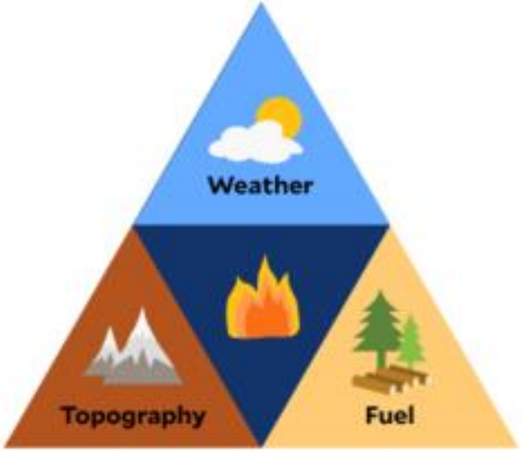
FIRE BEHAVIOR

FIRE BEHAVIOR

The expression *fire behavior* refers to the manner in which *fuel ignites*, *flame develops*, and *fire spreads* and exhibits other related phenomena, under the influence of weather, topography, fuels, and their interactions.

https://sustainability.yale.edu/explainers/yale-experts-explain-wildfires



Fire Behavior Triangle

The factors involved in the severity, intensity, duration, size, and season of wildfires

https://sustainability.yale.edu/explainers/yale-experts-explain-wildfires

FIRE BEHAVIOR

The *growth of a fire* may have various *phases*: ignition, transition to spread and acceleration, steady-state spread, increase in intensity, and extreme behavior. Not all stages are presente in all fires.

Fires typically *start at a point*. When the fuel is consumed at the ignition spot flames spread out, forming a linear perimeter that gradually expands into a *circular crown* (donut) shape that has a burned core.

https://sustainability.yale.edu/explainers/yale-experts-explain-wildfires

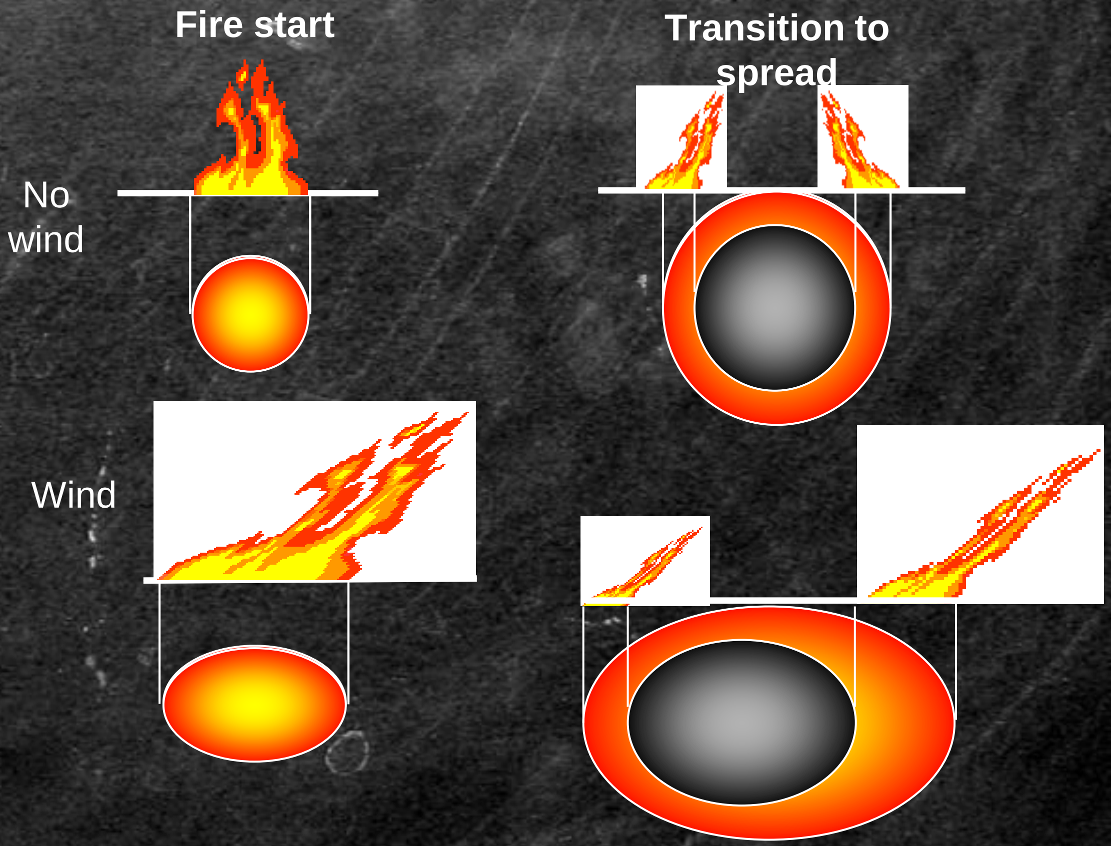
Once the fire acquires this shape, aeration of the combustion increases, temperature drops, and flame height decreases relatively to the initial stage of the fire.

FIRE BEHAVIOR

On ***flat ground and without wind*** (assuming homogeneous fuels), fire spreads equally fast in all directions and acquires a ***circular shape***.

In ***sloping terrain and/or with wind***, flames tilt and the fire shpe becomes ***elliptical***.

After a while, the fire starts displaying different parts, or sections, such as ***head, or front, back, and flanks***.



FIRE BEHAVIOR

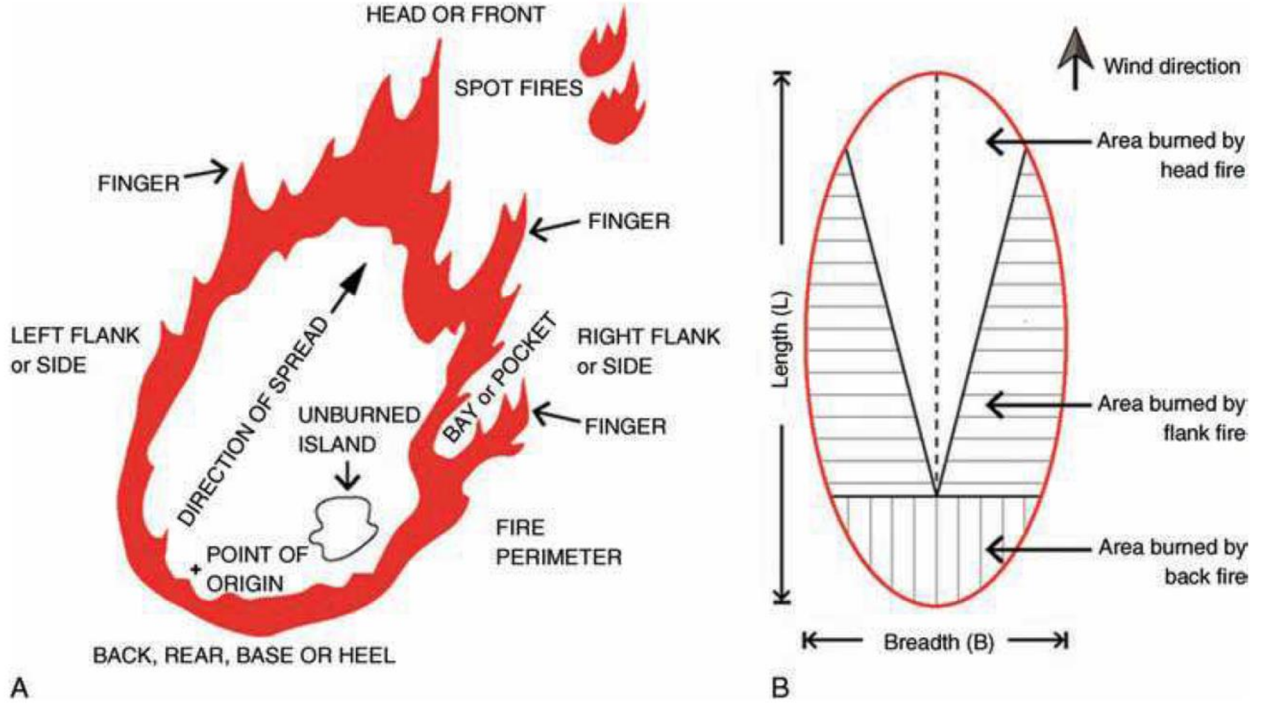


Figure 14.4 Schematic diagrams illustrating: (A) the parts of a free-burning, wind-driven wildland fire (after Moberly *et al.*, 1979); (B) a simple elliptical fire growth model (after Van Wagner, 1969), with the point of ignition or origins located at the junction of the four area growth zones. Reproduced with permission of the Canadian Institute of Forestry–Institut forestier du Canada.

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. Ch. 14.

FIRE BEHAVIOR

When the rate of fire spread stops accelerating the fire reaches a so-called equlibrium stage, or *steady-state behavior*. This does not imply that the fire will grow at constant rate of spread and intensity, regardless of environmental conditions.

Fire behavior under steady state is controlled by the environmental conditions that determine the fire perimeter geometry and they spread continuously through surface fuels.

This behavior is *different from* that of a *starting fire*, where there are interactions between different zones of the fire perimeter, and from *extreme fires*, which generate environmental conditions that feed-back on their own behavior.

FIRE BEHAVIOR

The *steady-state fire behavior* stage displays some distinctive characteristics:

Growth is *self-sustained*, the fire releases enough energy to continue spreading without external input.

Displays an *approximately elliptical* perimeter.

Shape change and area grows, but the fire *intensity varies* within a relatively *narrow range*.

Spread through surface fuels with *heat transfer dominated by radiation*, which is complemented by convection at the head of the fire.

FIRE BEHAVIOR

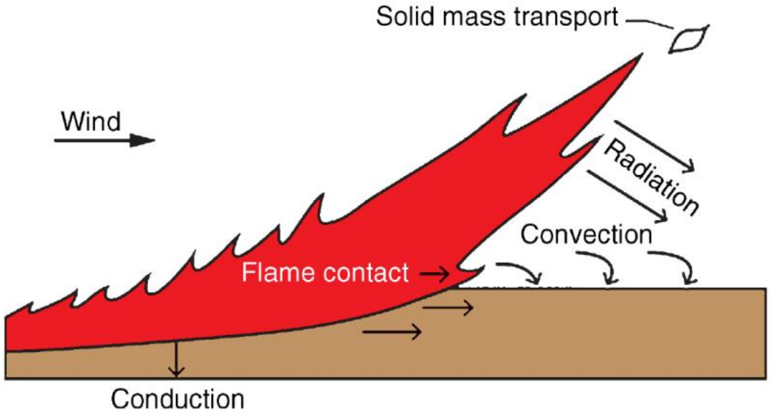
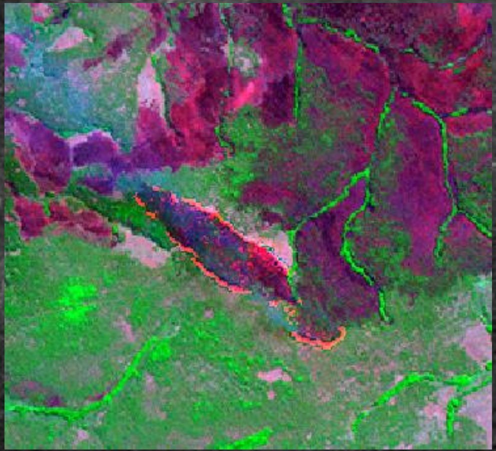
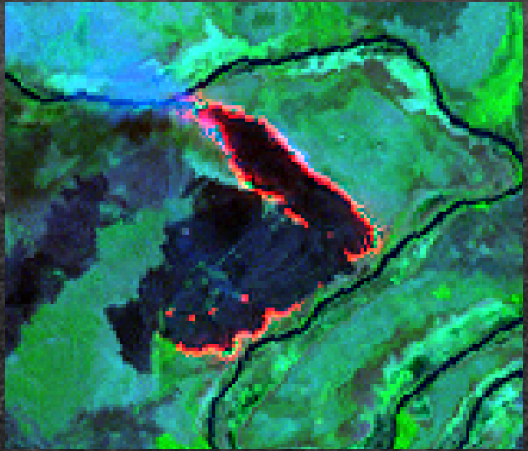


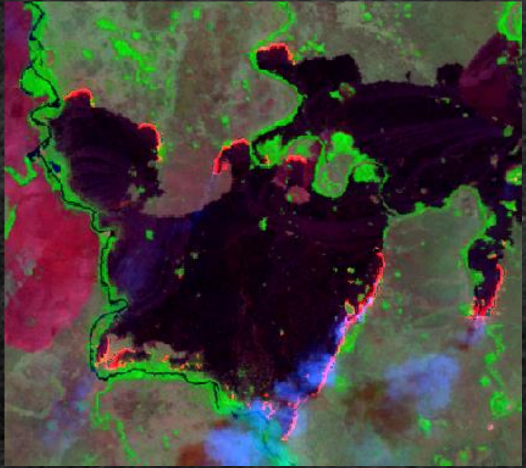
Figure 14.5 Schematic diagram illustrating the mechanisms of heat transfer involved in a wind-driven surface fire on level terrain (after Rothermel, 1972).

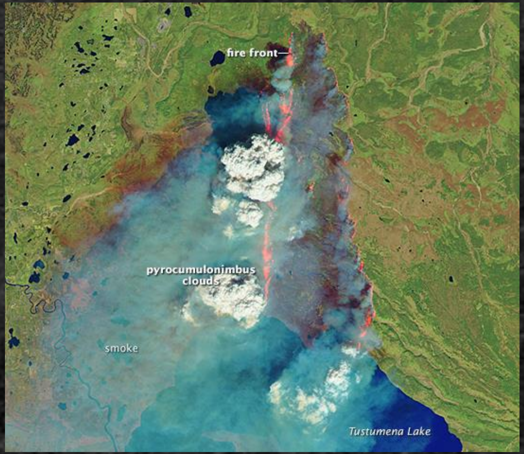
Fire on Earth: An Introduction, First Edition. Andrew C. Scott, David M.J.S. Bowman, William J. Bond, Stephen J. Pyne and Martin E. Alexander. Ch. 14.

