and, in turn, fireline intensity and fire size, as well as crowning and spot fire development. In this sense, fuels management constitutes a means of fire prevention, at least in the case of reducing the number of large fire occurrences.

The basic premise behind fuels management is that we are not capable of controlling the air mass or weather component of the fire environment (nor of modifying the weather), or reshaping the topographical features of the earth. However, we can influence the quantity and character of wildland fuels and, therefore, we can manage them to a certain extent.

The four principal means of directly managing or treating wildland fuels that are regularly applied include:

- Fuel reduction (e.g. by prescribed broadcast burning, pile burning, livestock grazing and the physical removal of fuels from the site other than by logging);
- Fuel manipulation (e.g. by pruning, pre-commercial thinning, mulching or mastication, chipping, crushing);
- Fuel conversion (i.e. a change in vegetative cover from a flammable case to a far less flammable one); and
- Fuel isolation (i.e. by the use of fuel breaks and firebreaks).

Clive Countryman's (1974) publication *Can Southern California Wildland Conflagrations Be Stopped?* represents a *tour du force* on the subject of fuels management. In the United States, the Joint Fire Science Program has supported the development of several state-of-the-art guides to fuels management practices in recent years (e.g. Jain *et al*., 2012).

Of course, prescribed fire – the knowledgeable and controlled application of fire to a specific land area in order to accomplish planned resource management objectives (Waldrop and Goodrick, 2012) – is used for purposes other than fuels management (Figure 16.7). Such purposes may include ecosystem restoration, wildlife habitat, insect and disease control and range improvement – there are often multiple objectives for prescribed fires. General fire behaviour knowledge and predictive aids are used in developing burning prescriptions designed to accomplish the stated objectives of a particular prescribed fire. Fernandes and Botelho (2003) noted that 'Conclusive statements concerning the hazard-reduction potential of prescribed fire

Figure 16.7 View of the Blackstone Capping Unit prescribed fire in progress, south-western Alberta, May 15, 2007. This prescribed fire was carried out to create a landscape-scale fuel break, to enhance wildland habitat, to improve range conditions and also for fire crew training (photo Dennis Quintilio, D. Quintilio and Associates, Glenevis, Alberta).

application are not easily generalized, and will ultimately depend on the overall efficiency of the entire fire management process'.

Fuel reduction and fuel manipulation are often considered as a single entity – namely, fuel modification. Their resultant outcomes or effects on fire behaviour are, nevertheless, quite distinct. Fuel reduction involves fuel removal, and this correspondingly leads to a direct reduction in rate of spread and fireline intensity potential. The first published empirical proof of this concept did not appear until the late 1940s (Figure 16.8).

Fuel manipulation, on the other hand, involves only a rearrangement of the fuel. This might, for example, influence crowning potential (Figure 16.9), but the end result is that the total fuel load remains the same.

Both fuel reduction and fuel manipulation techniques may be used jointly in a fuel treatment (e.g. commercial thinning followed by prescribed under-burning). Fuel conversion involves a more or less permanent change (e.g. from a spruce stand to a deciduous or hardwood stand, by mechanical means and/or prescribed fire).

Firebreaks and fuel breaks are designed to stop outright or impede a fire's progress (Figure 16.10); they may also serve as a control line or anchor point to carry out fire suppression work from. While fuel breaks will contain burnable material (e.g. trembling aspen fuel break), firebreaks technically do not burn – and, if they do, the fuels are exceedingly sparse. A temporary firebreak might be created by ploughing a field of grass, or a permanent firebreak can be constructed by establishing and maintaining a gravel road adjacent to a community surrounded by conifer forests.

The principle of fuel isolation at a local level (e.g. a house or an entire community) certainly seems doable. At a landscape-scale, though, the task seems utterly daunting (Figure 16.11). In this respect, we need to pay attention to the lessons provided by Mother Nature (Box 16.4).

