What's fire behaviour ?

Standard definition : *the manner in which a fire reacts to the influences of fuel, weather, and topography.*

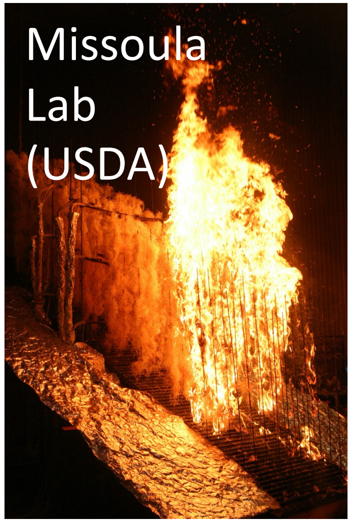
It refers to the manner in which fuel ignites, flame develops and fire spreads.

How do we know it ?

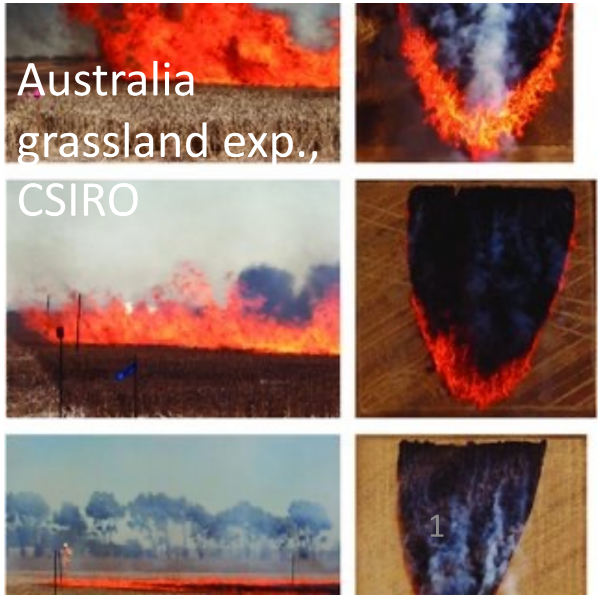
Experimental fires

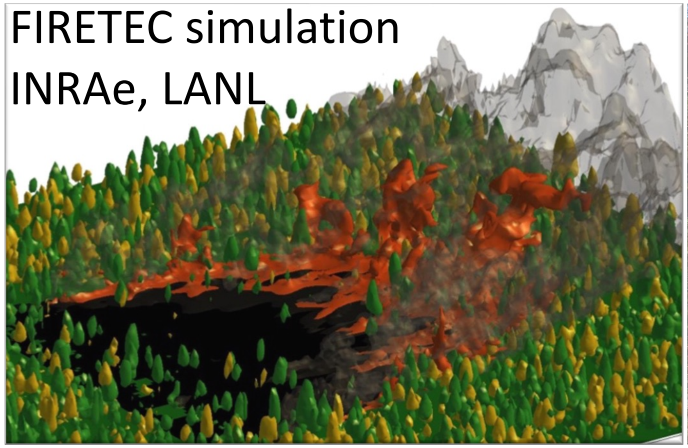
Prescribed fire and wildfire observations

Simulation of complex fire models



DOI: 10.1371/journal.pbio.0020054.g001
Figure 1. Northwest Crown Fire Experiment
(Photograph used by permission of the USDA Forest Service.)





Fire description

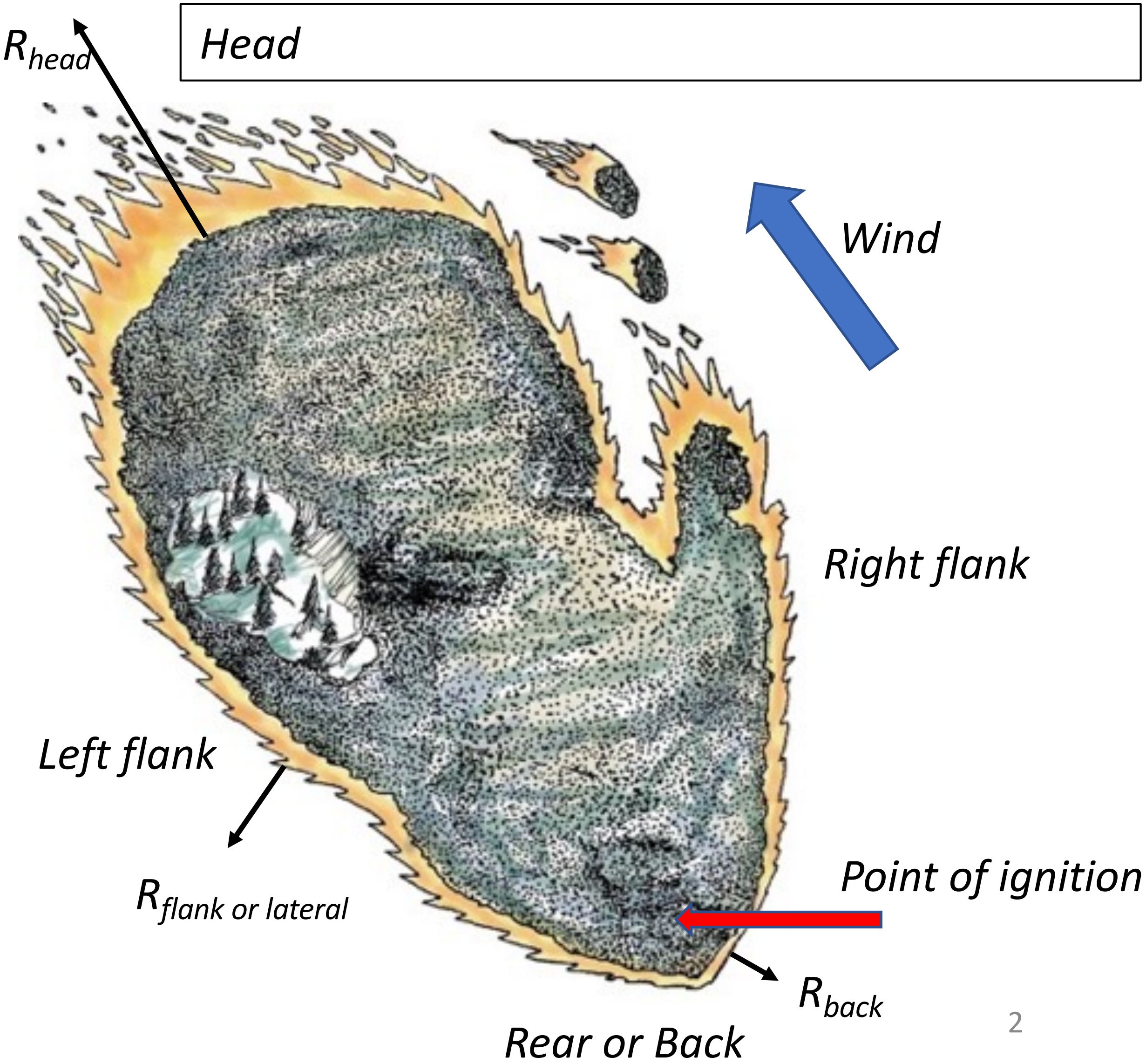
Point of origin (ignition point)

