

What are the safety implications of crown fires?

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Abstract. In his pioneering work on the common denominators of fire behavior associated with fatal and near-fatal wildland fires published in 1977, Carl Wilson pointed out that many firefighters were surprised to learn that tragedy and near-miss incidents occurred in fairly light fuels, on small fires or isolated sectors of large fires, and that fire behavior was relatively quiet just before the incident. This is certainly a valid conclusion as the general belief had been that high-intensity crown fires in timber were responsible for entrapping and burning-over firefighters. The focus of this paper is on contrasting several fire behavior characteristics (e.g. forward or head fire rate of spread, fireline intensity, flame depth) between fully-cured grass and conifer forest in relation to wind speed for a fixed set of burning conditions. The results of this comparison coupled with the new knowledge gained from research studies undertaken since the late 1970s, indicate that there is a general need for a readjustment in the emphasis placed on certain aspects of fire behavior in current firefighter safety awareness training.

Additional keywords: crowning, fire behavior, fire environment, firefighter fatalities, fireline intensity, flame depth, flame front residence time, flame height, flame length, rate of fire spread.

Introduction

With respect to the title of this paper and after looking at Fig. 1, is it not obvious that crown fires pose a serious risk to the safety of wildland firefighters? As author Norman Maclean (1992) so eloquently stated in his seminal book ‘Young Men & Fire’:

As for big fires in the early history of the Forest Service, a young ranger made himself famous by answering the big question on an exam, “What would you do to control a crown fire?” with the one-liner, “Get out of the way and pray like hell for rain.”

In discussing the various types of free-burning wildland fires, Brown and Davis (1973) had this to say about crown fires:

This is the most spectacular kind of forest fire. Since it is over the heads of ground forces it is uncontrollable until it again drops to the ground, and since it is usually fast-moving it poses grave danger to fire fighters and wildlife in its path. It is the most common cause of fire fighters becoming trapped and burned.

The purpose of this paper is explore the specific aspects of crown fire behavior that should be a cause of concern for wildland firefighters as well as members of the general public with

regard to their personal safety. This is discussed in light of Carl Wilson's (1977) ground-breaking research into the common denominators of fire behavior on fatal and near-fatal fires.

The International System (SI) of units is used throughout this paper. A list of SI-to-English unit conversion factors is given in the Appendix.



Fig. 1. Crown fire advancing through a radiata pine (*Pinus radiata*) plantation (~15 m tall) towards a grazed pasture consisting of fully-cured grasses with scattered eucalypt trees, located near Wandong in central Victoria, Australia. Photo by Alan Sewell, Country Fire Authority, 14 January 1998.

Wilson's common denominators of fire behavior on fatal fires

Based on his analysis of 67 fatal fires involving 222 wildland firefighter deaths in the US over a 61-year period (1926-1976), Wilson (1977) identified some common features connecting these incidents. The five common denominators of fire behavior 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 behavior. (Helicopter and air tanker vortices have been known to cause flare-ups.)

Although not explicitly noted in the above list, surely it is a given that dead and(or) live fuel moistures are at critically dry levels. Furthermore, ‘worst-case’ fuel conditions must also apply. For example, grasslands would have been in a fully-cured state as was the situation on the Mann Gulch Fire in northwestern Montana in August 1949 (Maclean 1992) or when hardwood forests are in a leafless stage, as was the case on the Pepper Hill Fire in north-central Pennsylvania in the fall of 1938 (Schultz 2001).

Wilson’s (1977) findings were subsequently reprinted in several popular, pocket-sized booklets over the years (Wilson and Sorensen 1978, 1992, 1996) and included within many other publications (e.g. Goodson and Adams 1998; Alexander *et al.* 2011). Quite often only the first four common denominators are given and presented in slightly altered forms from Wilson’s (1977) original concept. For example, ‘the four major common denominators of fire behavior on tragedy fires’ are (from Wilson and Sorensen (1996):

1. Most incidents happen on small fires or on isolated sections of large fires.
2. Flare-ups generally occur in deceptively light fuels, such as grass and light brush.
3. Most fires are innocent in appearance before unexpected shifts in wind direction and/or speed result in flare-ups. Sometimes tragedies occur in the mop-up stage.
4. Fires respond to large- and small-scale topographic conditions, running uphill Surprisingly fast in chimneys, gullies, and on steep slopes.