FIRE BEHAVIOR

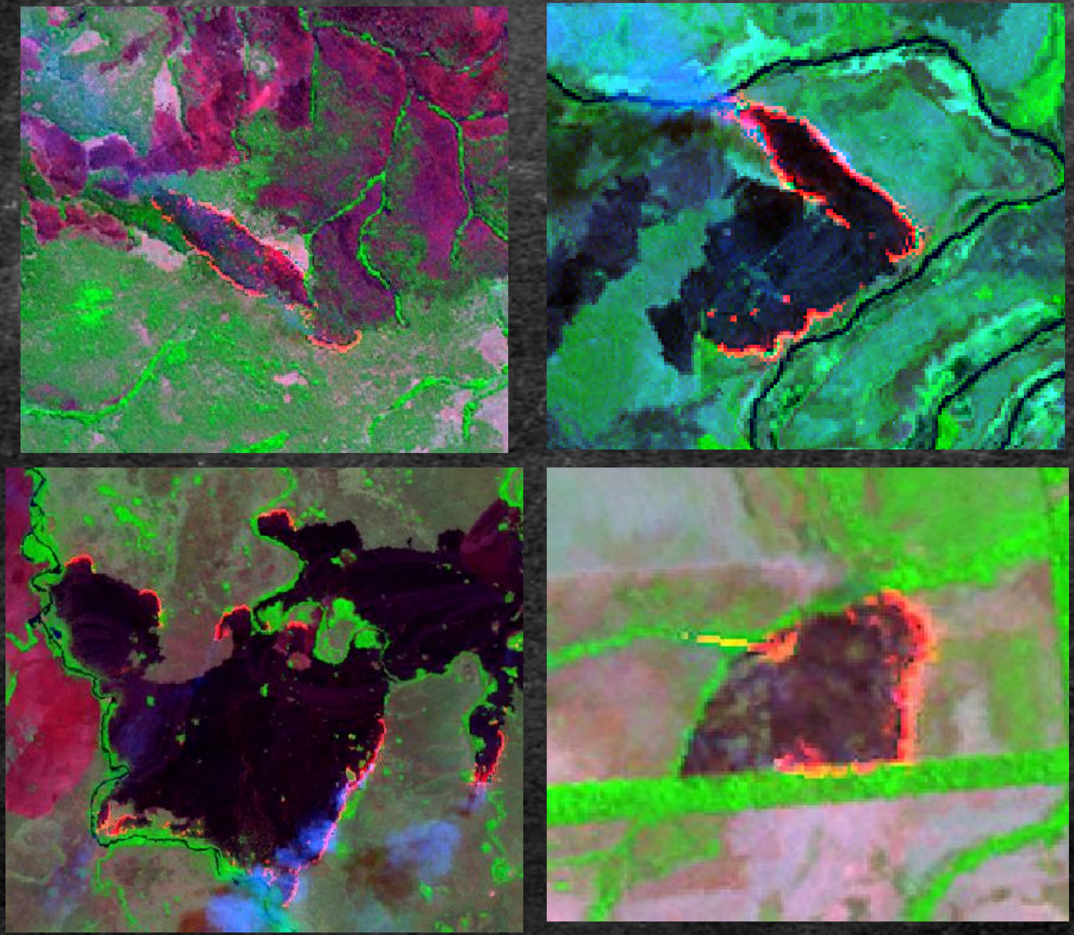








FIRE BEHAVIOR



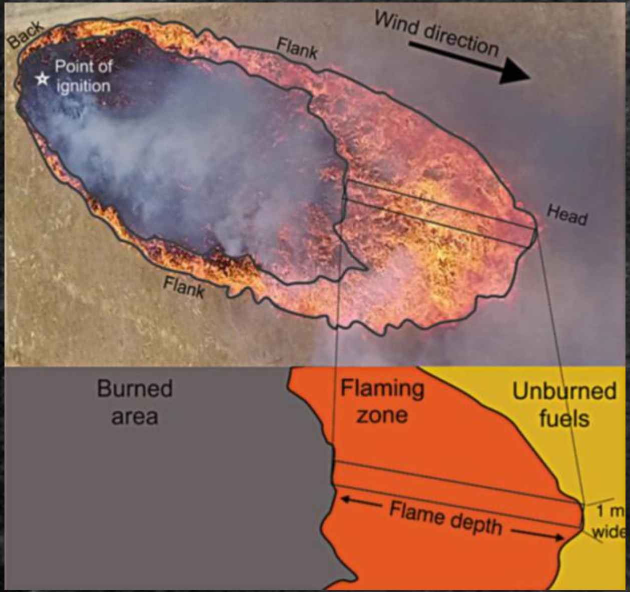
Satellite images of fires spreading under steady-state conditions. Notice linear, often elliptical flame fronts.

Surface spread is interrupted by low flammability landscape features, such as rivers and riparian vegetation corridors.

FIRE BEHAVIOR

FIRE BEHAVIOR

Fire intensity is its rate of heat release, i.e. the quantity of heat released per unit time. The most widely used intensity measure is ***fireline intensity***, or Byram's intensity (I_B). It measures the ***rate of heat release per linear meter of the flame front***.



$$I_B = h * w * r$$

I_B – fireline intensity ($kW.m^{-1}$)

h – fuel heat content ($kJ.kg^{-1}$)

w – fuel consumed ($kg.m^{-2}$)

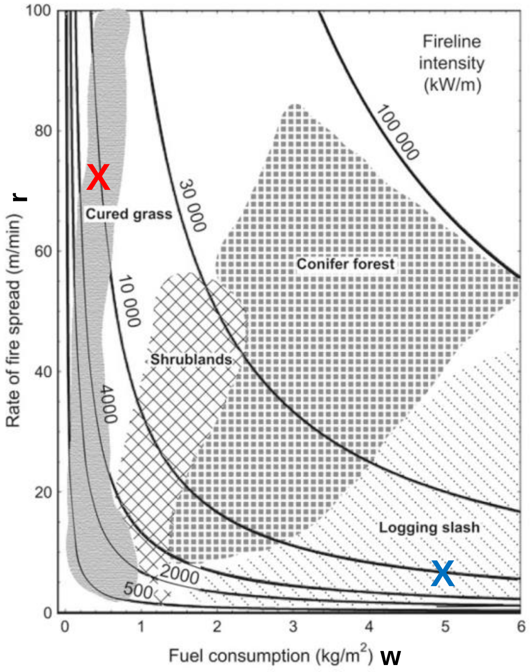
r – fire rate of spread ($m.s^{-1}$)

$kJ.\cancel{kg}^{\cancel{-1}}.\ \cancel{kg}.m^{\cancel{-2}-1}.\ \cancel{m}.s^{-1}$

$kJ.s^{-1}.m-1 \Leftrightarrow kW.m^{-1}$

FIRE BEHAVIOR

Fireline Intensity, Fig. 2 Graphical representation of five distinct levels of fireline intensity as a function of rate of fire spread and fuel consumption, assuming a "net" fuel low heat of combustion of 18,000 kJ/kg, for four broad fuel complexes as described in Stocks and Kauffman (1997) based on experimental field fires. (From Page et al. 2013)



The fire characteristics curve expresses I_B as the product of the heat released by the fire per unit area, h.w ($kJ.m^{-2}$), by the fire rate of spread, r ($m.min^{-1}$). The figure on the left assumes a fuel heat content of 18.000 $kJ.kg^{-1}$.

The cured (dry) ***grass fires consume little fuel*** per unit area, but when they ***spread very fast*** are highly intense.

The ***logging slash fires***, which ***spread*** much more ***slowly***, may also become very intense because they ***consume large quantities of fuel*** per unit area.

X (cured grass fire) – high **r**, low **w** → I_B = 10.000 $kW.m^{-1}$

X (logging slash fire) – low **r**, high **w** → I_B = 10.000 $kW.m^{-1}$

Fireline Intensity. Martin E. Alexander and Miguel G. Cruz. In S. L. Manzello (ed.), *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*.

FIRE BEHAVIOR

Fireline Intensity, Table 1 Range in fireline intensities and average flame heights in open eucalypt forests in Australia by various categories (After Cheney 1981)

Fireline intensity rating	Fireline intensity (kW/m)	Maximum flame height (m)	Remarks
Low	<500	1.5	Upper limit recommended for fuel-reduction burning
Moderate	500–3000	6	Scorch of complete crown in most forests
High	3000–7000	15	Crown fires in low forest types – Spotting > 2 km
Very high	7000–70,000	>15	Crown fire in most forest types – Fire storm condition at upper intensities

Practical interpretations of fireline intensity

Fireline Intensity, Table 2 Fire suppression interpretations of flame length and fireline intensity used in the USA (Adapted from Burgan 1979)

Flame length (m)	Fireline intensity (kW/m)	Fire suppression interpretations
<1.2	<346	Fire can generally be attacked at the head or flanks by persons using hand tools. Handline should hold the fire
1.2–2.4	346–1730	Fires are too intense for direct attack on the head by persons using hand tools. Handline cannot be relied on to hold fire. Equipment such as plows, dozers, pumpers, and retardant aircraft can be effective
2.4–3.4	1730–3459	Fires may present serious control problems – torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective
>3.4	>3459	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective

Fireline Intensity. Martin E. Alexander and Miguel G. Cruz. In S. L. Manzello (ed.), *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*.

FIRE BEHAVIOR

Table 2
Fire weather conditions, and observed and predicted fire behavior values associated with the experimental fires

Fire no.	Temp. (°C)	Relative humidity (%)	Open wind speed, 1.8 m (m min^{-1})	Rate of spread (m min^{-1})		Fuel consumption (kg m^{-2})		Fire intensity (kW m^{-1})	
				Observed	Predicted	Observed	Predicted	Observed	Predicted
1	27.9	51.0	10.9	6.6	5.6	2.4	2.4	6125.7	5380.7
2	27.7	50.0	10.8	4.2	4.5	1.3	1.3	2533.6	2906.8
3	26.9	55.0	11.8	5.5	5.4	1.7	1.7	4130.5	4428.9
4	26.7	52.0	11.3	5.1	5.2	1.7	1.8	3852.1	4154.6
5	26.0	61.0	9.0	5.1	5.3	3.1	3.1	5654.4	5865.2
6	25.7	67.0	6.7	3.1	3.8	2.5	2.6	3110.9	3970.4
7	25.9	65.0	5.8	4.2	2.9	2.6	2.3	3650.0	2487.8
8	26.5	65.0	6.3	3.3	2.9	2.1	1.8	2603.9	2187.2
9	26.5	65.0	6.7	2.4	3.1	2.1	1.8	1913.9	2400.8
10	26.0	65.0	7.4	2.7	2.9	1.6	1.5	1787.6	1644.3
11	29.3	55.0	4.9	2.0	2.0	1.8	1.7	1499.1	1210.4
12	28.4	58.0	2.8	0.8	1.8	2.2	2.3	748.5	1977.5
13	27.3	62.0	7.7	3.1	3.6	1.5	1.6	2522.7	2905.9
14	27.3	62.0	8.1	4.9	3.8	1.8	1.7	3906.2	3095.3
15	27.3	62.0	1.0	0.8	0.3	1.7	1.7	622.8	350.0
16	26.1	65.0	14.8	8.9	8.3	3.2	3.1	10355.3	8955.4
17	24.2	74.0	11.6	6.0	5.3	1.8	1.7	4514.0	4343.7
18	24.2	74.0	9.8	3.1	4.0	1.0	1.3	1878.0	2437.6
19	22.5	77.0	7.2	2.6	3.3	2.1	2.2	2082.6	2570.9
20	22.5	77.0	5.8	5.1	4.6	2.8	4.4	6990.1	6376.9
21	22.5	77.0	4.4	2.8	2.9	2.9	2.8	2990.0	3398.5
22	23.4	71.0	3.9	2.5	2.3	2.6	2.5	2415.3	2469.3
23	23.4	71.0	4.9	2.8	1.7	1.3	1.4	1838.5	477.4
24	25.2	69.0	11.0	4.1	5.2	1.9	1.8	3254.9	4405.1
25	25.8	66.0	7.0	3.6	4.5	2.9	3.1	4142.1	5321.4

min I_B →
Max I_B →

Range of rate of spread, fuel consumption, and *fireline intensity* in 25 experimental shrubland fires in Turkey (h = 19.000 kJ.kg^{-1}). Here, wind speed is the main meteorological driver of the differences in behavior between the most (#16) and least (#15) intense fires.

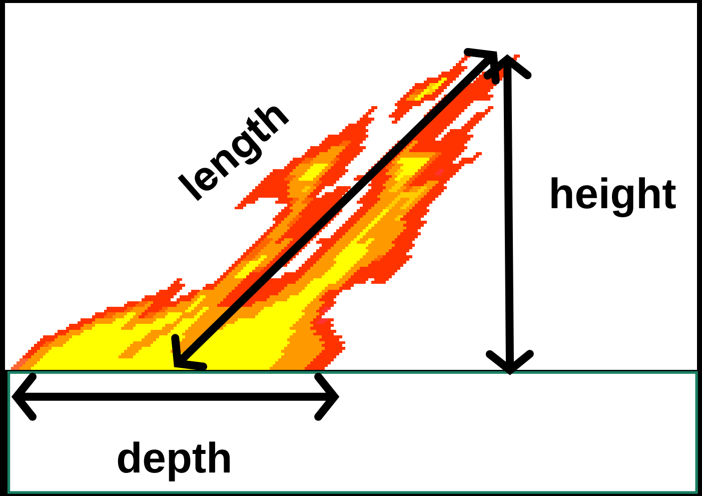
Bilgili, E., & Saglam, B. (2003). Fire behavior in maquis fuels in Turkey. *Forest Ecology and Management*, *184*(1-3), 201-207.

FIRE BEHAVIOR

Fireline intensity can be estimated from flame length, according to the relationship:

$$I_B = 273 * L_f^{2.17}$$

where I_B is the fireline intensity ($kW.m^{-1}$) and L_f is the flame length (m).



This relationship is useful for assessing fire intensity without having to measure rate of spread or consumed fuel, but visual estimation of flame length in the field is not easy.

Van Wilgen, B. W. (1986). A simple relationship for estimating the intensity of fires in natural vegetation. *South African Journal of Botany*, 52(4), 384-385.