Perimeter

Head, Flanks, Rear

Rate of spread, ROS (R, m/s)

ROS is the first fundamental metric of fire behaviour, chracterizing **fire spread**



Fire types

- **Ground fire**
  burning forest floor (soil organic matter)

- **Surface fire**
  burning above ground dead fuels, grasses, shrubs

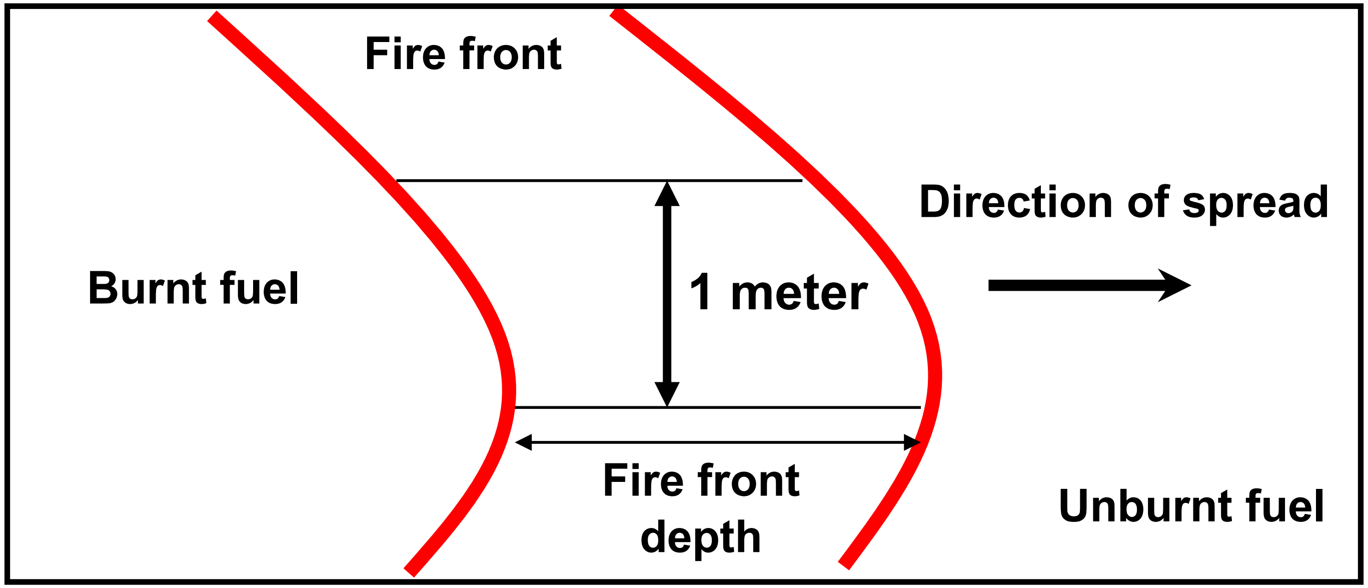
- **Crown fire**
  burning all vegetation layers including tree crowns

Fire intensity

Fire intensity (FLI) is the heat released per unit time and per unit length of the fireline
FLI is the second fundamental metric of fire behaviour

Intensity = Heat of combustion X Fuel consumed per unit area X Rate of spread

$FLI\ (kW/m) = \Delta H_c\, Wc\, R$ (ΔHc : kJ/kg ; W_c : kg/m^2 ; R : m/s)



Fire intensity

$FLI\ (kW/m)\ = \Delta H_c\, Wc\ R$ (ΔHc : kJ/kg ; W_c : kg/m^2 ; R : m/s)

Low heat of combustion ΔH_c is relatively constant and often set to 18 kJ/g (range : 16-22)

Fuel load consumed W_c typically ranges between 0.3 kg/m^2 and 3 kg/m^2

Rate of spread R usually ranges between 1 cm/s and 1 m/s, but may reach 3 m/s in dry grasslands (for flaming fires)

Fireline intensity hence typically ranges between 50 and 50000 kW/m

Exceptional values above 100 000 kW/m have been reported in North-America conifer forests.

NB : in smouldering fires (ex peat fires)
- The effective heat of combustion drops to 6-12 kJ/g (incomplete combustion)
- R tyically ranges between 1-3 cm/hour

Fire intensity

In many situations, fire intensity largely determines fire effects on their environment.

It also contributes to the difficulty of fire control ... but it is usually unknown !