Note in the latest edition of the *Incident Response Pocket Guide* (NWCG 2010) or IRPG, as it is frequently called, that the indication is that firefighter fatalities often occur:

1. On relatively small fires or deceptively quiet areas of large fires.
2. In relatively light fuels, such as grass, herbs, and light brush.
3. With unexpected shifts in wind direction or wind speed.
4. When fire responds to topographic conditions and runs uphill.

As Wilson (1977) so perceptively pointed out, many firefighters were surprised to learn that tragedy and near-miss incidents occurred in fairly light fuels, on small fires or on isolated sectors of large fires, and that the fire behavior was relatively quiet just before the incident, even in the cases involving aircraft (Countryman *et al.* 1969). Many have been lead to believe that it is the conflagration or large, high-intensity crown fire in timber or heavy brush that traps and kills firefighters. Some of the fatality fires involving crown fire runs in conifer forests that come to mind, two of which were part of Wilson’s (1977) study, include for example:

- 1937 Blackwater Fire – Wyoming: 15 fatalities (Brown 1937)
- 1958 Wandilo Fire – South Australia: 8 fatalities (McArthur *et al.* 1966)
- 1967 Sundance Fire – Idaho: 2 fatalities (Anderson 1968)
- 1977 Bass River Fire – New Jersey: 4 fatalities (Brotak 1979)
- 1980 Mack Lake Fire – Michigan: 1 fatality (Simard *et al.* 1983)
- 1990 Dude Fire – Arizona: 6 fatalities (Goens and Andrews 1998)
- 1994 Sabie – South Africa: 10 fatalities (de Ronde 2002)
- 2001 Thirtymile Fire – Washington: 4 fatalities (Maclean 2007)

Yet, with some rare exceptions, Wilson (1977) claims that most fatal fires that he examined were innocent appearing just before the fatal moment.

Wilson’s (1977) common denominators have been the accepted doctrine with respect to wildland firefighter safety and fire behavior for some 35 years now. It is our belief that we should reexamine these established beliefs in the light of new fire behavior research and operational experiences accumulated since 1977.

Defining and characterizing fire behavior

One wildland fire management glossary defines fire behavior as ‘the manner in which fuel ignites, flame develops, fire spreads and exhibits other related phenomena as determined by the fire environment’ (Merrill and Alexander 1987). The more important fire behavior characteristics from the practical standpoint of fire suppression are considered to be (Alexander 2000):

- Forward or head fire rate of spread
- Fireline intensity
- Flame front dimensions
- Spotting pattern (densities & distances)
- Fire size and shape
- Rate of perimeter increase
- Burn-out or smoulder time

The thermal environment of a wildland fire is perhaps best characterized by the record or signature it leaves in the form of a time-temperature trace as the moving flame front passes by a given point (Fig. 2). Photography from within the fire itself offers yet another perspective. See for example the still photographic images presented in Taylor *et al.* (2004) and the ‘Inside the Fire’ video at http://www.youtube.com/watch?v=zvPa_yEE4E, both from the International Crown Fire Modelling Experiment, Northwest Territories, Canada (Stocks *et al.* 2004).

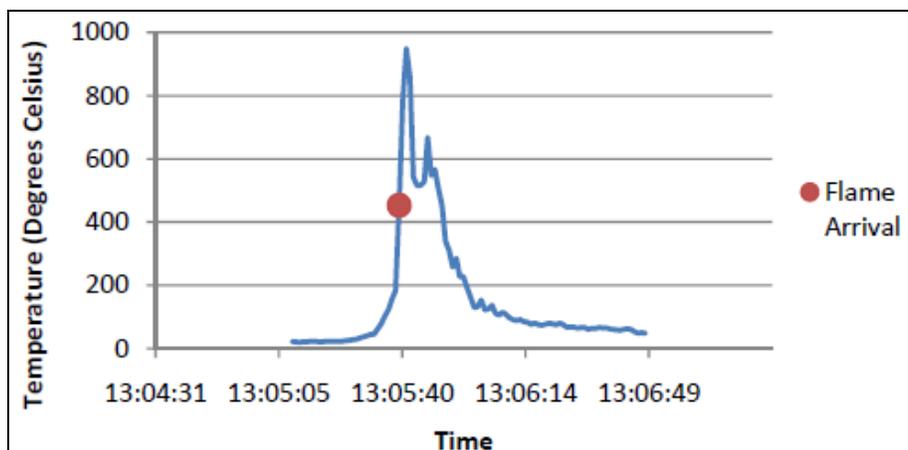


Fig. 2. Example of a time-temperature trace obtained from a thermocouple and an electronic datalogger (i.e. a ‘thermo-logger’) for a single height above the ground surface just prior to, during, and immediately following passage of the flame front. In this case, the thermal signature is for a grass fire in southern Ontario, Canada (from Kidnie 2009).