Every unwanted human-caused fire can be considered as a fire prevention failure. Even if we could

Figure 16.8 Pre-fire view of the more heavily grazed area (left of the fence) versus the more lightly grazed area (right of the fence) involved in the experimental fire study on the Nebraska National Forest, Nebraska, USA. Parallel plots, approximately 150 m by 30 m, were established on each side of the fence. Both plots were ignited so as to burn simultaneously as heading fires. The reduction in fuel (i.e. lightly grazed vs. more heavily grazed) led to a three-fold decrease in the average rate of fire spread (28 vs. 9.7 m/min) and a five-fold decrease in the average flame height (1.5 vs. 0.3 m) (from Davis, 1949). USDA Forest Service.

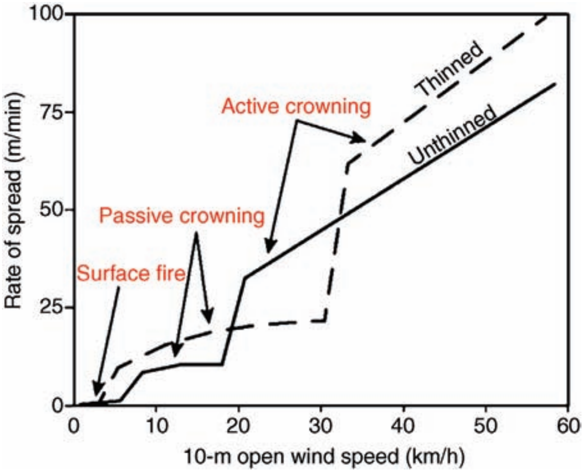

Figure 16.9 Head fire rate of spread as a function of wind speed for 12-year-old thinned (50% basal area reduction treatment) and unthinned pine plantation stands based on the Pine Plantation Pyrometrics (PPPY) fire modelling system (adapted from Cruz *et al.*, 2008). Courtesy of Taylor & Francis.

prevent all such fires, we would still have to contend with lightning-ignited fires. Is it realistic to expect that we can control all fires before they reach conflagration levels? On some days, adverse fuel, weather and topographic conditions, coupled with an ignition source, lead to instances of extreme fire behaviour for which it is impossible to effect containment until burning conditions ameliorate.

Clive Countryman considered that the best prospect for alleviation of the problem was the creation of a fuel-type mosaic that would reduce the fuel energy output. In this regard, see (for example) the case study completed by Salazar and Gonzáles-Cabán (1987) of the 1985 Wheeler Fire on the Los Padres National Forest in southern California, and the earlier analyses by Rogers (1942).

To decide how much fuel is considered acceptable requires the integration of many factors (Figure 16.12). This can be done systematically in a three-step process (Brown *et al.*, 1977; Alexander, 2007):