Fire intensity (kW/m) and fire-fighting (adapted from Hough and Albini 1978, Andrews and Rothermel 1982)

0-350 easy to fight

350-1750 fight with light ground means

1750- 3500 fight with heavy ground means

3500-7000 fight with heavy ground means and aerial means, spotting possible

7000-20000 almost uncontrollable fire, frequent spotting

> 20000 kW/m extreme fire intensity, uncontrollable

Flame geometry

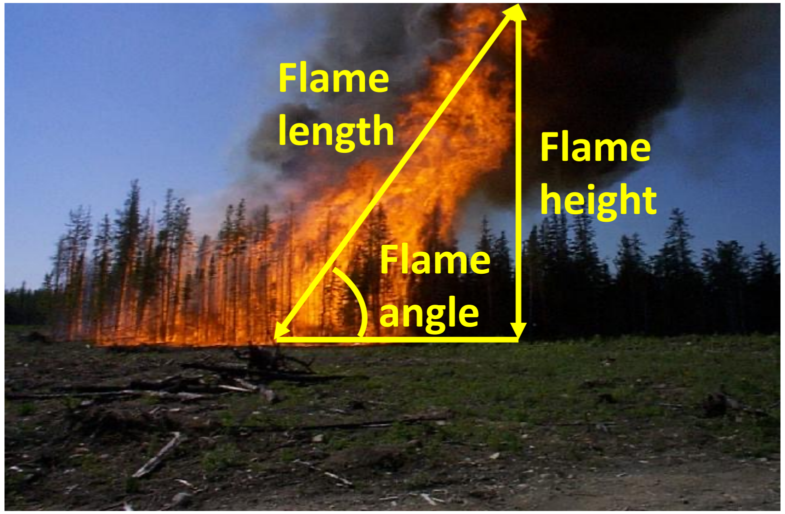
Flame length *L (m)* and fireline intensity (FLI) are correlated

Typically : $L = 0.0775\ FLI^{0.46}$ (Byram 1959)

Thus *FLI* may be estimated from *L* as observed in the field :