Simulation of fire behavior characteristics

Our initial intent was to contrast fire behavior potential in three broad fuel complexes, namely grass, shrubland, and conifer forest, each exhibiting relatively simple structural characteristics, both vertical and horizontally. Furthermore, it was our desire to use models for predicting fire behavior derived from empirical datasets covering a wide range of burning conditions (Cruz and Gould 2009), as opposed to theoretical or physical based models that have undergone limited evaluation. In this respect, the empirical based models for predicting rate of fire spread described by Cheney *et al.* (1993, 1998) for the natural or ungrazed pasture grass fuel type and by Cruz *et*

al. (2008) for the conifer forest using the litter fuel model of Cruz and Fernandes (2008) were considered most suitable. A similar, compatible model or modeling system for chaparral could not be found, although qualitative comparisons against the other two fuel complexes were considered possible (Table 1) on the basis of empirical field studies of fire behavior, wildfire observations, and model simulations of fire behavior (Chandler *et al.* 1963; Green and Schimke 1971; Rothmel and Philpot 1973; Countryman 1974; Stephens *et al.* 2008). The fire behavior simulations focused on forward or head fire rate of spread, fireline intensity, and flame dimensions (Fig. 3).

Table 1. Relative rankings of simulated fire behavior characteristics presented in Figs. 4-6 as well as nominal numerical values for other fire behavior characteristics amongst three broad fuel complexes

Fire behavior characteristic	Grass	Chaparral ^A	Conifer forest
Forward or head fire rate of spread	Highest	Intermediate	Lowest
Fireline intensity	Lowest	Intermediate	Highest
Flame length/height	Lowest	Intermediate	Highest
Flame depth	Lowest	Intermediate	Highest
Flame front residence time (sec)	5-10	10-20	30-60
Maximum spotting distance (km)	<0.1	~6.5	~16
Burn-out or smoulder time (min)	1	1-3	10-20
Maximum firewhirl size potential	Small	Moderate	Large

^AAssuming a live moisture content of 75%.

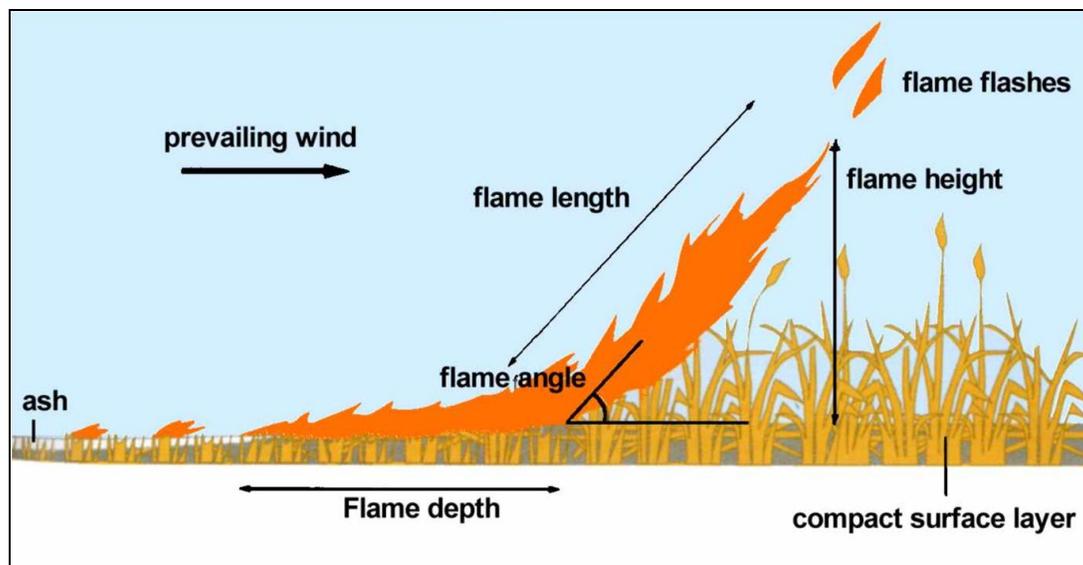


Fig. 3. Idealized cross-section of a surface head fire in grass fuels on level terrain (from Cheney and Sullivan 2008).