FIRE BEHAVIOR

- Fire behavior modelling can provide invaluable assistance for tasks such as:
- Afforestation planning
- Planning of pre-suppression infrastructure
- Decision support regarding attack methods, sizing, and positioning of personnel and equipment
- Decision support regarding population evacuation

The first efforts to quantitative model fire behavior date back to the 1930s.

FIRE BEHAVIOR

Fire modeling deals with mathematical simulation of wildland fires to understand and predict their behavior. Fire modeling aims to ***predict fire behavior variables***, namely how fast the fire spreads, and how intense it is.

Fire behavior models may also be used to predict the likelihood of a surface fire climbing to the ***forest canopy level***, and provide useful information to assess whether the behavior of large wildfires is dominated by wind, or by the formation of a convection column.

Fire behavior models are used to ***estimate fire effects on vegetation, soils, water, and the atmosphere***, including plant biomass consumption, and tree mortality.

FIRE BEHAVIOR

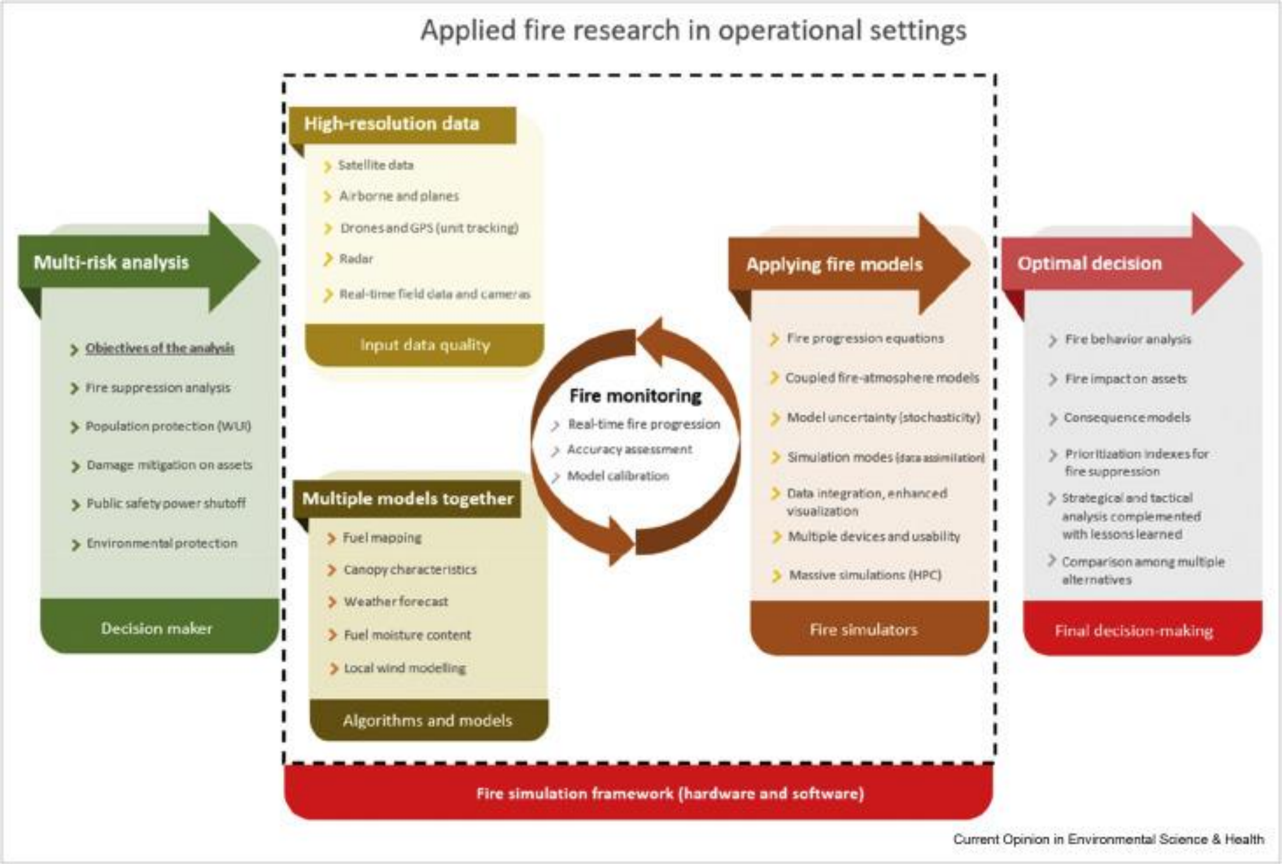


Figure 1. Innovative fire simulation frameworks including enhanced fire modeling capabilities through high-input data quality, improved models and algorithms, and accurate fire monitoring allow agencies to make decisions in operational settings, based on multi-risk analysis and specific objectives.

Cardil, A., Monedero, S., Schag, G., de-Miguel, S., Tapia, M., Stoof, C. R., ... & Ramirez, J. (2021). Fire behavior modeling for operational decision-making. *Current Opinion in Environmental Science & Health*, *23*, 100291.

FIRE BEHAVIOR

The most widely used fire spread model was originally developed by Richard Rothermel in the 1970s and it is the basis of most software applications for fire behavior prediction, such as *BEHAVE*, *FarSite*, and *FlamMap*.

Rothermel's model is *semi-empirical* and estimates the *rate of spread* of *surface fires*. Semi-empirical models are built using simple, general theoretical expressions, complemented by experimentation. They should be used for the range of conditions encompassed by the experimental model calibration work.

FIRE BEHAVIOR

Application of Rothermel's fire spread model assumes ***fuel horizontal continuity***, ***fuel uniformity*** (i.e. a single fuel model), ***fuel height <2m***, and ***steady-state fire behavior*** conditions.

Therefore, the model as originally designed was ***inappropriate*** to deal with smoldering and glowing combustion, crown fires, spotting and ignition of secondary fires, fire whirls, and prescribed burns.

Subsequently, the development of various ***modules*** that couple with Rothermel's model overcame several of these limitations.

FIRE BEHAVIOR

The basic concept of Rothermel's fire model is very simple. The fire rate of spread (*r*) is given by the ratio between a heat source and a heat sink:

$$r = \frac{heat\ source}{heat\ sink}$$

The ***heat source*** numerator represents the rate (min^{-1}) of heat (kJ) generated per unit fuelbed area (m^{-2}) burned, and the ***heat sink*** denominator represents the heat (kJ) required to raise to ignition temperature a unit volume (m^{-3}) of fuelbed.

$$r = \frac{\cancel{kJ}.m^{-2}.min^{-1}}{\cancel{kJ}.m^{-3}} = m^{3}.\cancel{m^{-2}}.min^{-1} = m.min^{-1}$$

FIRE BEHAVIOR

Heat source: ξ(csi), ϕ(phi)

$I_R . \xi . (1 + \phi_w + \phi_s)$, where

I_R – ***Reaction intensity*** (kJ.m^{-2}.min^{-1}). Rate of heat release per unit fuelbed area. Increases with fuel load and heat content; decreases with increasing bulk density and moisture content.

ξ – ***Propagating flux ratio*** (dimensionless). How much of the reaction intensity contributes to forward fire spread by heating fuel ahead of the flaming front. Most I_R heat is lost to the atmosphere, such that $\xi < 0.2$.

ϕ_w and ϕ_s – ***Wind and slope factors*** (dimensionless). ϕ_w is a function of wind speed and σ. ϕ_s depends on slope steepness and ρ_b. When wind and/or slope increase, a larger fraction of I_R is transferred to fuels ahead of the flaming front.

Andrews, P. L. (2018). The Rothermel surface fire spread model and associated developments: A comprehensive explanation. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Scott, Joe H. 2012. *Introduction to Wildfire Behavior Modeling*. National Interagency Fuels, Fire, & Vegetation Technology Transfer.

FIRE BEHAVIOR

Heat sink ε (epsilon)

$\rho_b . \varepsilon . Q_{ig}$ where

ρ_b – ***Bulk density*** ($kg.m^{-3}$). A measure of fuelbed compactness, it quantifies how much fuel mass is packed into a given volume.

ε – ***Effective heating number*** (dimensionless). The fraction of the total fuel load that must be heated to ignition. Nearly all of very fine fuel particles, like grass stems are heated to ignition temperature, so such fuels have $\varepsilon \approx 1$. Only the outer portion of coarse fuel particles are heated to ignition, so those fuels have << ε. $\varepsilon = f(\sigma)$

Q_{ig} – ***Heat of ignition*** ($kJ.kg^{-1}$). The amount of energy required to heat a given mass of fuel to its ignition temperature. It is a function of moisture content because the moisture must be vaporized before raising the fuel temperature to ignition.

Andrews, P. L. (2018). The Rothermel surface fire spread model and associated developments: A comprehensive explanation. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Scott, Joe H. 2012. *Introduction to Wildfire Behavior Modeling*. National Interagency Fuels, Fire, & Vegetation Technology Transfer.

FIRE BEHAVIOR

BOX 3.5 THE ROTHERMEL (1972) SPREAD EQUATION

$$R = \frac{I_R \,\boldsymbol{\xi}\,(1 + \Phi_w + \Phi_s)}{\rho_b \,\varepsilon Q_{ig}}$$

where

R = forward rate spread of the flaming front, measured in m min^{-1} (ft min^{-1})

I_R = reaction intensity, a measure of the energy release rate per unit of area of flaming front, in kJ m^{-2} min^{-1} (Btu ft^{-2} min^{-1})

ξ = propagating flux ratio, the proportion of the reaction intensity reaching the adjacent fuel, dimensionless

Φ_w = wind coefficient, which accounts for the effect of wind increasing the propagating flux ratio, dimensionless

Φ_s = slope coefficient, a multiplier for the slope effect on the propagating flux ratio, dimensionless

ρ_b = fuelbed bulk density, a measure of the amount of fuel per unit of volume of the fuelbed, measured in kg m^{-3} (lb ft^{-3})

ε = effective heating number, the proportion of the fuel that is raised to ignition temperature, dimensionless

Q_{ig} = heat of pre-ignition, which is the amount of heat necessary to ignite 1 kg (1 lb) of fuel, measured in kJ kg^{-1} (Btu $1b^{-1}$)

Van Wagtendonk, J. W. (2006). Fire as a physical process. *Fire in California's ecosystems*, 38-57.

FIRE BEHAVIOR

Underlying most variables in Rothermel's fire spread model are ***empirical equations obtained experimentally in combustion chambers and combustion trays***, which are based on fuel model parameters. This is what ***gives the model its predictive ability***: we can predict fire behavior based on predefined fuel models, combined with observed or hypothetical meteorological and topographic data.

For example, ***reaction intensity***, (I_R), is the product of ***reaction velocity*** (Γ', min^{-1}) times the ***consumed fuel load*** (w_n), times the ***heat content of the fuel*** (h):

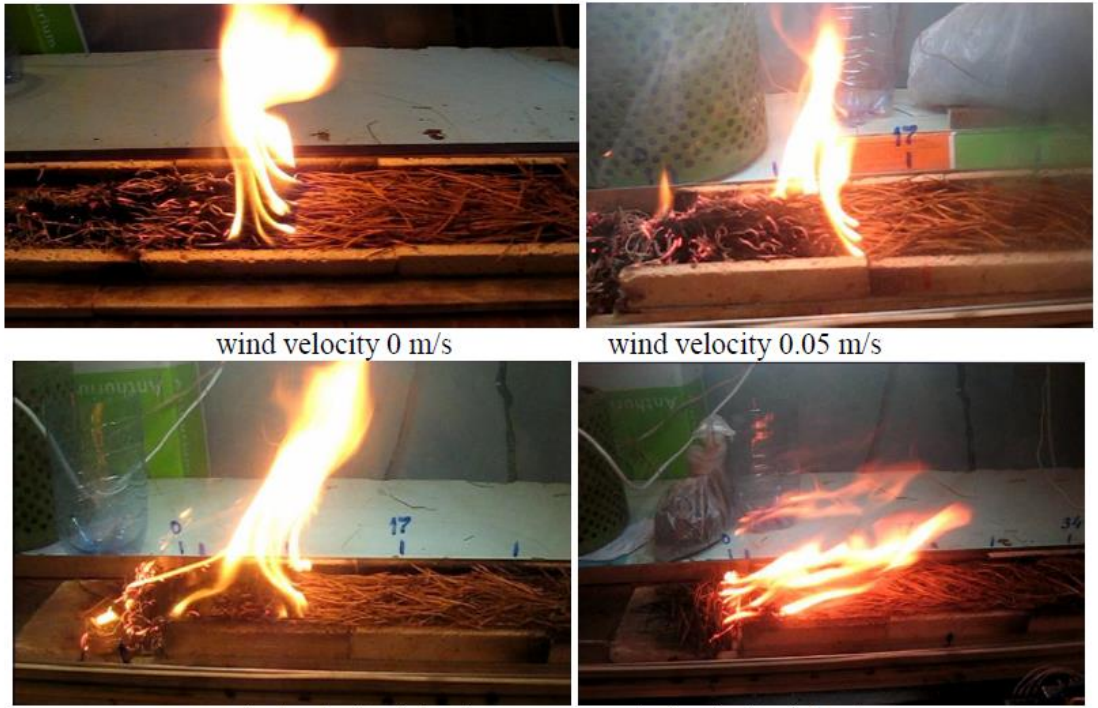
$$I_R = \Gamma'.w_n.h$$

and ***reaction velocity*** (Γ'), the rate of fuel consumption by combustion, is given by:

$$\Gamma' = \Gamma'_{max}(\frac{\beta}{\beta_{op}})^{A}.e^{A.1-(\frac{\beta}{\beta_{op}})},$$ where

β is the fuelbed ***packing ratio***, and A is an empirical parameter dependent on the fuel particle ***surface/volume ratio***, σ.

FIRE BEHAVIOR



wind velocity 0 m/s | wind velocity 0.05 m/s

wind velocity 0.1 m/s | wind velocity 0.2 m/s

Figure 6. The photos of flame spread across a bed of pine needles depending on the wind velocity in the range from 0 to 0.2 m/s.