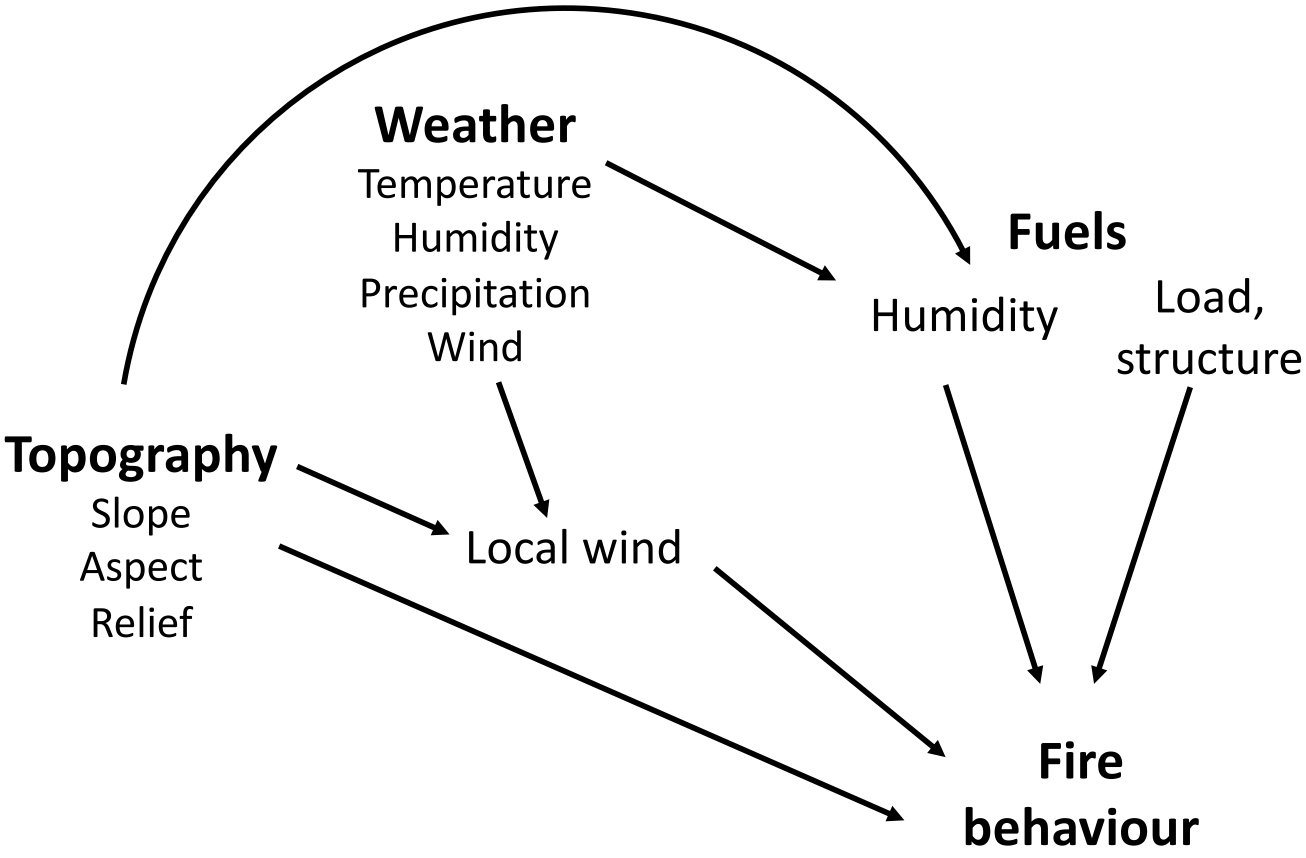
$$FLI = 260\ L^{2.174}$$

This is very rough estimation, but often the only available in practice



L (m)	*FLI (kW/m)*
0.5	60
1	260
2	1200
4	5300
8	24000

Fire factors



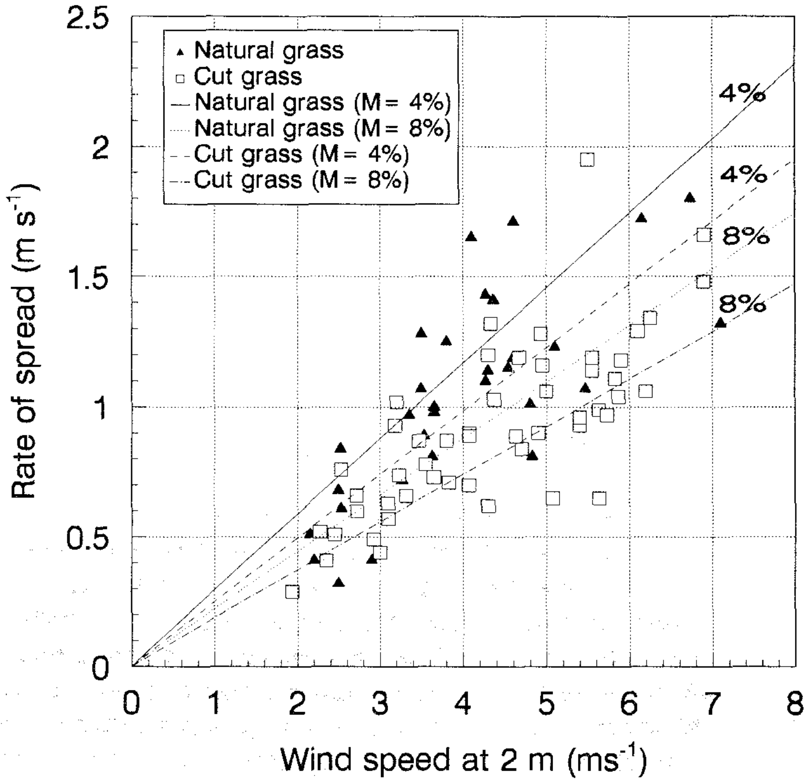
Wind effect on fires

Wind direction (in interaction with topography) determines the main direction of fire spread.
Wind speed strongly influences fire rate of spread (ROS).
Wind may reduce fuel burning times

Wind effect on ROS

Grasslands

Experimental fires (121 tests in natural and cut grass)
(Cheney, Gould and Cathpole 1993)



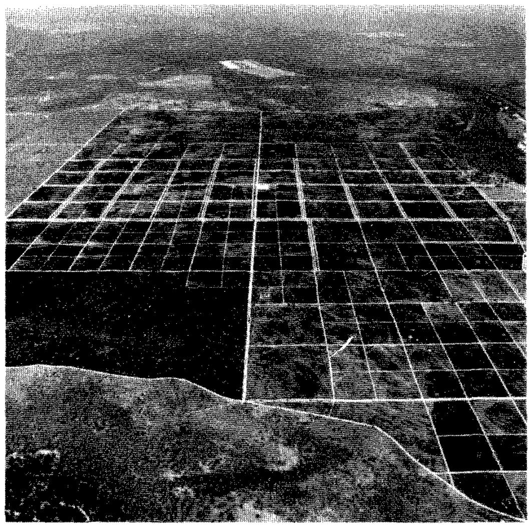
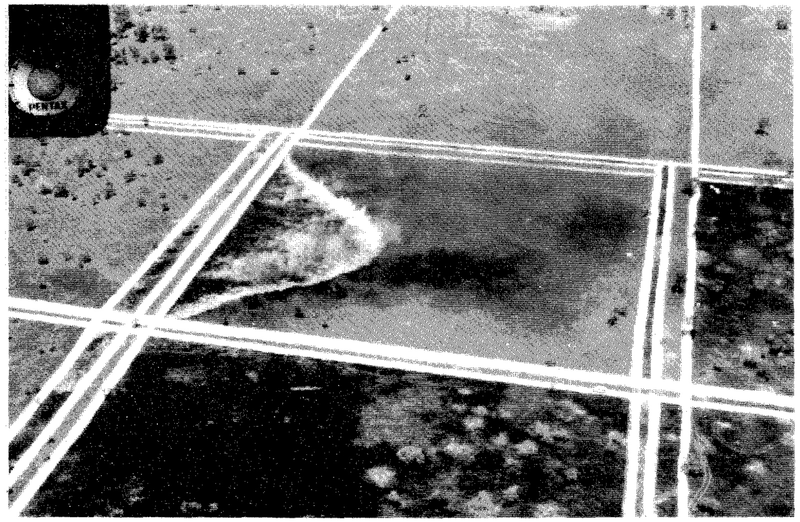


Figure 1. Aerial view of the 2500 ha experimental site Annabaroo, N.T.