Nominal fuel characteristics were selected for the simulations of fire behavior. For grass, this involved a fuel load and height of 0.35 kg/m² and 35 cm, respectively (representing roughly the average values the model is based on), and a 100% degree of curing. The conifer forest was viewed to be 14 m tall with a canopy base height of 6 m, canopy bulk density of 0.23 kg/m³, and

available surface fuel load of 1.3 kg/m²; this is similar to the red pine plantation fuel complex described by Van Wagner (1968, 1977). The best way to contrast differences in fire behavior potential between the two fuel complexes was to vary the wind speed. For the purposes of the fire behavior simulations the following environmental conditions, viewed as being reasonably 'severe', were held constant: slope steepness – 0% (i.e. flat to gently undulating topography); air temperature – 30 °C; relative humidity – 20%. This equates to 4.8% moisture content in fully-cured grass (Cheney and Sullivan 2008) and 6.0% fine dead surface fuel moisture content in the conifer forest (Rothermel 1983).

What distinguishes wildland fires from structural or urban fires is their horizontal spread potential. The forward or head fire rate of spread versus wind speed simulation for the two fuel complexes presented in Fig. 4 clearly shows that grass has a higher potential spread rate than the conifer forest. However, it is worth noting the sudden increase in spread rate with the onset of crowning in the conifer forest evident in Fig. 4.

Fireline intensity (I , kW/m) represents the energy output rate per unit length of fire front and is directly related to flame size (Byram 1959). Numerically, it is equal to the product of the net low heat of combustion (H , kJ/kg), amount of fuel consumed in the active flaming front (w , kg/m²), and a spreading fire's linear rate of advance (R , m/min):

$$I = (H \times w \times R) \div 60 \quad (1)$$

A nominal value of 18 000 kJ/kg is commonly assigned to H for the purposes of calculating fireline intensity (Stocks *et al.* 2004).

It is quite evident from the simulation of fireline intensity versus wind speed for the two fuel complexes (Fig. 5), that varying combination of spread rates and fuel consumption levels can lead to a more complicated pattern than was the case with rate of fire spread. Again, the effect of the onset of crowning is evident both in terms of the increased spread and the additional fuel consumed from within the canopy layer or strata. Below this crown fire threshold, grass fires yield higher fireline intensities than surface fires in conifer forests.

The average flame height of fully-developed crown fires is generally regarded as being at least two times the stand height (Cruz and Alexander 2010). Empirical relationships have been established between forward or head fire rate of fire spread and flame height for grazed and ungrazed pastures Cheney and Sullivan (2008, p. 38, Fig. 4.6) based on experimental fires carried out in grass as described by Cheney *et al.* (1993).

The flame depth (D , m) of a spreading wildland fire is a product of R and the flame front residence time (t_r , min) which represents the duration that a moving band or zone of continuous flaming combustion persists at or resides over a given location (Fons *et al.* 1963):

$$D = R \times t_r \quad (2)$$

Flame front residence times for conifer forest fuel types at the ground surface are commonly 30 sec to 1 min compared to 5 to 10 sec in fully-cured grass fuels (Table 1). The simulations of fire behavior shown in Fig. 6 are based on a flame front residence time of 0.75 min (i.e. 45 sec) for conifer forest at the ground surface and 0.125 min (i.e. 7.5 sec) for grass. Free-burning fires in conifer forests are capable of producing very deep flame fronts compared to grass fires, once crowning commences (Fig. 6).