Korobeinichev, O. P., Tereshchenko, A. G., Paletsky, A. A., Shmakov, A. G., Gonchikzhapov, M. B., Bezmaternykh, D., ... & Liu, N. (2014). The velocity and structure flame front at spread of fire across the pine needle bed: experiment. *Advances in Forest Fire Behavior*, DX Viegas (ed.). DOI:http://dx.doi.org/10.14195/978-989-26-0884-6_52

FIRE BEHAVIOR

Korobeinichev, O. P., Tereshchenko, A. G., Paletsky, A. A., Shmakov, A. G., Gonchikzhapov, M. B., Bezmaternykh, D., ... & Liu, N. (2014). The velocity and structure flame front at spread of fire across the pine needle bed: experiment. *Advances in Forest Fire Behavior*, DX Viegas (ed.). DOI:http://dx.doi.org/10.14195/978-989-26-0884-6_52

FIRE BEHAVIOR

Forest Fire Research Centre (CEIF), U. Coimbra, Portugal

FIRE BEHAVIOR

US Forest Service Missoula Fire Lab

FIRE BEHAVIOR

Purely ***empirical models, based on statistical relationships*** between the same major sets of variables as Rothermel's model (fuels, weather, and topography) and fire behavior can be very accurate, when applied within the range of conditions under which they were developed.

A study with 29 ***experimental shrubland fires***, on flat terrain (slope < 5%) and under Winter/Spring weather conditions was developed in Portugal, to ***support planning of prescribed fires***.

Four shrubland fuel types:

tall gorse, **UE** (*Ulex europaeus*);

tall heath, **EArb** (*Erica arborea*), gorse (*Ulex parviflorus*) , and gum rose (*Cistus ladanifer*);

medium heath, **EA** (*Erica australis*) and prickly broom (*Chamaespartium tridentatum*);

short prickly broom, **CT–EU** (*Chamaespartium tridentatum*) and heath (*Erica umbellata*).

Fernandes, P. A. M. (2001). Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and Management*, 144(1-3), 67-74.

FIRE BEHAVIOR

Table 2
Range of values for each fuel variable[a]

	cov. (%)	h (m)	W_f (t ha^{-1})	W_t (t ha^{-1})	% Fine	ρ_{pf} (kg m^{-3})	ρ_{pt} (kg m^{-3})
Average	84	0.7	14.6	19.8	82	2.7	2.3
Minimum	50	0.2	4.8	4.9	56	1.6	3.4
Maximum	95	1.9	36.6	64.9	99	3.5	5.0

[a] cov.: vegetation cover; h: vegetation height; W_f: elevated fine (<6 mm) fuel load; W_t: elevated total fuel load; ρ_{pf}: fine fuel bulk density; ρ_{pt}: total fuel bulk density.

Table 1
Range of values for rate of fire spread, weather and fuel moisture variables[a]

	R (m min^{-1})	U (km h^{-1})	T (°C)	RH (%)	M_d (%)	M_l (%)	S (%)
Average	4.4	9	14	53	21	85	1
Minimum	0.7	1	6	30	10	72	0
Maximum	20.0	27	22	93	40	113	5

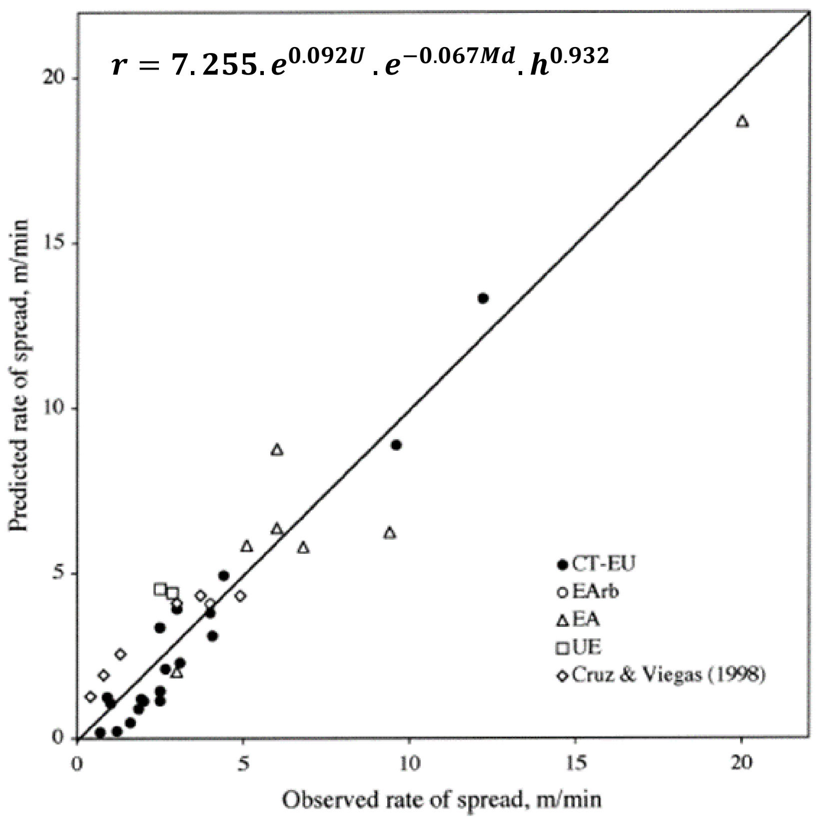
[a] R: rate of fire spread; U: surface wind speed at 2 m height; T: air temperature; RH: air relative humidity; M_d: fine (<6 mm) dead fuel moisture content; M_l: fine live fuel moisture content; S: slope steepness.

Statistically significant model variables

Experimental fires performed under cool, humid, mostly calm weather conditions, typical for prescribed burning.

Fernandes, P. A. M. (2001). Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and Management*, 144(1-3), 67-74.

FIRE BEHAVIOR



Predicted vs. observed rate of spread with an ***empirical model*** based on ***wind speed*** (U), ***dead fuel moisture*** (M_d) and ***vegetation height*** (h), separated by fuel type.

An empirical model, should not be extrapolated outside the range of values used to derive it. Therefore, this model is ***inappropriate*** for e.g., ***summer weather*** conditions, or fires in ***steep terrain***.

Fernandes, P. A. M. (2001). Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and Management*, 144(1-3), 67-74.

Crown Fires

Crown fires are ***intense, spread fast, and have damaging effects***. Their behavior is more complex than that of surface fires and crown fire modeling is less mature.

Therefore, crown fire danger assessment focuses on the estimation of their probability of occurrence, i.e. the identification of favorable environmental conditions.

The occurrence of crown fires is always dependent on the combination of adequate fuels, weather, and topographic conditions that facilitate their initiation and sustained spread.

Evaluation of crown fire probability is based on the determination of ***critical environmental conditions that lead to crown fires with distinctive types of behavior***.

Topic sources: Scott, J.H. and Reinhardt, E.D. (2001). *Assessing crown fire potential by linking models of surface and crown fire behavior* (No. 29). US Department of Agriculture, Forest Service, Rocky Mountain Research Station.
Scott Ritter's Lecture 10 – Modeling Crown Fire Initiation (https://www.youtube.com/watch?v=5EZgcJIiWiM) and Lecture 11 – Van Wagner 77 Criteria for Crown Fire Spread (https://www.youtube.com/watch?v=M9uR59KVuLE&t=1196s)

Crown Fires

Crown fire modeling addresses *two basic questions*:

- *transition* of a surface fire *to the crown level*
- fire *spread through the crown* layer

Charles van Wagner established quantitative criteria to predict:

- *torching of individual trees* by a surface fire (*passive* crown fire)
- transition to *continuous fire spread through the crown* layer (*active* crown fire)
- emergence of *independent* crown fire, without an underlying surface fire

The currently available theory and experimentation concerning crown fires applies to temperate and boreal *conifer forests* only.

Crown Fires

In a *passive crown fire* there is *torching*, or ignition of trees, isolated or in small clusters, but without formation of a dense, sustained, flame front spreading through the forest canopy.

Passive crown fire (torching)

Crown Fires

An ***active crown fire*** involves the entire fuel complex, from ground fuels to crown fuels. However, the crown fire remains ***dependent on the heat influx supplied by the surface fire to continue spreading***.

Active crown fires are characterized by the presence of a continuous flame front extending from the surface of the soil to beyond the top of the forest canopy.

Active crown fire

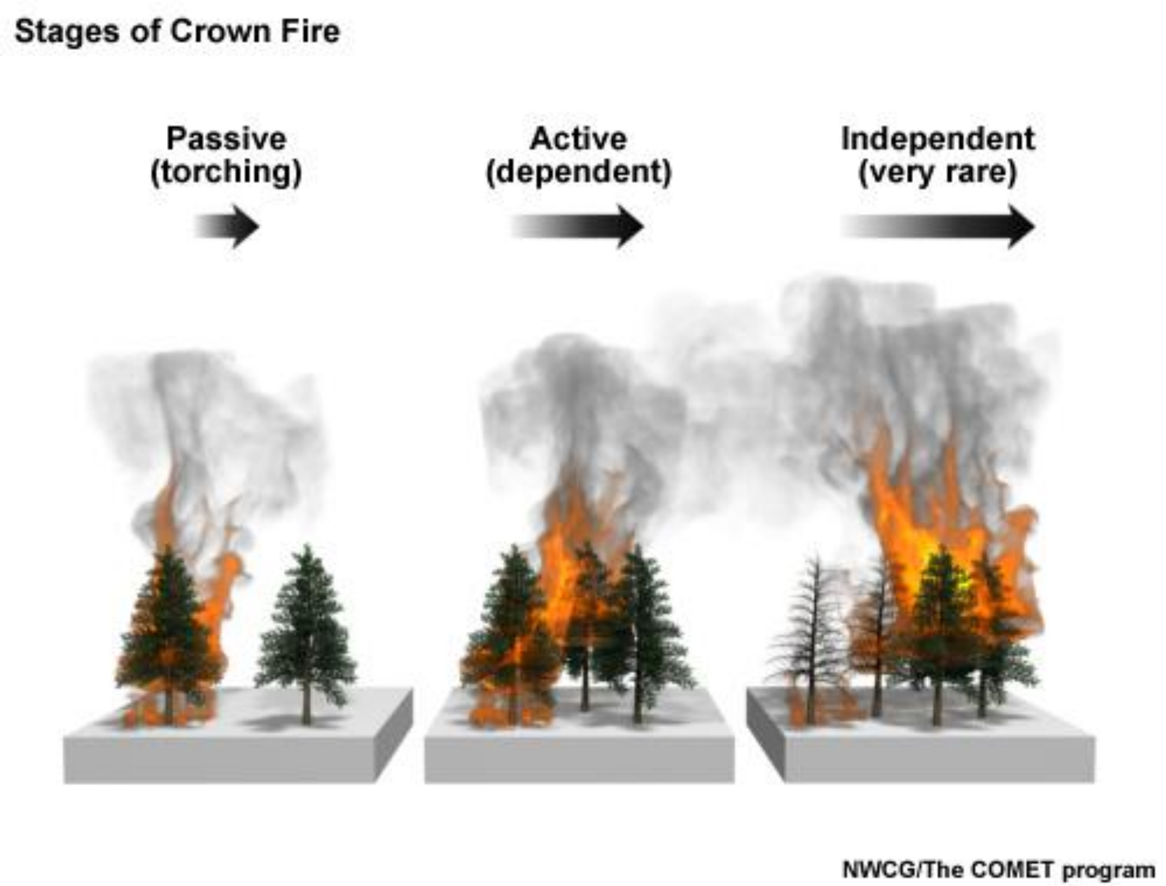
Crown Fires

An ***independent crown fire*** burns through the crown layer ***without the support of an underlying surface fire***.

It is a rare, transient phenomenon that requires a combination of ***strong wind, steep slope, and dense, severely dry tree crown foliage***.

Independent crown fire

FIRE BEHAVIOR



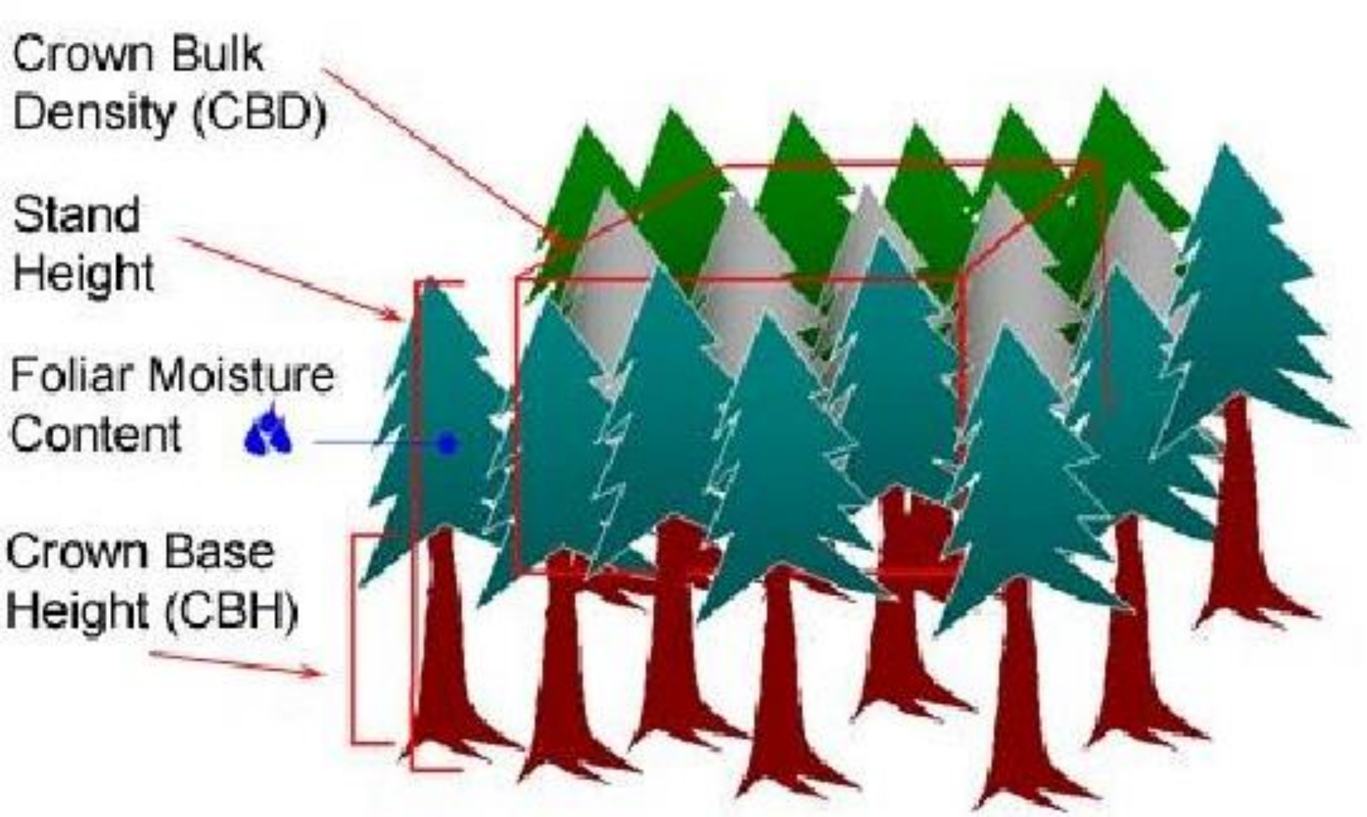
Crown Fires

Crown fires consume aerial fuels, including live and dead foliage, lichens, and fine, live and dead twigs. Typically, these fuels are *more moist and more porous than surface fuels*.