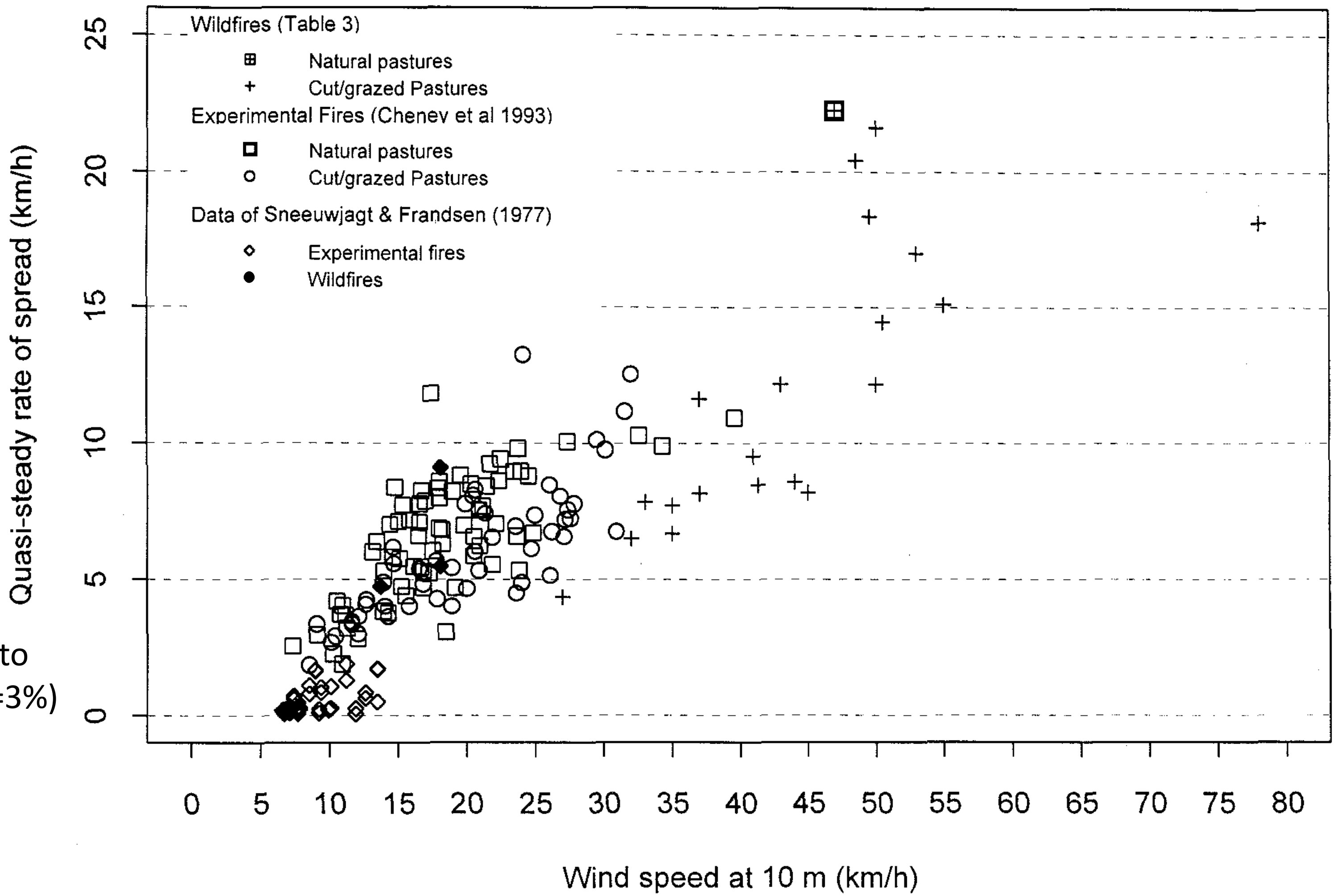


Wind effect on ROS

Grasslands

ROS as a function of wind speed in grassland experimental fires and wildfires

Cheney, N.P., Gould, J.S., and Catchpole, W.R. 1998



(ROS adjusted to constant FMC=3%)

Wind effect on ROS

Shrublands

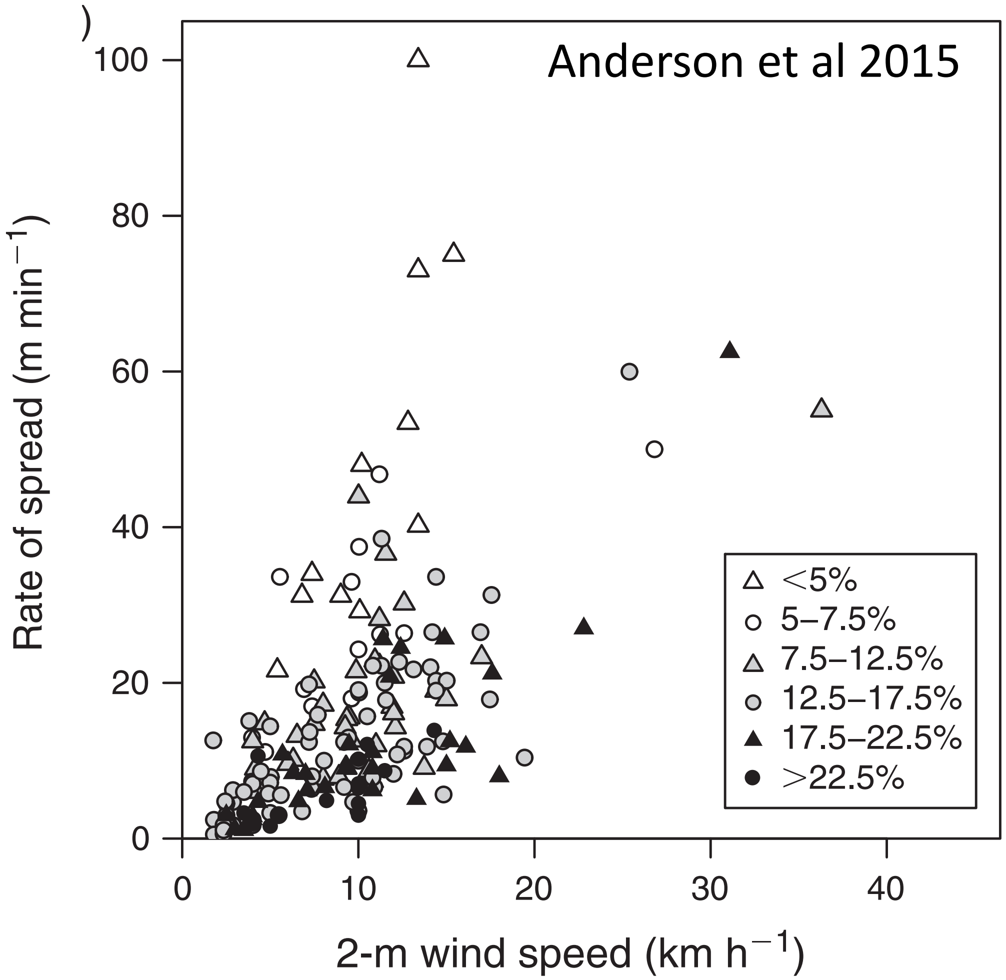
Data sources (Anderson et al 2015)