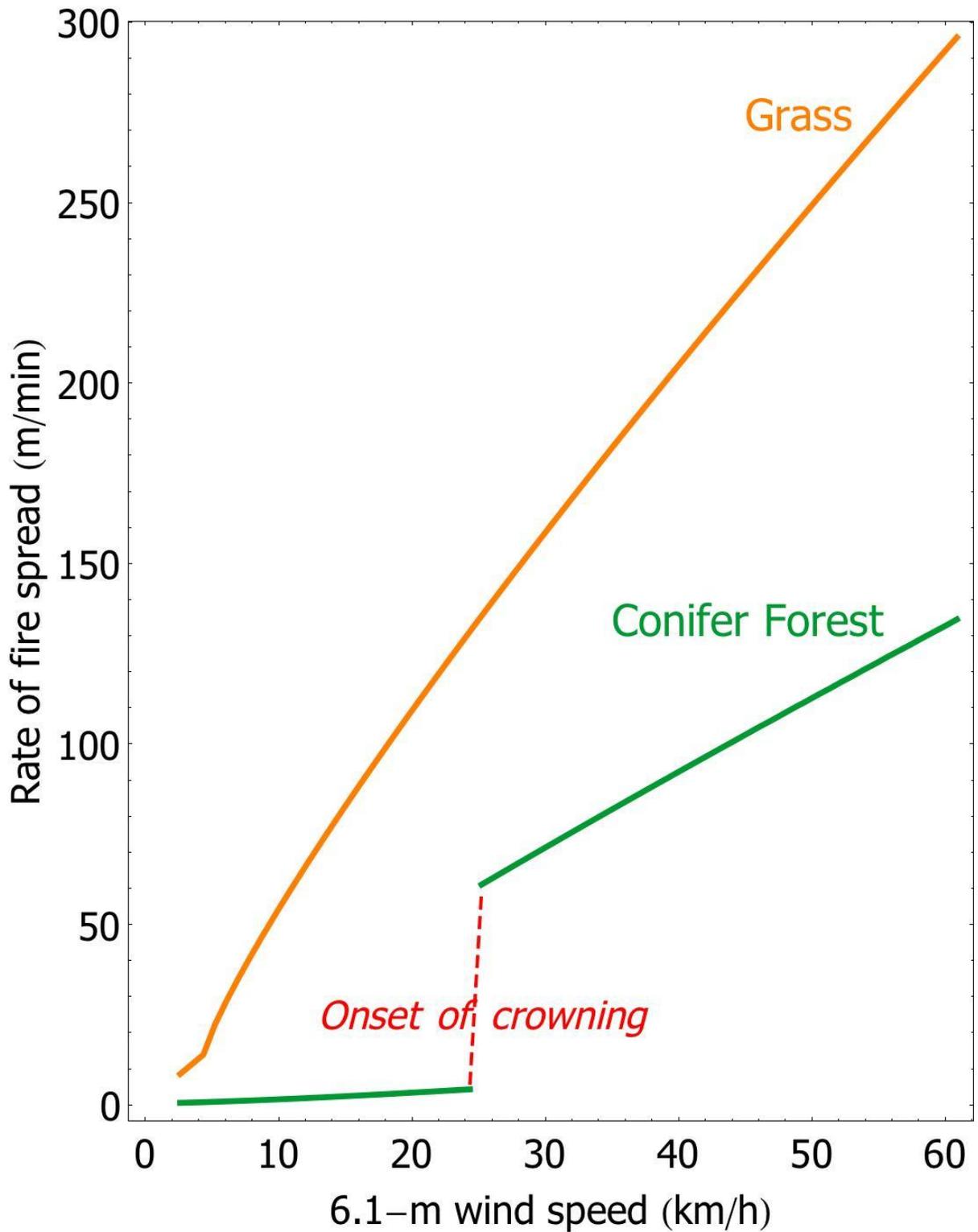


Fig. 4. Comparison of simulated rate of fire spread on level to gently undulating terrain as a function of wind speed for two broad fuel complexes. Refer to the text for specific details on fuel characteristics and other environmental conditions.