The three *key aerial fuel variables* are *canopy bulk density* (ρ_b, or CBD), *crown base height* (CBH), and *foliar moisture content* (FMC). Bulk density refers to the *forest canopy*, and not to an individual tree crown, i.e., it includes canopy gaps in its volume.

Crown base height also refers to the stand level and is harder to define. To assess the likelihood of surface-to-crown fire transition, CBH is the lowest height above the ground at which there is enough aerial fuel to spread the fire vertically into and through the forest canopy.

Crown Fires



Crown Bulk Density (CBD)
Stand Height
Foliar Moisture Content
Crown Base Height (CBH)

FIRE BEHAVIOR

Canopy base height (CBH) represents the mean height from the ground surface to the lower live crown base of the conifer trees in a forest stand (fig. 9.4.). CBH is defined as the lowest height above which the ***aerial fuel bulk density is at least 0.011 kg.m^{-3}***. This definition includes ladder fuels, such as lichens, vines, dead branches, and small trees.

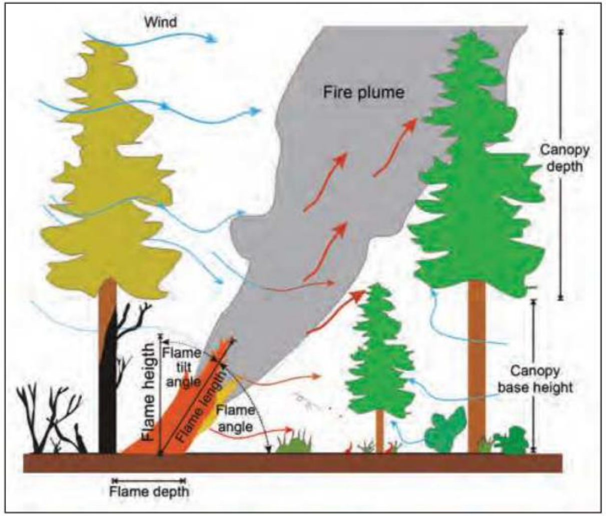
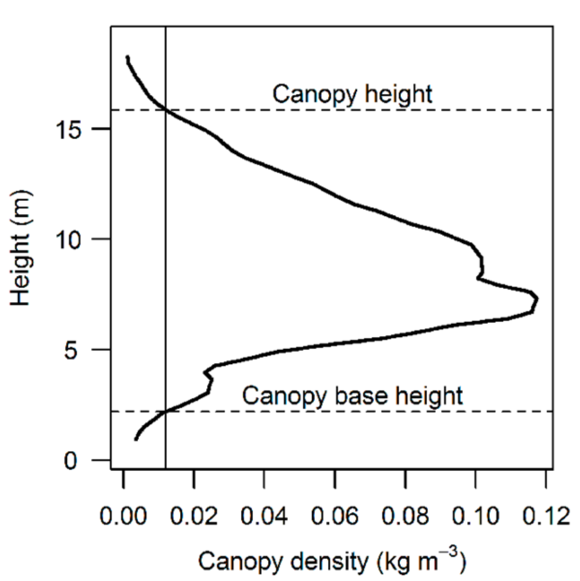


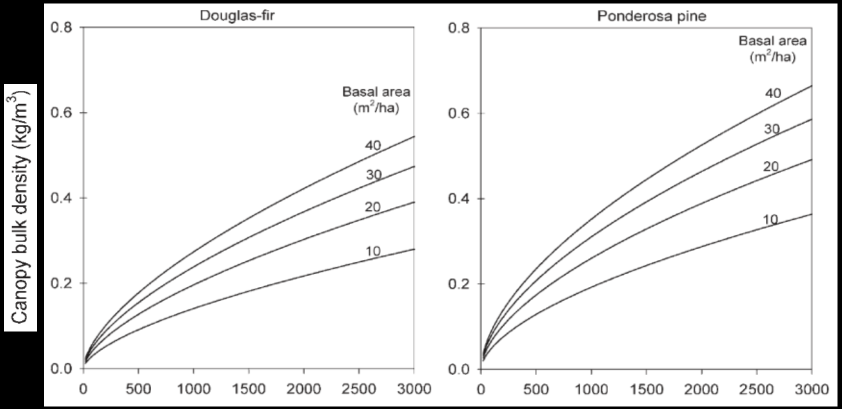
Figure 9-4—Cross section of a stylized, wind-driven surface head fire spreading behind a conifer forest canopy on level terrain.



Synthesis of Knowledge of Extreme Fire Behavior: Volume 2 for Fire Behavior Specialists, Researchers, and Meteorologists. Chapter 9: Crown Fire Dynamics in Conifer Forests. *Martin E. Alexander and Miguel G. Cruz*

FIRE BEHAVIOR

Canopy bulk density (CBD) represents the amount of ***available crown fuel within a unit volume of the canopy***. CBD is the ***ratio of canopy fuel load*** (CFL) ***to canopy depth*** (fig. 9.4), which represents the mean tree height of the stand minus the CBH. The CFL represents the quantity of crown fuel typically consumed in a crown fire, mainly needle foliage. Both the CBD and CFL are, in turn, functions of stand structure characteristics (figs. 9.7 and 9.8).



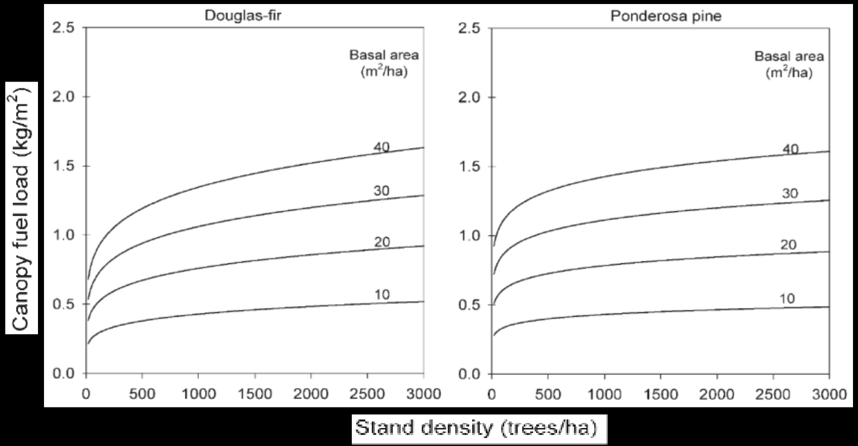


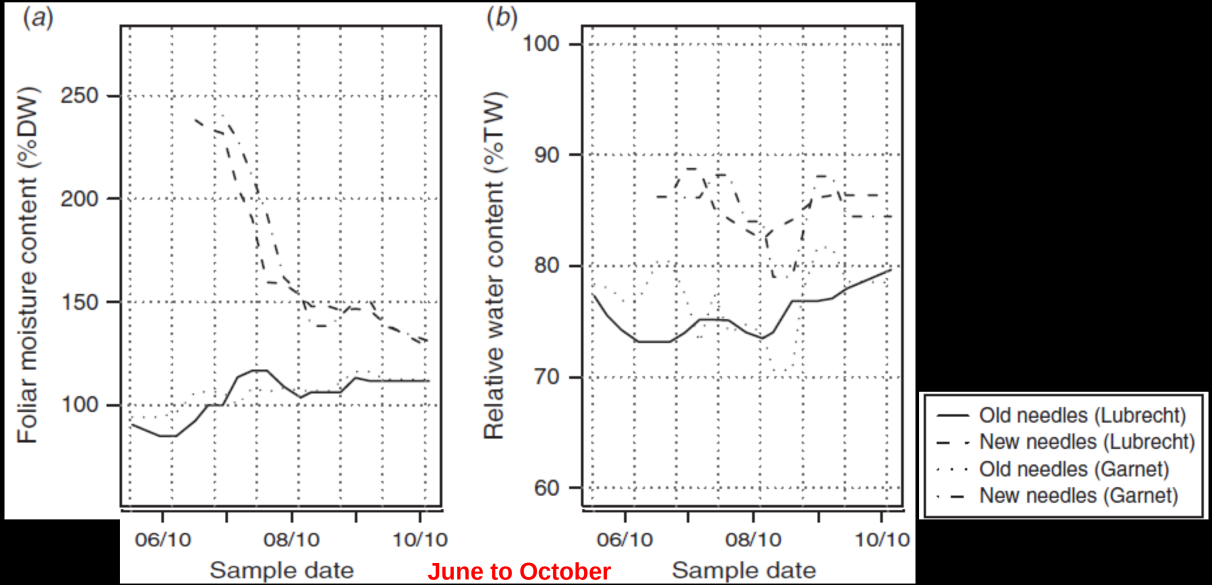
Figure 9-7—Canopy bulk density for four Western U.S. conifer forest fuel types as a function of stand density and basal area according to Cruz et al. (2003a). The regression equations used to produce these graphs do have upper limits in terms of both stand density and basal area (see Alexander and Cruz 2010).

Figure 9-8—Canopy fuel load for four Western U.S. conifer forest fuel types as a function of stand density and basal area according to Cruz et al. (2003a). The regression equations used to produce these graphs do have upper limits in terms of both stand density and basal area (see Alexander and Cruz 2010).

Synthesis of Knowledge of Extreme Fire Behavior: Volume 2 for Fire Behavior Specialists, Researchers, and Meteorologists. Chapter 9: Crown Fire Dynamics in Conifer Forests. *Martin E. Alexander and Miguel G. Cruz*

FIRE BEHAVIOR

Foliar moisture content (FMC) is a ***weighted average moisture content for the various needle ages*** found within the canopy fuel layer. ***Needles decrease in moisture content with age*** following their initial flushing. A general rule of thumb for living conifers is that **crown fire potential is high whenever needle moisture drops below 100% of dry weight**.



Synthesis of Knowledge of Extreme Fire Behavior: Volume 2 for Fire Behavior Specialists, Researchers, and Meteorologists. Chapter 9: Crown Fire Dynamics in Conifer Forests. Martin E. Alexander and Miguel G. Cruz

Crown Fires

The theory of surface fire spread states that ***a fire will stop spreading if the heat flux from the flame front is too low, or if the heat required to ignite the fuels is too high***:

$$r = \frac{heat\ flux\ from\ flame\ to\ fuel}{heat\ required\ for\ fuel\ ignition}$$

The same theory applies to ***crown fires***:

$$R = \frac{E}{\rho_b . Q_{ig}}$$

where

R – rate of fire spread ($m.min^{-1}$)
E – heat flux per unit canopy area required for sustained crown fire spread ($kW.m^{-2}$)
ρ_b – canopy fuel bulk density ($kg.m^{-3}$)
Q_{ig} – fuel heat of ignition ($kJ.kg^{-1}$)

Crown Fires

The transition criteria between crown fire types are defined as a function of fireline intensity and fire rate of spread. Surface fire intensity, $I_{surface}$, has to ***exceed a minimum threshold***, $I'_{initiation}$, (kW.m^{-1}) ***for a surface fire to ignite the tree crowns***:

$$I'_{initiation} = (C.Q_{ig}.CBH)^{1.5} = [0.01.(460 + 26FMC).CBH]^{1.5},$$ where

C – empirical constant estimated in experimental crown fires
Q_{ig} – heat of ignition of the crown fuels (kJ.kg^{-1})
FMC – leaf moisture content of crown foliage (%)
CBH – crown base height (m)

The surface fire needs to release enough energy to dry out the crown foliage and raise its temperature to the ignition point. The surface fire intensity required to ignite the tree crowns is ***higher when FMC*** and ***CBH are higher***.

Crown Fires

Once the fire has climbed to the crown level, its horizontal spread through that layer depends on the balance between ***the speed at which fire must advance*** *vs.* the ***amount of crown fuel it consumes***. Therefore, a crown fire will stop spreading if its rate of spread through the crowns, R_{active}, or if canopy bulk density, ρ_b, drop below some critical threshold.

We can rearrange the energy balance equation such that both these limiting factors are on the same side:

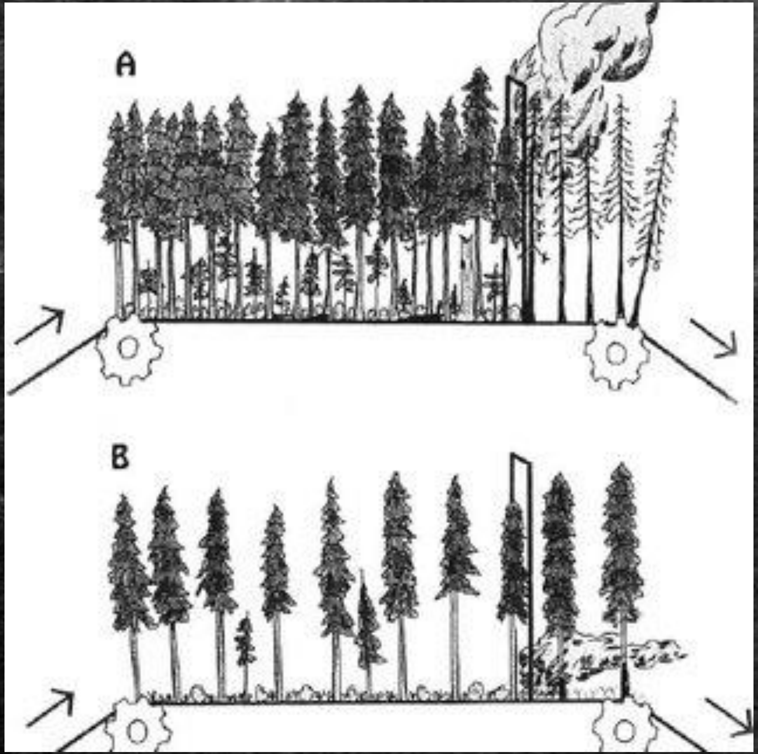
$$R_{active} \cdot \rho_b = \frac{E}{Q_{ig}}$$

We can replace $\frac{E}{Q_{ig}}$ by a new term, ***S*** ($kg.m^{-2}.s^{-1}$), representing the ***mass flow rate*** through the forest canopy:

$$R_{active} \cdot \rho_b = S$$

The lowest mass flow rate required to keep fire spreading through the crown layer (***critical S***) is S_0.