Source	Code	Country	Number of fires	Use	Dominant vegetation	Main reference
Jonkershoek Forestry Research Centre	ZA	South Africa	14	Model development	Fynbos	van Wilgen *et al.* (1985)
University of NSW	WC	Australia	3	Ignition line length	East coast dry and temperate wet heath	Catchpole (1987)
National Parks and Wildlife Service of NSW	NSW	Australia	10	Model evaluation	East Coast dry heath AND woodland	Bradstock and Auld (1995)
Tasmania Parks and Heritage	BGM	Australia	34	Model evaluation	Temperate wet heath (buttongrass)	Marsden-Smedley and Catchpole (1995*b*)
Forestry Research Centre of Lourizan	SP	Spain	19 + 13	Model development, ignition line length	Mixed heathland	Vega *et al.* (1998)
University of Trás-os-Montes and Alto Douro	PT	Portugal	8 + 25	Model development, ignition line length	Mixed heathland	Fernandes (2001); Vega *et al.* (2006); unpublished data
CSIRO	SA	Australia	10	Model development	Central lowland heath	Cruz *et al.* (2010)
Scion	NZ	New Zealand	28	Model development	Mixed heath–shrubland	Anderson (2009)
Tasmania Parks and Heritage	Tas.	Australia	11	Model evaluation	Mixed heathland and moorland	Unpublished data
Department of Environment and Primary Industries, Victoria	VGM	Australia	11 + 1	Model evaluation, ignition line length	East Coast temperate wet heath	Unpublished data

Wind effect on ROS

Shrublands

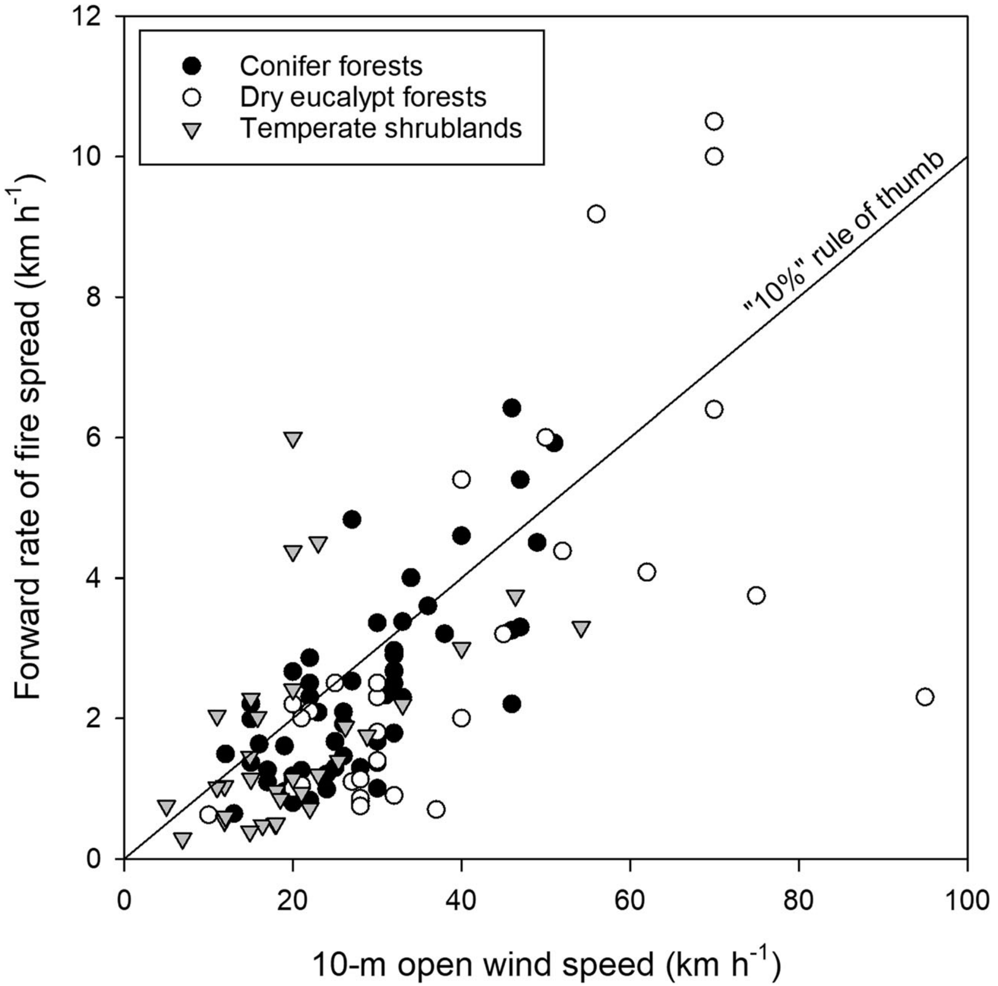
ROS as a function of wind speed in shrublands, by class of *dead* fuel moisture content
79 fires



Wind effect on ROS

Forests and shrublands

ROS as a function of wind speed in woody fuels (forests and shrublands)
118 wildfires