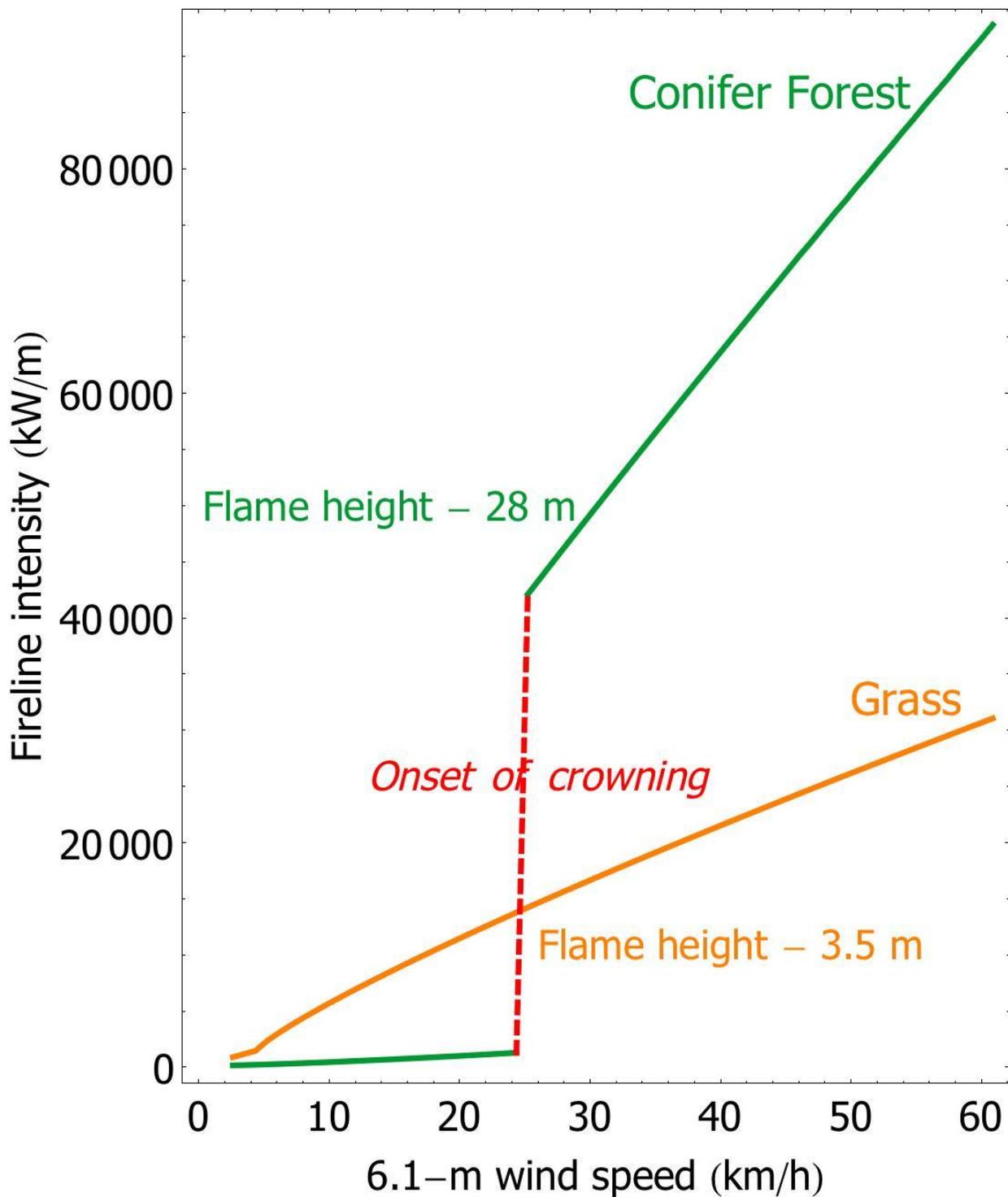


Fig. 5. Comparison of simulated fireline intensity and associated flame heights (at the onset of crowning) on level to gently undulating terrain as a function of wind speed for two broad fuel complexes. Refer to the text for specific details on fuel characteristics and other environmental conditions.