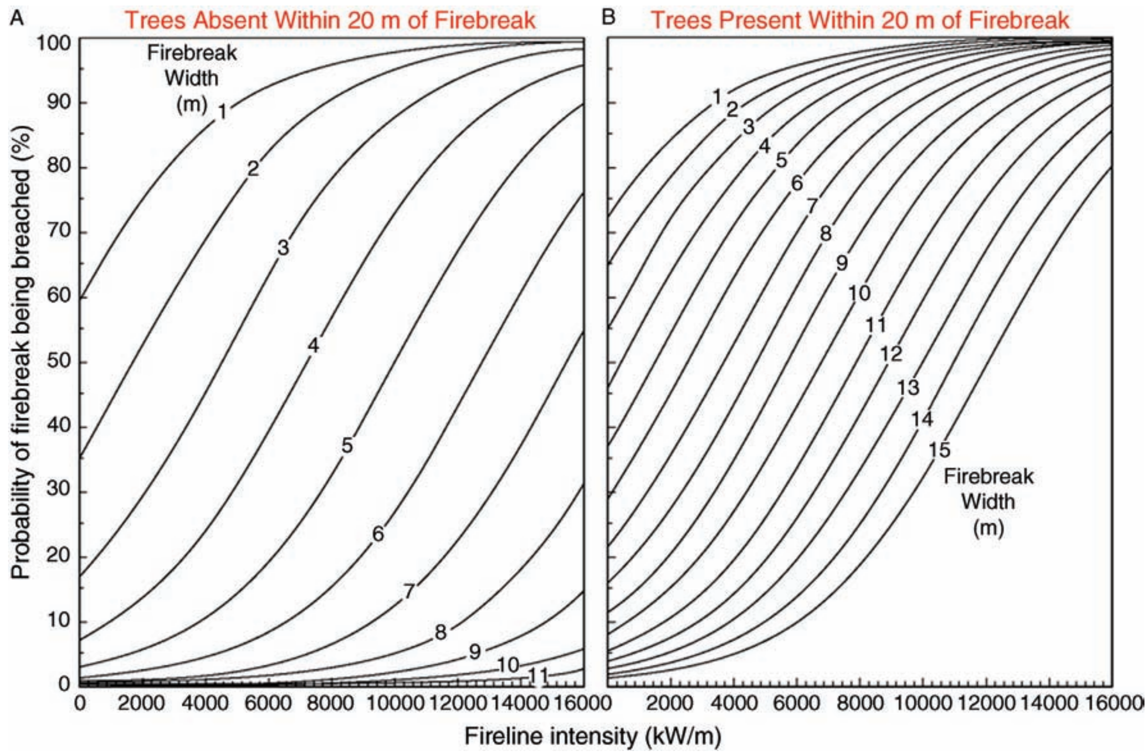

Figure 16.10 Probability of firebreak breaching by a grass fire for (A) trees absent, and (B) present within 20 m of the firebreak (adapted from Wilson, 1988b). Width of firebreak that is necessary to stop grass fires: Some field experiments. Canadian Journal of Forest Research 18, 682–687. © Canadian Science Publishing or its licensors.

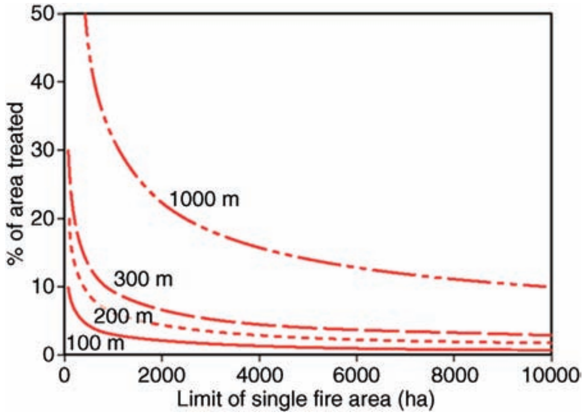

Figure 16.11 Geometrics of a proactive fuel isolation treatment. The lines are curves of the percentage of the landscape area that needs to be treated to provide a firebreak of a given width (100 m, 200 m, 300 m, 1000 m), such that the maximum fire size is limited to that shown on the *x*-axis. This assumes that the fuel isolation treatments are in a square grid pattern and act as perfect firebreaks in stopping further fire growth (from Amiro *et al.*, 2001). Courtesy of CSIRO Publishing.

Step 1: Consider management objectives and values at risk. For the latter, both resource values and risk of a fire during periods of critical fire weather, and fire danger causing damage, are jointly considered.

Step 2: Appraise fuels by (a) describing fuel loads and arrangement from inventory, prediction, or ocular estimation technique, and then (b) interpreting fire behaviour and fire impact potential, such as rate of spread, intensity, flame length, crown scorch height and degree of crown fuel consumption.

Step 3: Consider other fire-related factors, such as fuel and fire behaviour potential on adjoining lands, suppression capability, frequency and severity of historical fires, and fire's ecological role.