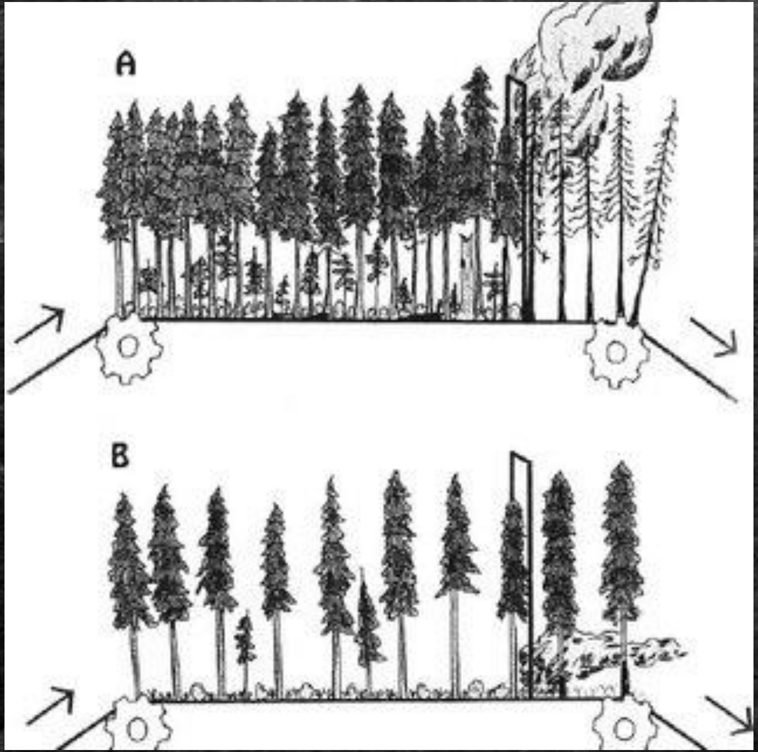
Crown Fires



We can think of the ***mass flow rate, S***, as the rate of fuel consumption ($kg.m^{-2}.s^{-1}$) through a vertical plane (oriented parallel to the flame front) placed within the forest canopy. It is the ***product of fire rate of spread***, R_{active} ($m.s^{-1}$), ***by the fuel bulk density***, ρ_b, in the canopy layer ($kg.m^{-3}$).

The critical threshold (S_0) for the mass flow rate may be imagined as a forest on a conveyor belt being fed to a stationary flame wall.

Crown Fires



In A) with rapid spread and high fuel bulk density the product $R'_{active}.\rho_b$ is high and the canopy fuel mass passes rapidly through the wall of flames, exceeds the critical mass flow rate ($R.\rho_b = S > S_o$) and produces an ***active crown fire***.

In B) canopy bulk density, ρ_b is much lower for the same R_{active}, the fuel mass flow rate remains sub-critical ($R'_{active}.\rho_b = S < S_o$) and the ***fire stays at the surface***. A lower value of R_{active} (e.g., due to lower wind speed) may lead to the same outcome.

Crown Fires

The rate of spread, R_{active}, can also be expressed as a ***critical value***, R'_{active}, meaning that ***there is a rate of spread value below which fire no longer spreads through the forest crowns***:

$$R'_{active} = \frac{S_0}{\rho_b}$$

The value of S_0, the critical threshold for the mass flow rate, determined in experimental crown fires is 0.05 kg.m^{-2}.s^{-1}. Therefore, van Wagner's final crown fire spread model is:

$$R'_{active} = \frac{0.05}{\rho_b}$$

This model does not predict the rate of crown fire spread. It identifies the ***combinations of rate of spread and canopy bulk density for which an active crown fire is possible***.

Crown Fires

To recapitulate, van Wagner's equations provide a framework to estimate:

- the critical (minimum) surface fire intensity needed to *ignite tree crowns*:

$$I'_{surface} = (C.Q_{ig}.CBH)^{1.5} = [0.01.(460 + 26FMC).CBH]^{1.5}$$

- the critical (minimum) rate of spread required for *horizontal crown spread*:

$$R'_{active} = \frac{0.05}{\rho_b}$$

We can now quantitatively defined the various types of fire behavior:

If $I_{surface} < I'_{surface}$ $\Rightarrow$ *surface fire*
If $I_{surface} > I'_{surface}$ and $R_{active} < R'_{active}$ $\Rightarrow$ *passive crown fire* (torching)
If $I_{surface} > I'_{surface}$ and $R_{active} > R'_{active}$ $\Rightarrow$ *active crown fire*

Crown Fires

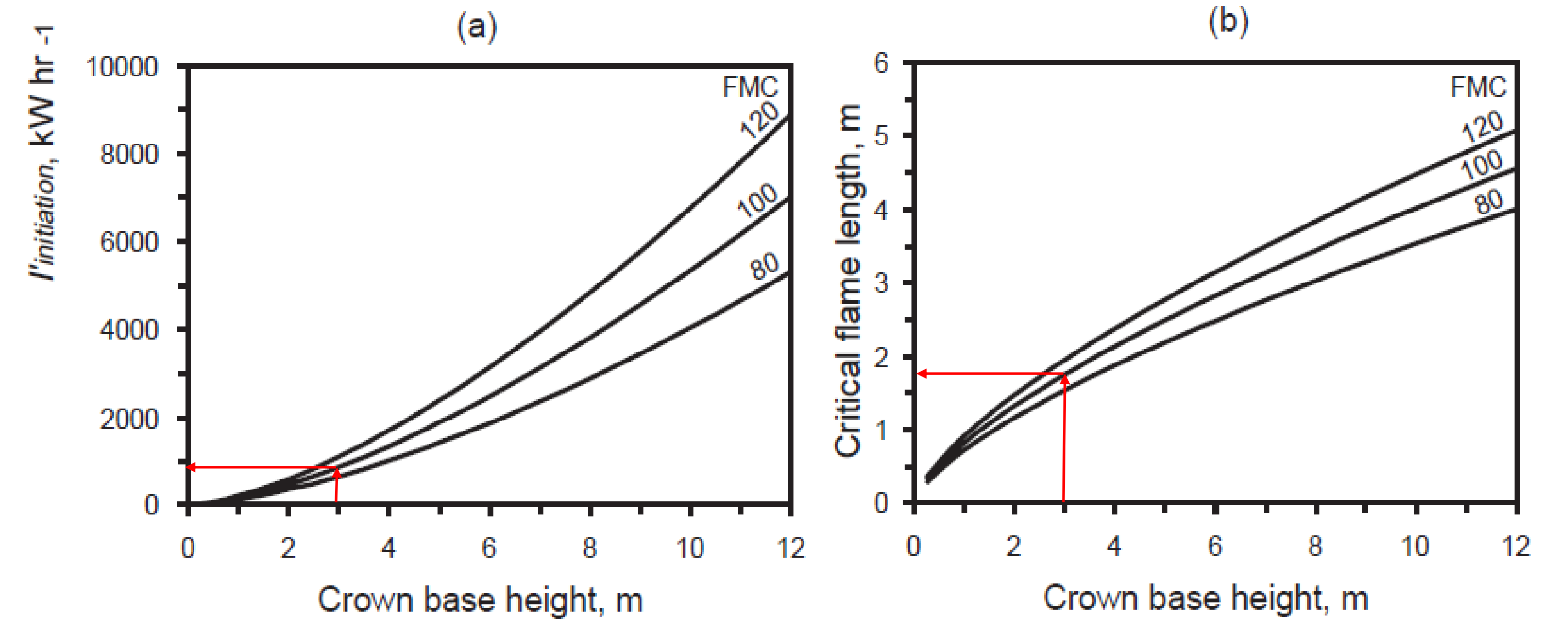
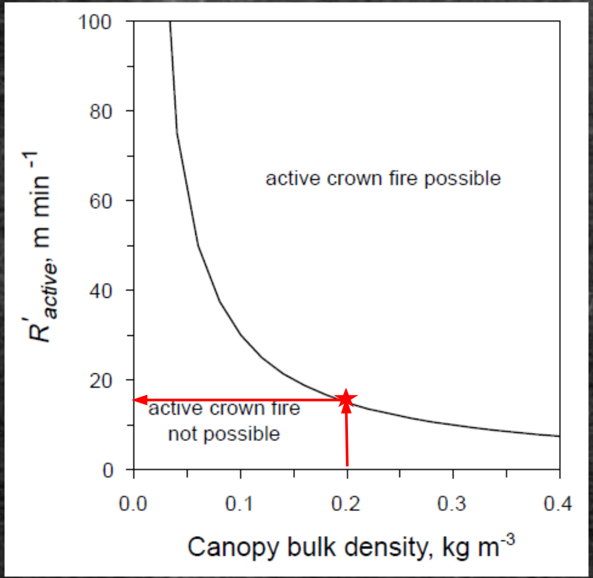


Figure 4 – ***Van Wagner's crown fire initiation criterion expressed as critical surface fireline intensity*** (a), ***and critical flame length*** using Byram's (1959) flame length model (b). Note that critical flame length is less than canopy base height (CBH) for CBH greater than about 1 m. ***Example***: a stand with CBH of 3 m and 100 percent FMC requires surface fireline intensity of 875 kW m–1 (flame length 1.7 m) to initiate crowning.

Crown Fires



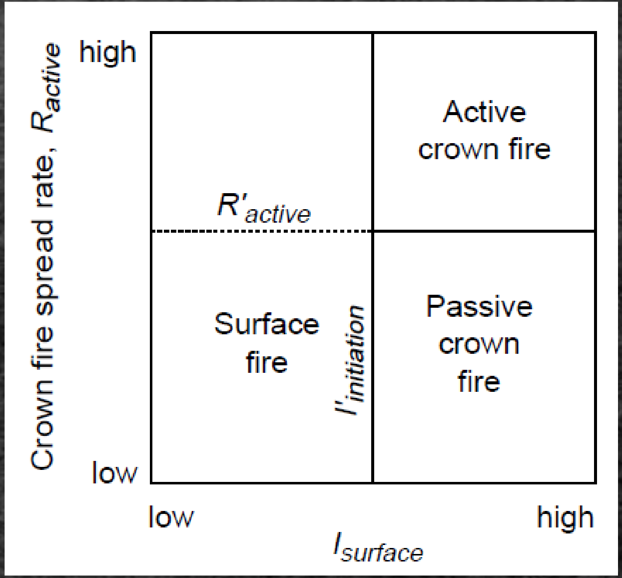
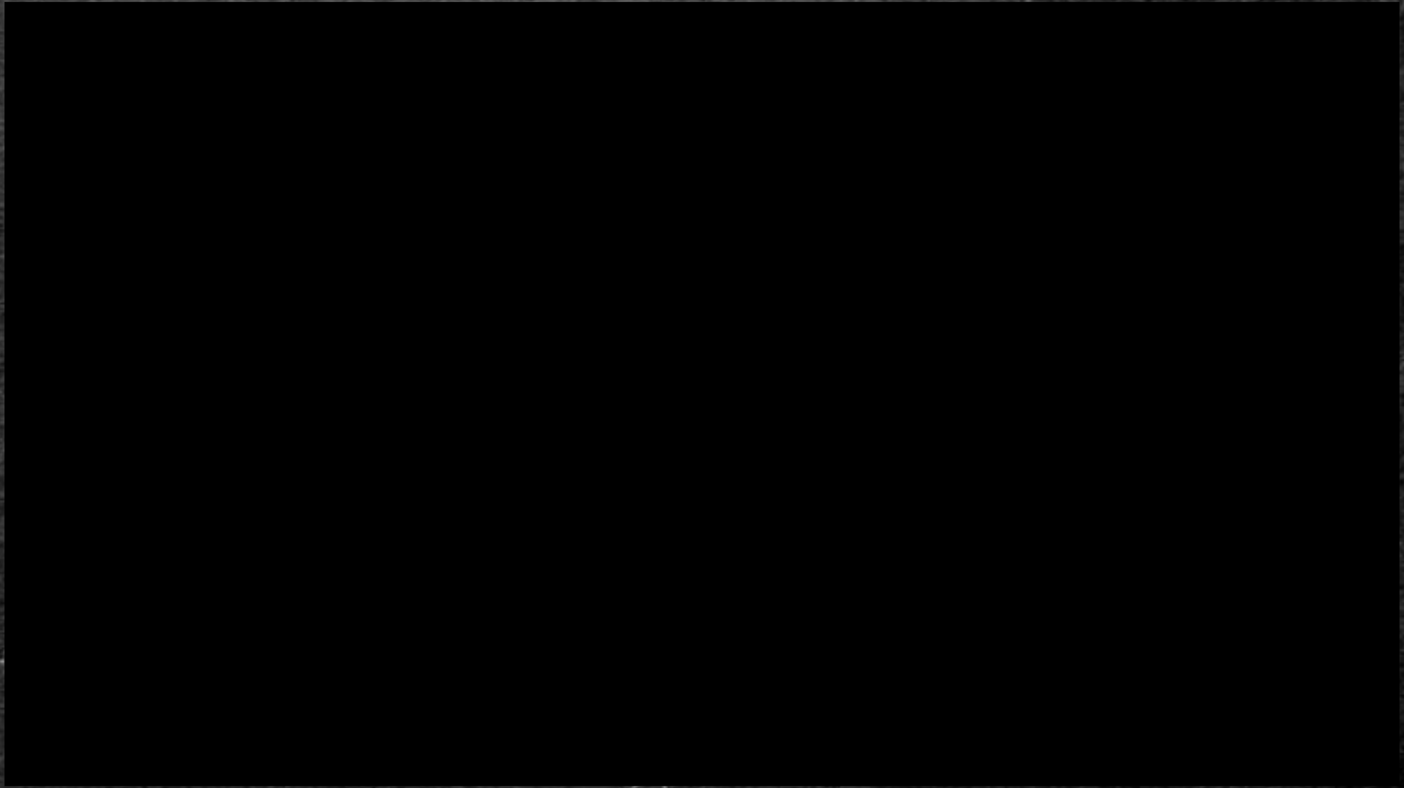


Figure 5– *Van Wagner's criterion for sustained active crown fire spread based on a minimum horizontal mass-flow rate of 0.05 kg m^{-2} min^{-1}*. Example: a stand with ρ_b (CBD) of 0.2 kg m^{-3} requires a spread rate of 15 m min^{-1} to sustain active crowning.