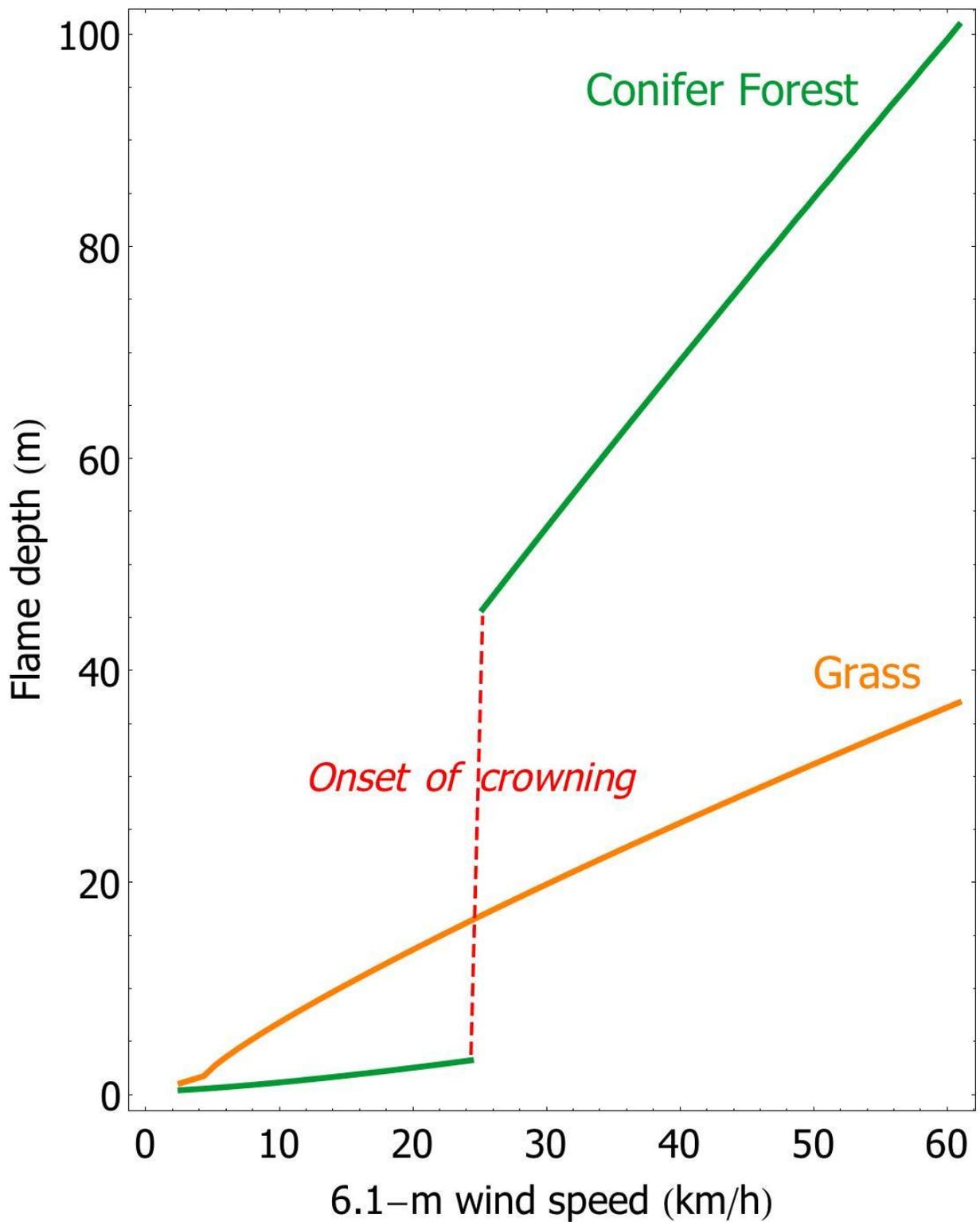


Fig. 6. Comparison of simulated flame depth on level to gently undulating terrain as a function of wind speed for two broad fuel complexes. Refer to the text for specific details on fuel characteristics and other environmental conditions.

Discussion of fire behavior simulations in light of firefighter safety

A summary of the relative rankings in simulated fire behavior for grass, shrubland and conifer forest fuel complexes is given in Table 1 along with nominal values for other characteristics of fire behavior. There are other elements that one might wish to consider adding to the list, including direct implications for fire suppression such as firefighter travel rates for escape routes (Alexander 2011b) and fireline production rates (Broyles 2011).

The implications for fire safety between grass and conifer forest as a result of differences in fire behavior are clear. Grass fires are certainly far more responsive to the influence of wind than surface and crown fires in conifer forests which can easily lead to very sudden changes in the rate of spread and the direction of fire spread as a result of the natural variability in winds (Cheney *et al.* 2001). However, the heavy fuel loads associated with conifer forests easily lead to far more intense flame fronts than grass fires are capable of producing (Alexander *et al.* 2009a), thereby requiring larger safety and survival zones for firefighters (Sullivan *et al.* 2003; Alexander *et al.* 2009), especially for the case of crown fires (Alexander *et al.* 2009b). Furthermore, the burn-out or smoulder times associated with conifer forests are considerably greater than those experienced in grass fuelbeds (Table 1) (Sullivan *et al.* 2002; Cheney and Sullivan 2008). Both of these factors effectively eliminate at two of the four survival options available to a person during a wildland fire entrapment or burnover (Alexander *et al.* 2011), namely numbers 2 and 4:

1. Retreat from the fire and reach a safe haven.
2. Burn out a safety area.
3. Hunker in place.
4. Pass through the fire edge into the burned-out area.

A word on the significance of the surface fire-to-crown fire transition phenomena found in conifer forests is in order. This has been described in laymen's terms as the fire 'shifting gears' (R. Arthur, Alberta Sustainable Resource Development, pers. comm., 2011). If a conifer forest stand is capable of active crown fire propagation, the most obvious thing that occurs with the onset of crowning is the dramatic increase in flame height (and in turn the radiant heat flux) -- from perhaps nearly 3 m to almost 30 m in a span of a few seconds. It is worth noting that this abrupt change in fire behavior is not presently featured in fire modeling systems like NEXUS (Scott and Reinhardt 2001), FFE-FVS (Reinhardt and Crookston 2003), FARSITE (Finney 2004), FlamMap (Finney 2006) and FMAPlus (Carlton 2005), but rather a gradual increase in potential crown fire behavior. Warnings regarding this deficiency have been issued (Alexander 2010, 2011a). Recent fire research in Australia has identified wind speed thresholds in shrubland fuel complexes similar to those displayed in Figs. 4-6 (Cruz and Gould 2010; Cruz *et al.* 2010).