The CFIS system mentioned in Chapter 15 allows one to evaluate the impacts of proposed fuel treatments on potential crown fire behaviour, based on its ability to manipulate three characteristics of a fuel complex (i.e. available surface fuel load, canopy base

Box 16.4 A lesson learned regarding landscape-scale fuel management (adapted from Alexander, 1998).

'Logic would dictate that the chance(s) of a high-intensity crown fire occurrence would gradually increase as the size of the total plantation estate increases. The value of a dispersed pattern of relatively small to moderately sized plantations, especially in fire-prone environments exhibiting very high ignition risk coupled with an adverse fire climate, was demonstrated during the 1983 Ash Wednesday Fires in the south-eastern portion of South Australia and Victoria.

'State-owned plantations in the region managed by the Woods and Forests Department amount to approximately 80 000 ha and are comprised of a few large, more or less contiguous blocks of land. On February 16, 1983, some 21 000 ha of exotic pine plantations were burnt over in South Australia alone, most very severely, by eight fires that covered a gross area of around 120 000 ha. In contrast, private forest industry in the region, with a comparable estate of around 70 000 ha, but comprised of many smaller parcels scattered across the region, more as a result of circumstances rather than by any strategic design, suffered only minor (40 ha) wildfire losses.'

height and canopy bulk density) by silvicultural and other vegetation management techniques.

The first two research papers that used mathematical modelling to gauge the effectiveness of fuel treatments on fire potential (Anderson, 1974; Brown, 1974) were the direct result of the release of the Rothermel (1972) surface fire spread model two years earlier. The fuel appraisal process requires the coupling of mathematical or simulation modelling with experienced judgment and comparison against case study knowledge. Reliance entirely upon fire behaviour simulations based on fire modelling systems has shown to be foolhardy (e.g. Cruz and Alexander, 2010).

The number of years between fuel reduction burns in the eucalypt forests of Australia typically depends on the litter accumulation rates and the fire climatic conditions. The fuel reduction burning programme developed for the eucalypt forests in the south-western region of Western Australia, born out of the disastrous 1961 Dwellingup fires (Underwood, 2011) is unparalleled (McCaw, 2013). The interval between fuel hazard reduction burns was initially established on the basis of practical fire experience. However, it was later verified by fuel measurements and experimental fire studies carried out by fire researchers within the operational organization.

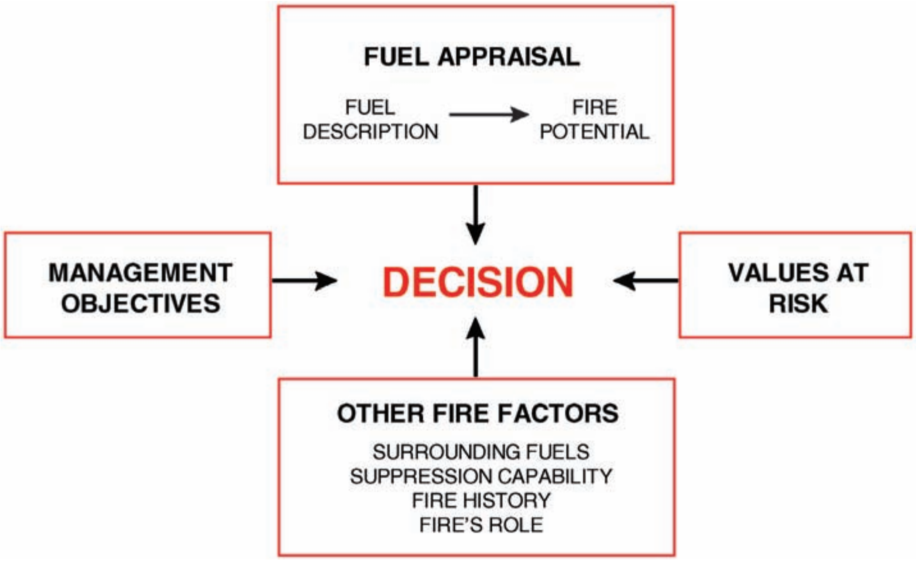

Figure 16.12 The factors considered to be important when deciding how much fuel is considered acceptable (from Brown *et al.*, 1977). USDA Forest Service.