Figure *6–Fire classification* based on Van Wagner (1977) and Alexander (1988). A fire for which ***surface fire intensity*** ($I_{surface}$) is less than critical ($I'_{initiation}$) falls in the surface fire class; one for which $I_{surface}$ exceeds $I'_{initiation}$ is either a passive or active crown fire depending on the crown fire spread rate criterion. Passive crowning occurs where a crown fire initiates ($I_{surface} > I'_{initiation}$) but cannot be sustained ($R_{active} < R'_{active}$). An active crown fire occurs when both criteria are exceeded.

Crown Fires

A ***blow-up fire*** is characterized by a sudden change of spread and energy release rates. It involves a ***rapid transition from a surface fire exhibiting relatively low intensity, to a fire burning in the whole vegetation complex, surface to canopy***, and displaying much larger flame heights, higher energy release rates, and faster rates of spread.



New South Wales, Australia 2019–20 bushfires: the moment a surface fire becomes a crown fire, outside Sydney.

Crown Fires

There is a very simple empirical model to *estimate the rate of spread of wind-driven crown fires*:

$$R_{active} = 3.34(R_{10})_{WAF0.4}\,,$$ where

R_{active} – active crown fire rate of spread ($m.s^{-1}$)
R_{10} – predicted rate of spread of surface fire in fuel model 10 (timber litter and understory)
WAF0.4 – Forest canopy wind attenuation factor of 0.4 (wind speed in the forest understory is reduced to 40% of the wind speed out in the open due to presence of the forest canopy)

The model simply states that the mean rate of spread for the experimental crown fires used to develop it was *3.34 times faster than that predicted for the surface fire.*

This moderately accurate model *allows quantitative assessment of crown fire hazard*.

Crown Fires

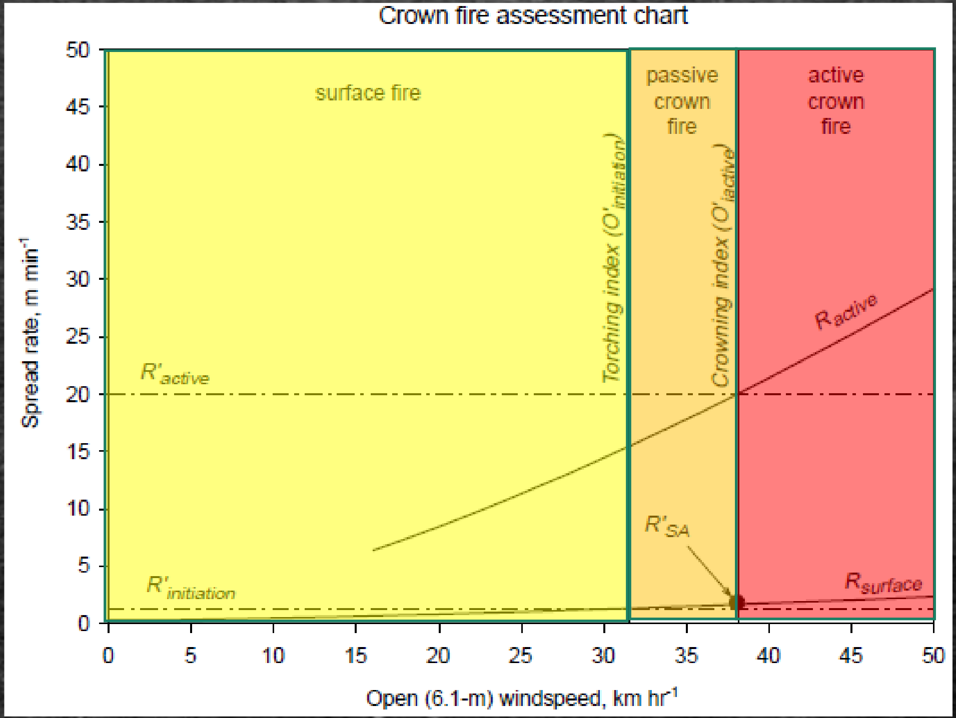
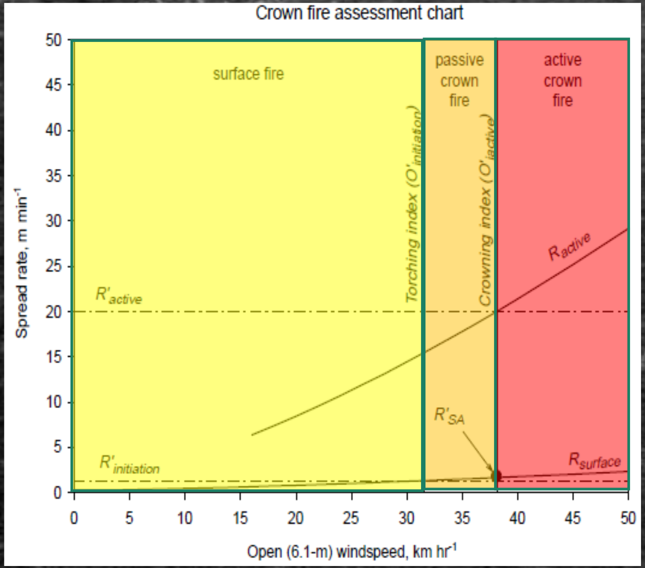


Figure 8—The ***Torching and Crowning Indices*** can be determined graphically on a crown fire assessment chart. ***The open windspeed, $O'_{initiation}$ at which $R_{surface}$ exceeds $R_{initiation}$ (same as $I_{surface} > I_{initiation}$) is the Torching Index*** (TI). ***The open windspeed, O'_{active} at which R_{active} exceeds R'_{active} is the Crowning Index. A surface fire is expected at windspeeds below TI. Windspeeds greater than TI but less than CI lead to passive crowning. Active crown fire is expected at windspeeds above CI. Inputs:*** fuel model 10 (timber litter and understory), canopy base height = 1.5 m, canopy bulk density = 0.15 kg m−3, foliar moisture content = 100 percent, normal summer surface fuel moisture condition, and wind reduction factor = 0.15.

Crown Fires



The purpose of crown fire behavior simulations is to *assess the relative fire potential in forest stands, not to predict the behavior of an actual fire*.

TI and CI are windspeed values. *The higher the windspeed value required to initiate (TI) and spread (CI) fire through the crowns, the lower the fire potential, and the less vulnerable to fire is the forest*.

Understory fuel model, crown base height (CBH), and crown bulk density (CBD) are the variables we can manipulate to manage fire danger.

Less dense forest stands will haver lower CBD, reducing the likelihood of fire spread through the crown (*higher CI*). However, this *promotes fuel growth and increases windspeed in the understory* (*lower TI*). It may also decrease overall stand productivity. Resolving this *paradox* is a context-specific problem that depends on local/regional forest vegetation ecology, forest management goals, and overall fire danger.

Crown Fires

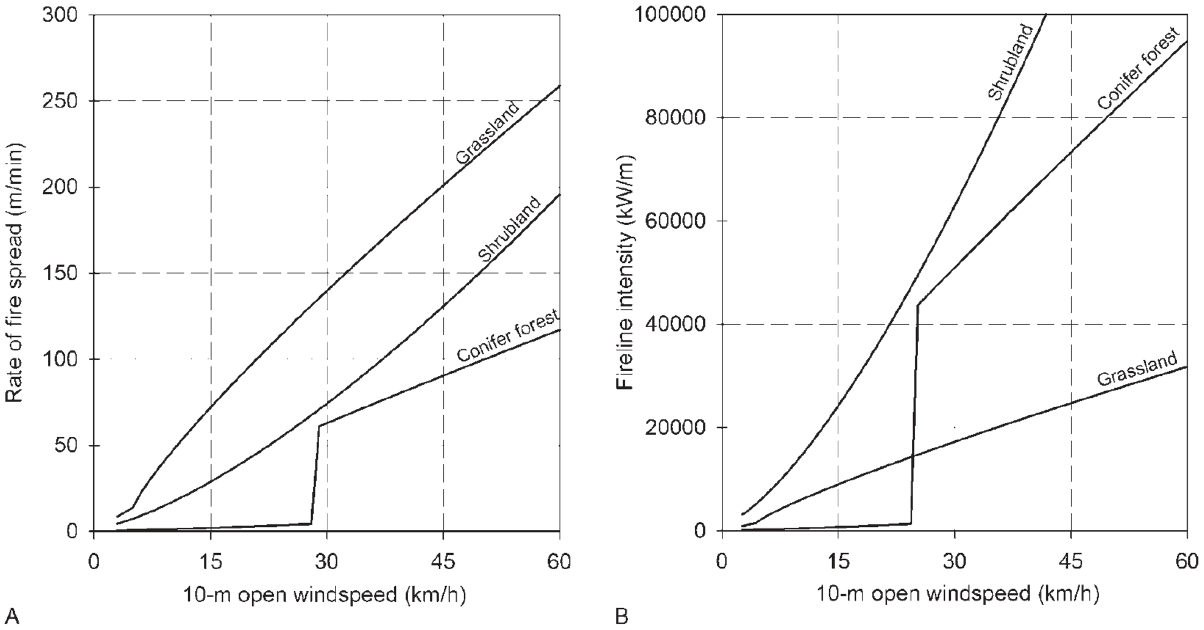


Figure 14.24 Graphical representations of (A) rate of fire spread and (B) fireline intensity as a function of wind speed for three broad fuel complexes. The following environmental conditions are assumed: slope steepness, 0%; ambient air temperature, 30°C; relative humidity, 20%; foliar moisture content for conifer forest, 110%; and shrub live fuel moisture content, 75%. The vertical 'kink' in the conifer forest curves represents the point of surface-to-crown fire transition (adapted from Alexander and Cruz, 2013c).

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Crown Fires

1997 International Crown Fire Modeling Experiments

EXTREME WILDFIRE EVENTS

A change in weather conditions, or in the type and amount of available fuels may cause the onset of an *extreme wildfire event (EWE)*.

EWE display much higher rates of heat release and prevalence of different mechanisms of heat transmission, with *convection becoming substantially more important* than in normal wildfires.

Pedrógão Grande, Portugal, June 2017.

Serra da Estrela, Portugal, August 2022.

EXTREME WILDFIRE EVENTS

The most complete *definition of EWE* focuses on *physical factors of fire behavior that influence suppression capacity*, considering that:

(i) the greatest likelihood of adverse social impacts is when response abilities are overwhelmed;

(ii) suppression abilities are a social variable that can, to a large degree, be assessed consistently across contexts; and

(iii) the physical dynamics that influence fire behavior are the same around the world. (Table 2, next slide).

Fire behavior characteristics with potential to have major impacts on people and assets are *fireline intensity (FLI), rate of spread (ROS), spotting, and the sudden change of fire behavior*.

FLI is the key behavior parameter, as it determines the capacity for fire control;

Tedim, F., Leone, V., Amraoui, M., Bouillon, C., Coughlan, M. R., Delogu, G. M., ... & Xanthopoulos, G. (2018). Defining extreme wildfire events: Difficulties, challenges, and impacts. *Fire*, 1(1), 9.

EXTREME WILDFIRE EVENTS

EFB: Extreme fire behavior.

Table 2. Criteria for the definition of EWE and their social implications and outcomes.

Criteria	Indicators		Social Implications and Outcomes
Fire behavior	FLI	≥10,000 kWm^{-1}	DURING FIRE SPREAD AND SUPPRESSION **Increase of the area of intervention:** (i) Requires more fire suppression resources; (ii) Increases the threatened area and potential losses and damages. **Response capacity of suppression crews:** (i) Reorganization of suppression activities is made difficult by the increasing ROS; (ii) Deployed crews are rapidly overwhelmed. **Capacity of reaction of people and displacement capacity** is overwhelmed by ROS and massive spotting. **Impacts:** (i) Smoke problems: increased hospital admissions during and immediately after the fires; poor visibility; impacts on displacement and on the use of firefighting aircraft; (ii) Loss of lives. AFTER SUPPRESSION **Short -term and long-term impacts:** (i) Loss of lives and injured people; (ii) Economic damages; (iii) High severity.
	Plume dominated event with EFB	Possible pyroCb with downdrafts	
	FL	≥ 10 m	
	ROS	≥ 50 m/min	
	Spotting	Activity Distance	
	Fire behavior sudden changes	Unpredictable variations of fire intensity Erratic ROS direction Spotting	
Capacity of control	Difficulty of control	Fire behavior overwhelms capacity of control Fire spreads unchecked, as suppression operations are either not attempted or ineffective	DURING SUPPRESSION **Immediate consequences:** (i) Entrapments and fire overruns; (ii) Unplanned last moment evacuations; (iii) Entrapments with multiple fatalities and near misses; (iv) Fatal fire overruns.

Note: The criteria to define EWE are only contained in the first and second column. The integration in the table of social implications and outcomes (fourth column) has the purpose to show the interplay of fire behavior and capacity of control with several social issues. The implications and outcomes are not exhaustively listed and they are not exclusive and specific for EWEs but certainly they can be magnified in case of EWEs occurrence.

Tedim, F., Leone, V., Amraoui, M., Bouillon, C., Coughlan, M. R., Delogu, G. M., ... & Xanthopoulos, G. (2018). Defining extreme wildfire events: Difficulties, challenges, and impacts. *Fire*, 1(1), 9.