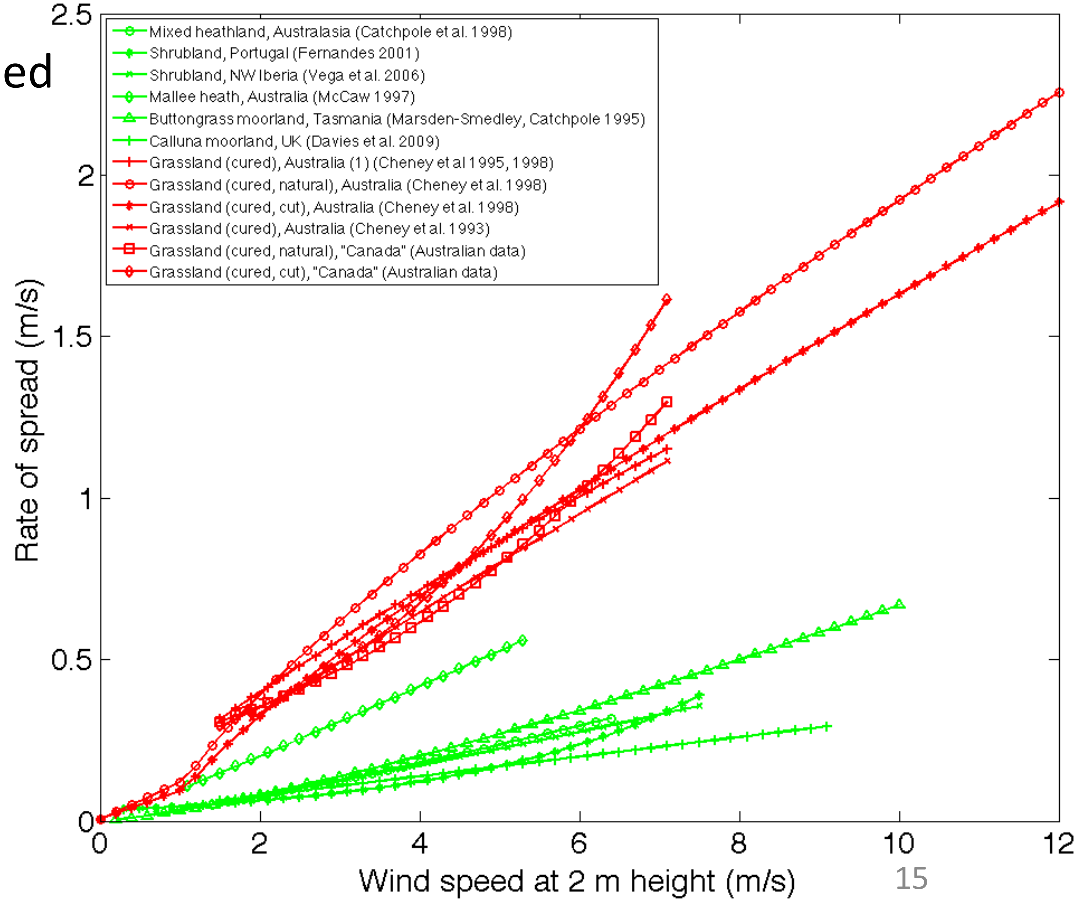
Wind effect on ROS

All data (field and lab observations) show increasing fire ROS with wind speed

That increase is often near linear in each study/fuel type.

The ROS-Wind relationship depends on fuel moisture content (evidenced for dead fuel), and to a lesser extent, on fuel type

Relationship between ROS and wind speed according to 12 empirical models in **shrublands** and **grasslands**



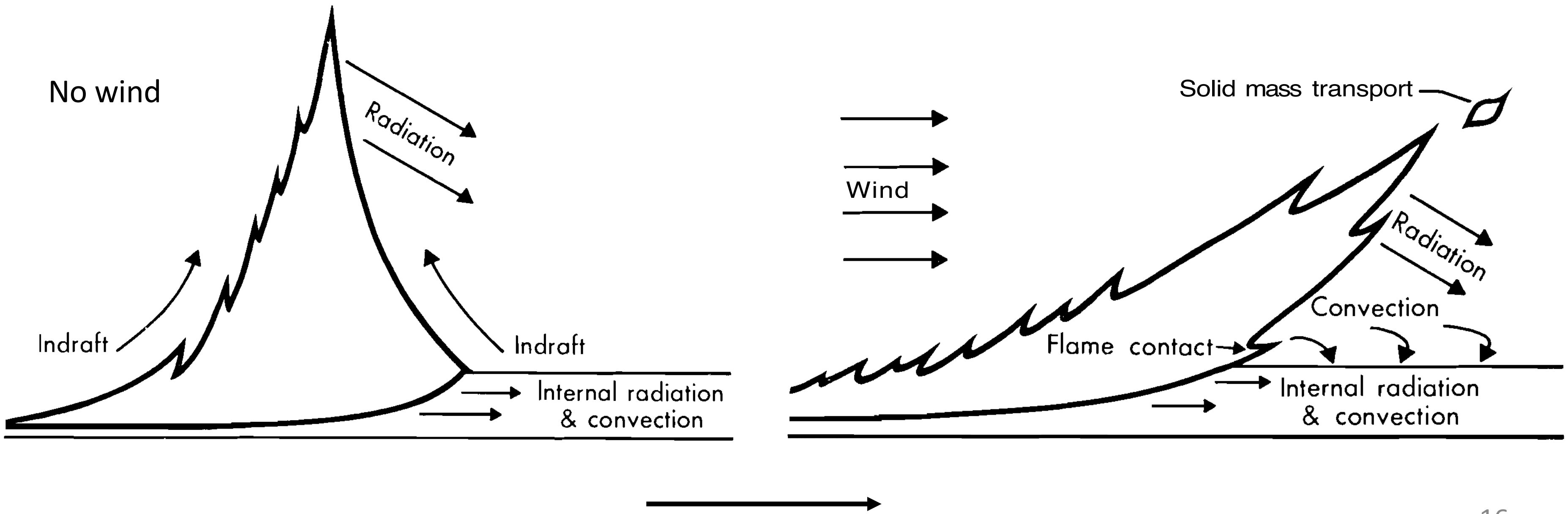
Wind effect on ROS

What are the processes behind this effect ?

Enhance heat transfer (especially convection) to unburnt fuel

Enhance mixing in the combustion zone (oxygen supply)

Decrease temperature in the combustion zone (cooling by "fresh" air)



Rothermel (1972)

Fuel effects on fire behaviour

Fuels show many variations and may have contrasted effects on fires

Several fuel-related factors influence fire behaviour

- chemical composition (lignin content, VOCs, see basic processes)
- water content (fuel moisture content, FMC)
- size and geometry of fuel elements
- fuel load and fuel arrangement (spatial structure)



Fuel moisture content (FMC)

Fuels are made of dead and live elements

Dead elements exhibit FMC between 0 and 30 %, they readily burn when FMC < 20%.
In dry hot conditions, values are typically between 5 and 10%

Live elements exhibit much higher FMC values, typically 60-150 % (and more in wet periods)
They can burn despite such high moisture contents

Dead elements are necessary to start fires and usually to get sustained fire spread