Concluding remarks

The results obtained from the simulations of fire behavior suggest that one needs to be wary of the tendency to generalize too much when it comes to describing the safety implications of wildland fires amongst firefighters as well as members of the general public. The following are the key 'take-home' messages emanating from the analyses reported on in this paper:

- Wildland fires are complex and varied, dependent on numerous combinations of fuels, topography and weather. We must be very careful not to think, when dealing with this complexity, that a single set of fire safety guidelines will always fit every situation. Examination of the firefighter fatalities due to entrapments and burnovers,

including near-fatal fires (e.g. Pearce *et al.* 2004), that have occurred since 1976 would be in order (Morse 1990), especially in light of changes in fuel conditions and climate change.

- There is a general need to emphasize that there are many aspects or characteristics of wildland fire behavior and we need to strive to relate fire behavior more directly to fire suppression (e.g. fireline production rates, firefighter travel rates for escape routes, safety and survival zone sizes) -- in other words, a more holistic approach to the overall wildland fire environment, including the human dimension (Sutton 2011).
- Provide scientific explanation for Wilson's (1977) common denominators in light of fire behavior research completed since that time (e.g. Sneeuwjagt and Frandsen 1977; Clark 1983; Cheney and Gould 1995, 1997; Cheney and Sullivan 2008; Alexander and Cruz 2009; Cruz 2010), including 'lessons relearned' (e.g. Butler *et al.* 1998), and incorporate this information into fire behavior and fire safety training.
- Look to incorporate the latest insights into the dynamics of wildland fire behavior into training and operations. For example, rather than viewing fire spread rate as gradually increasing with increasing wind speed (see, for example, Rothermel 1972, p. 38, Fig. 25), emphasize the "step" pattern that occurs in many fuel types once wind speed thresholds are exceeded (McArthur 1967; Lindenmuth and Davis 1973; Davis and Dieterich 1976; Bruner and Klebenow 1979; Burrows *et al.* 1991; Cruz *et al.* 2005).

We believe these updates, integrated with Wilson's (1977) original five common denominators of fatal fires, would constitute a major step towards improving the forecasting of probable fire behavior with respect to ensuring the safety of firefighters and members of the general public.

Dedication

One of us (MEA) met Carl Wilson for the first time in 1980 and subsequently maintained contact with him over the years up until his death at the age of 94 on August 21, 2009¹. Carl was one of the globe's true pioneering wildland fire researchers. This paper is affectionately dedicated to his memory.

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¹ <http://www.berkeleydailyplanet.com/issue/2009-09-03/article/33676?headline=Carl-C.-Wilson-1915-2009>
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Appendix

Table A1. International System (SI)-to-English unit conversion factors

SI unit	Multiplication factor	English unit	Inverse factor
Degree Celsius (°C)	× 5/9 (°F -32)	= Degree Fahrenheit (°F)	(9/5 °C) +32
Kilogram per cubic meter (kg/m ³)	× 0.624	= Pound per cubic foot (lb/ft ³)	16.0
Kilogram per square meter (kg/m ²)	× 0.205	= Pound per square foot (lb/ft ²)	4.88
Kilojoule per kilogram (kJ/kg)	× 0.430	= Btu per pound (Btu/lb)	2.32
Kilometer	× 0.621	= Mile (mi)	1.61
Kilometer per hour (km/h)	× 0.621	= Mile per hour (mi/h)	1.61
Kilowatt per meter (kW/m)	× 0.289	= Btu per second per foot (Btu/s-ft)	3.46
Meter (m)	× 3.28	= Feet (ft)	0.305
Meter per minute (m/min)	× 3.28	= Feet per minute (ft/min)	0.305
Meter per minute (m/min)	× 2.98	= Chain per hour (ch/h)	0.335
Square meter per hectare (m ² /ha)	× 4.36	= Square feet per acre (ft ² /ac)	0.230
Number per hectare (no. /ha)	× 0.405	= Number per acre (no./ac)	2.47

Note: factors are given to three significant digits. To convert a English unit to a SI unit, multiply by the inverse factor given in the right-hand column. A “Btu” is a British thermal unit.

² [http://www.wildlandfire.com/docs/2003_n_before/carl-wilson\(1977\).pdf](http://www.wildlandfire.com/docs/2003_n_before/carl-wilson(1977).pdf) [Verified 12 July 2011]