16.6 Prediction of fire effects

First order fire effects are the immediate evident consequences or impacts of a fire. Research on fire effects extends back to the late 1890s. Methven (1977) remarked, at a fire ecology workshop held in Edmonton, Alberta, Canada, that 'the most conspicuous feature of the literature on fire ecology has been the lack of reference to the nature of the fires that caused the effects being measured.' He considered this another example of the 'two solitudes in forest fire research' (see Chapter 15, section 15.3.4), as noted by Charlie Van Wagner six years earlier, suggesting that 'in the case of ecological effects, the two solitudes have been composed of fire researchers concerned with behaviour and ecologists concerned with fire effects'.

The reality is that things take time. As the science of wildland fire behaviour description and measurement began to mature in the early 1960s, so too did concerted efforts to link fire effects to fire behaviour. The end result is that today we see a whole host of fire effects modelling systems that are based on largely on information collected up to the late 1980s.

One of the first was FOFEM (First Order Fire Effects Model), a national fire effects modelling system used in the USA for predicting tree mortality, fuel consumption, emissions or smoke production, mineral soil exposure and soil heating caused by prescribed fire or wildfire (Reinhardt, 2003). FOFEM represents a collation of many separate studies. For example, the probability of post-fire tree mortality function is based on regression equations derived from empirical data on tree size and crown scorch height collected from experimental fires, prescribed fires and wildfires (Figure 16.13).

Until just recently, fire effects models have been largely statistical in nature, as opposed to process-oriented or biophysical predictive models. Like models for predicting various characteristics of fire behaviour, there are pros and cons to purely statistical models, depending on how they are formulated. The journal *Fire Ecology* recently devoted an entire special issue of eight papers on 'strengthening the foundation of wildland fire effects prediction for research and management' (Dickinson and Ryan, 2010).

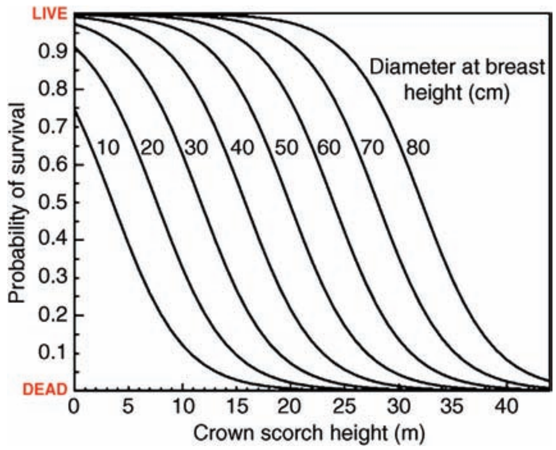

Figure 16.13 Post-fire probability of tree survival in interior Douglas-fir as a function of diameter-at-breast height and crown scorch height (adapted from Bevins, 1980). This graph is based on an equation derived from data collected on 176 trees on experimental fire plots in west central Montana, USA. USDA Forest Service.

While giving the appearance of being highly robust in nature, the developers of the few biophysical fire models produced to date seem to have failed to consider some practical considerations. For example, in the software application (*CROWN SCORCH*) of the crown scorch height model developed by Michaletz and Johnson (2006), the authors did not allow for the fact that crown scorch height can also be influenced by the ignition pattern. Their model considered only a single spreading line fire and their operational software application was, thus, limited to that case.