EXTREME WILDFIRE EVENTS

Table 3. Wildfire events classification based on fire behavior and capacity of control.

	Fire Category	Real Time Measurable Behavior Parameters			Real Time Observable Manifestations of EFB				Type of Fire and Capacity of Control *
		FLI* (kWm^{-1})	ROS (m/min)	FL (m)	PyroCb	Downdrafts	Spotting Activity	Spotting Distance (m)	
Normal Fires	1	<500	<5 [a] <15 [b]	<1.5	Absent	Absent	Absent	0	Surface fire Fairly easy
Normal Fires	2	500–2000	<15 [a] <30 [b]	<2.5	Absent	Absent	Low	<100	Surface fire Moderately difficult
Normal Fires	3	2000–4000	<20 [c] <50 [d]	2.5–3.5	Absent	Absent	High	≥100	Surface fire, torching possible Very difficult
Normal Fires	4	4000–10,000	<50 [c] <100 [d]	3.5–10	Unlikely	In some localized cases	Prolific	500–1000	Surface fire, crowning likely depending on vegetation type and stand structure Extremely difficult
Extreme Wildfire Events	5	10,000–30,000	<150 [c] <250 [d]	10–50	Possible	Present	Prolific	>1000	Crown fire, either wind- or plume-driven Spotting plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Chaotic and unpredictable fire spread Virtually impossible
Extreme Wildfire Events	6	30,000–100,000	<300	50–100	Probable	Present	Massive Spotting	>2000	Plume-driven, highly turbulent fire Chaotic and unpredictable fire spread Spotting, including long distance, plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Impossible
Extreme Wildfire Events	7	>100,000 (possible)	>300 (possible)	>100 (possible)	Present	Present	Massive Spotting	>5000	Plume-driven, highly turbulent fire Area-wide ignition and firestorm development non-organized flame fronts because of extreme turbulence/vorticity and massive spotting Impossible

Note: [a] Forest and shrubland; [b] grassland; [c] forest; [d] shrubland and grassland; *FLI classes 1–4 follow the classification by Alexander and Lanoville [125].

EXTREME WILDFIRE EVENTS

Wildfire driven by a convection column, or plume,

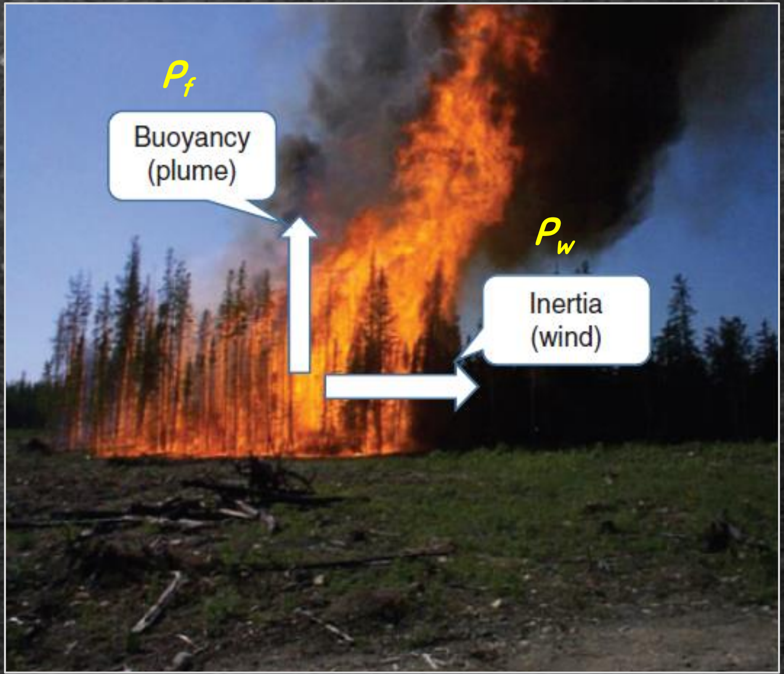
Wind-driven wildfire.

EXTREME WILDFIRE EVENTS

The energy flow rate in the wind field (***power of the wind, P_w***) is a rate of flow of ***kinetic energy*** through a vertical plane of unit area at a specified height, in a ***neutrally stable atmosphere****.

The energy flow rate in the convection column above a line of fire (***power of the fire, P_f***) is the rate at which ***thermal energy*** is converted to kinetic energy at the height specified for P_w in the convection column.

The ratio P_f/P_w can be useful in understanding and predicting the onset of erratic fire behavior and the occurrence of blowup fires. There is a ***strong relationship between the occurrence of blow-up fires and values of $Pf/Pw \geq 1$*** for at least 300 m above the fire.



NOTE: *One in which the temperature of unsaturated air decreases at 9.8 °C/km of height above the Earth's surface.

EXTREME WILDFIRE EVENTS

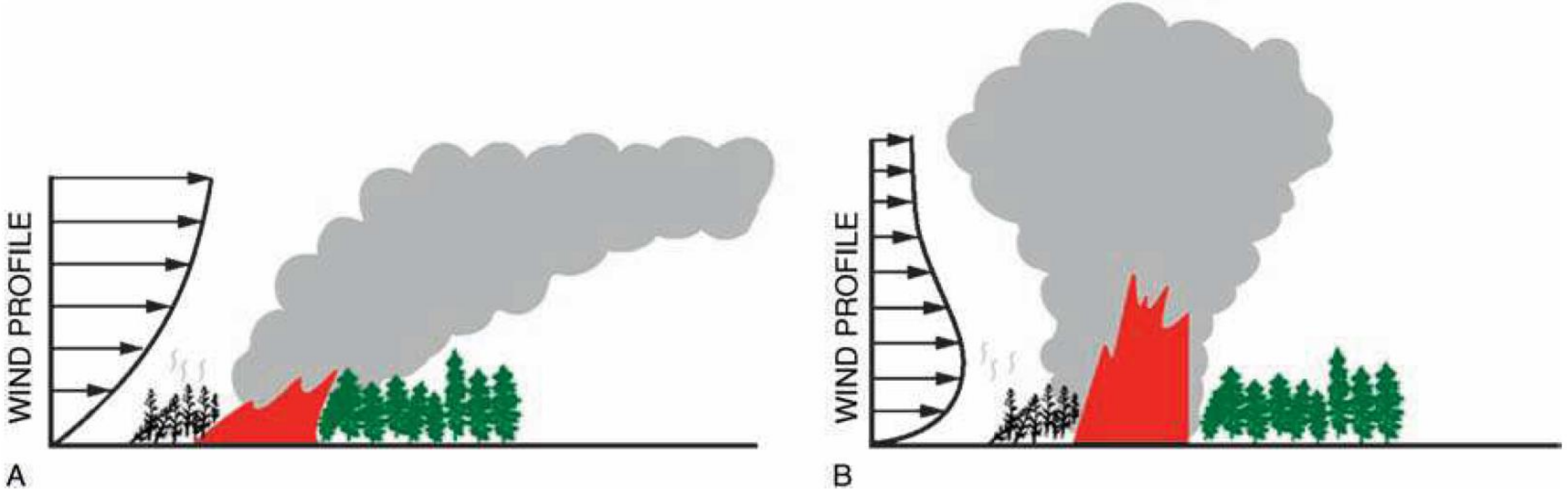


Figure 14.27 Schematic diagrams of: (A) a wind-driven crown fire with winds increasing with height; (B) a convection-dominated crown fire with light winds aloft (adapted from Rothermel, 1991b). Reproduced with permission of the Society of American Foresters.

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EXTREME WILDFIRE EVENTS

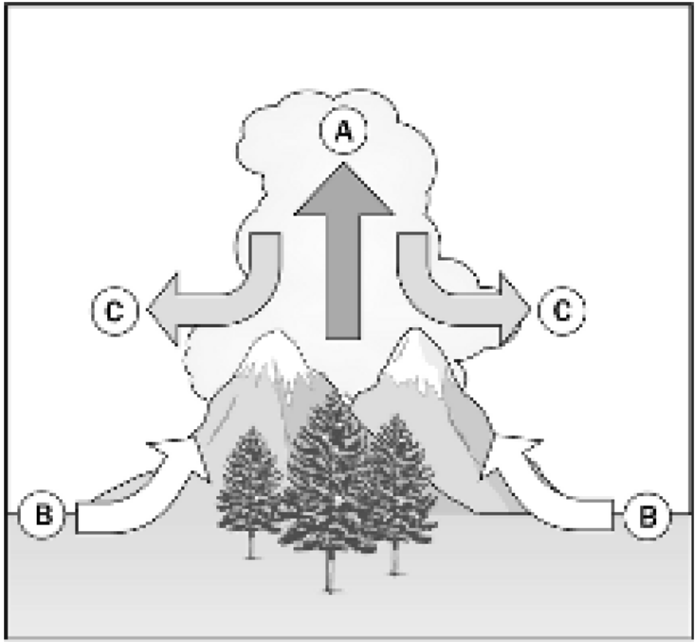

FIGURE 3.3. Under conditions of atmospheric instability, heat from the fire rises to form an updraft (A), causing an indraft of air near the surface (B). As the column collapses, strong downdraft winds can blow the fire in several directions (C).

Van Wagtendonk, J. W. (2006). Fire as a physical process. *Fire in California's ecosystems*, 38-57.

EXTREME WILDFIRE EVENTS

$$P_f = \frac{g.I_B}{C_p.T_0} \qquad P_w = \frac{1}{2}\rho(U_w - ROS)^3$$

$$N_c = \frac{P_f}{P_w} = \frac{2.g.I_B}{\rho.C_p.T_0.(U_w - ROS)^3} \qquad N_c = \frac{\cancel{m}.s^{-2}.kJ.\cancel{m^{-1}}.s^{-1}}{\cancel{kg}.m^{-3}.kJ.\cancel{kg^{-1}}.\cancel{K^{-1}}.\cancel{K}.(m.s^{-1})^3} = \frac{kJ.s^{-3}}{kJ.\cancel{m^{-3}}.\cancel{m^3}.s^{-3}} \Rightarrow N_c \text{ is dimensionless}$$

P_f – power of the fire (kW.s^{-2})
P_w – power of the wind (kW.s^{-2})
N_c – convection number (dimensionless)
g – acceleration of gravity (m.s^{-2})
I_B – fireline intensity (kW.$^{-1}$)
C_p – specific heat of air (kJ.kg^{-1}.K^{-1})
T_0 – ambient temperature (K)
ρ – air density (kg.m^{-3})
U_w – windspeed at 10m, in the open
ROS – fire rate of spread (m.s^{-1})

We can assume that ***g, ρ, and C_p are constant***. We can also take a ***reference value for T_0***, e.g. 313 K, or 40°C.
This simplifies the equations, such that:

P_f = f (I_B)
P_w = f (U_w, ROS)
N_c = f (I_B, U_w, ROS)

When Pf/Pw = N_c > 1) → ***plume dominated fire***

Morvan, D., & Frangieh, N. (2018). Wildland fires behaviour: wind effect versus Byram's convective number and consequences upon the regime of propagation. *International Journal of Wildland Fire*, *27*(9), 636-641.

EXTREME WILDFIRE EVENTS

Table 7.2 Dynamic fire behaviours [8]

Type	Definition
Spotting	Spotting is a behaviour of a fire producing firebrands or embers that are carried by the wind and which start new fires beyond the zone of direct ignition by the main fire [47].
Fire whirls	A fire whirl is a spinning vortex column of ascending hot air and gases rising from a fire and carrying aloft smoke, debris, and flame. Fire whirls range in size from less than 0.3 m to over 150 m in diameter. Large fire whirls have the intensity of a small tornado" [47].
Fire channelling	Fire channelling/lateral vortices is a rapid lateral fire spread across a steep leeward slope in a direction approximately transverse to the prevailing winds [170].
Junction fires	Junction fires/junction zones (jump fires previously) are associated with merging of two fire fronts intersecting at an oblique angle, producing very high rates of spread and with the potential to generate fire whirls and spotting [163].
Eruptive fires	Eruptive fires are fires that occur usually in canyons or steep slopes and are characterised by a rapid acceleration of the head fire rate of spread [163].
Crown fires	Van Wagner [171] recognized three types of crown fires according to their degree of dependence on the surface fire phase: passive, active, and independent. Active and independent crown fires are recognised as dynamic fire behaviours [8]. Active crown fire is "a fire in which a solid flame develops in the crowns of trees, but the surface and crown phases advance as a linked unit dependent on each other" [47]. Independent crown fires "advance in the tree crowns alone, not requiring any energy from the surface fire to sustain combustion or movement" [47].
Conflagrations	Conflagrations are raging, destructive fires [47] that occur when several fires grow up and unite. Their interaction will increase the burning rates, heat release rates, and flame height until the distance between them reaches a critical level [172].
Pyro-convective events	A pyro-convective event is an extreme manifestation of pyroconvection, the buoyant movement of fire-heated air. A flammagenitus cloud, generated by the heat of a bushfire, often rises to the upper troposphere or lower stratosphere [173], and transforms into cumulus (CuFg) or cumulonimbus (CbFg) cloud (also known as PyroCu or PyroCb).
Downbursts	Downbursts are violent and damaging downdrafts associated with cumulonimbus flammagenitus clouds [173], that induce an outburst of strong winds on or near the ground [174]. These winds spread from the location of the downbursts and may result in a fire spread contrary to the prevailing wind direction.

Other types of fire behavior associated with extreme events

8. Filkov AI, Duff TJ, Penman TD (2020) Frequency of dynamic fire behaviours in Australian Forest environments. *Fire* 3(1):1–19.

47. NWCG (2017) Glossary of wildland fire terminology. National Wildfire Coordinating Group

163. Viegas DX (2012) Extreme fire behaviour. Forest management: technology, practices and impact. Nova Science Publishers, Inc

170. Sharples JJ, McRae RHD, Wilkes SR (2012) Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channelling. *Int J Wildland Fire* 21(3):282–296.

171. Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian J For Res* 7(1):23–34.

172. Finney MA, McAllister SS (2011) A review of fire interactions and mass fires. *J. Combustion* 2011:548328.

173. International Cloud Atlas (2017) World Meteorological Organization.

174. Haines DA (2004) Downbursts and wildland fires: a dangerous combination. *Fire Management Today* 64:59–61

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