The outputs of other biophysical modelling efforts have, in some instances, been found to match reality (e.g. Choczynska and Johnson 2009), but this is not so in other cases (in spite of the best of intentions of the modellers). It is clear that there is no substitute for 'hands-on' experience in observing experimental fires, prescribed fires, and wildfires (Figure 16.14) and their resulting aftermath, coupled with a good command of the literature, as a basis for understanding and modelling the impacts and effects of free-burning fires in relation to their behaviour (Alexander and Cruz, 2012c).

Figure 16.14 A wildfire (Red Lake 200-76) burning through snags and tree reproduction in a 1967 fire origin jack pine stand in northwestern Ontario, Canada, during the 1976 fire season. The individual with his back to the camera photographing the oncoming flame front is Brian J. Stocks of the Canadian Forest Service. (photo Martin E. Alexander).

16.7 Getting on the road towards self-improvement

Few would argue with the notion that models and modelling have become an integral component of modern day fire management practices. But there is room to wonder if we have lost sight of the idea that models were always intended simply as tools to aid us in our decisions and actions (Alexander, 2009b).

Wildland fire researchers have, indeed, provided users with a host of fire behaviour decision-making aids and knowledge designed to address specific wildland fire-related issues. There is a plethora of fire modelling systems and a mass of literature on fire behaviour subjects. Some might consider it all overkill. In spite of great expectations (e.g. USDA Forest Service, 1966), history has shown time and time again over the past hundred years or so that fire research alone will not be enough. Adopters and implementers of fire behaviour knowledge are always needed.

One can regard the products produced by wildland fire research to date as having effectively synthesized the current theory as in the 'theory and practice' of wildland fire behaviour prediction. Effective 'practice' is, however, the onus of the individual person practising fire behaviour prediction. In this regard, live fire exercises should also be considered as a means of supplementing conventional fire training using operational prescribed fires (see Figure 16.7). This would be especially valuable in fuel types with which we have limited experience (Cheney, 1994).

There is no better means of practice than experience coupled with self-study. Wildland fire icon Paul Gleason regarded it as always being a 'student of fire' (Cook and Tom, 2003) – in other words having that constant, burning desire to continue to learn about fire. The use of experienced judgment (Gisborne, 1948) in assessing fire behaviour needs to be supported by more monitoring and documentation on wildfires and prescribed fires than has been the case in the past (see Box 15.3, chapter 15, Part Four). The preparation of fire behaviour case studies should not be viewed as strictly the domain of wildland fire behaviour research. Case study preparation (Box 16.5) should be complemented by review of existing case histories, as previous events tend to have a way of repeating themselves.

Box 16.5 Suggested outline for preparing a wildland fire behaviour case study report (adapted from Alexander and Thomas, 2003b). USDA Forest Service.

1 Introduction
- Significance of the fire.
- Regional map with fire location.

2 Fire chronology and development
- Cause.
- Time of origin and/or detection.
- Initial attack action.
- Forward spread and perimeter growth.
- Fire characteristics, e.g. spotting distances and crowning activity.
- Suppression strategy and tactics employed.
- Mop-up difficulty.
- Fire progress map, showing point of origin.
- Final area burnt and perimeter.
- Ground and aerial photos.

3 Details of the fire environment
- **Topography:** review major features; include topographic map and photos.
- **Fuels:** describe the principal fuel type(s); include a vegetation cover type map and photos.
- **Fire weather:** describe pre-fire weather as appropriate; summarize synoptic weather features and include surface map; present daily fire weather observations; present fire danger ratings, including drought indexes, and append monthly fire weather record form; present hourly weather observations; denote location of weather station(s) on regional map or fire progress map and comment on the relevance of the readings to the fire area, including notes about the station's instrumentation.

4 Analysis of fire behaviour
- Discuss the fire's behaviour in relation to the characteristics of the fire environment.
- Discuss the success/failure of the suppression operations.

5 Concluding remarks
- What, for example, did you learn about predicting fire behaviour and fire behaviour documentation?
- What, if anything, have you been able to contribute to the general fire behaviour knowledge base?

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