FMC is a major factor of fire ignition (see ignition tests) and fire spread

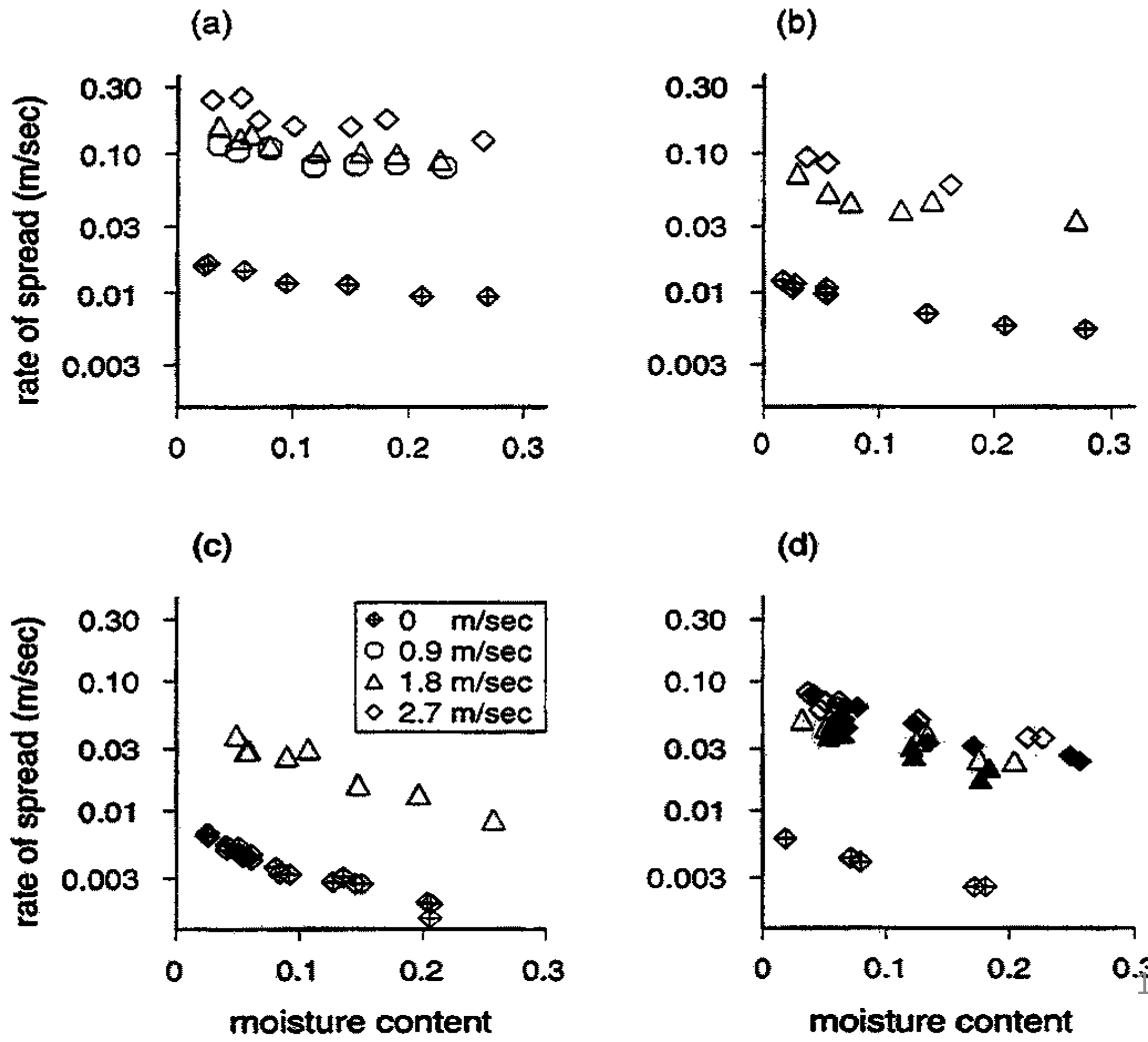
Fuel moisture content (FMC) effect on ROS

Rate of spread as function of FMC in various laboratory fuel beds (dead material)

Catchpole and Cathchpole 1998

Y-axis in logarithmic scale

In these experiments, ROS shows exponential decrease with FMC :
$R \propto \exp(-a\ FMC)$



Fuel moisture content (FMC) effect on ROS

ROS as function of dead FMC in lab and field experiments

Several functions are also exponential decays – Note the ranges of FMC

Sullivan 2009

Model	Field or laboratory	Fuel type	FMC function	FMC range (%)
Empirical				
CFS-accel	Laboratory	Pond./excel.	na	na
CALM Spinifex	Field	Spinifex	$-82.08M$	12–31
CFBP	Field	Forest	$e^{-0.1386M}(1+M^{5.31})$	?
PWSTas	Field	Buttongrass	$e^{-0.0243M}$	8.2–96
CALM Mallee	Field	Mallee	$e^{-0.11M_{ld}}$	4–32
CSIRO Grass	Field	Grass	$e^{-0.108M}$	2.7–12.1
Heath	Field	Heath/shrub	na	na
UdTM Shrub	Field	Heath/shrub	$e^{-0.027M}$	10–40
CALM Jarrah I	Laboratory	Litter	$\frac{1}{0.003+0.000922M}$	3–14
CALM Jarrah II	Field	Forest	$M^{-1.495}$	3–18.6
UdTM Pinaster	Field	Forest	$e^{-0.035M}$	8–56
Gorse	Field	Gorse	$-0.0004M$	22–85
Maquis	Field	Maquis	na	15.3–27.7
Helsinki	Field	Moss	na	7–94
CSIRO Forest	Field	Forest	$M^{-1.495}$	5.6–9.6
Quasi-empirical				
TRW	Laboratory	Match splints	na	na
NBRU	Laboratory	Match splints	na	na
USFS	Laboratory	Needles/excel.	$\frac{e^{-4.05M}}{(700+2260M)}$	2–33
Coimbra	Laboratory	Needles	na	10–15
Nelson	Laboratory/field	Birch sticks	na	na

Fuel moisture content (FMC) effect on ROS - theory

The FMC effect should be mostly due to the heat of pre-ignition

Figure shows the ratio of low heat of combustion to the heat of pre-ignition :

$$\frac{\Delta Hc}{Q_{ig}}$$

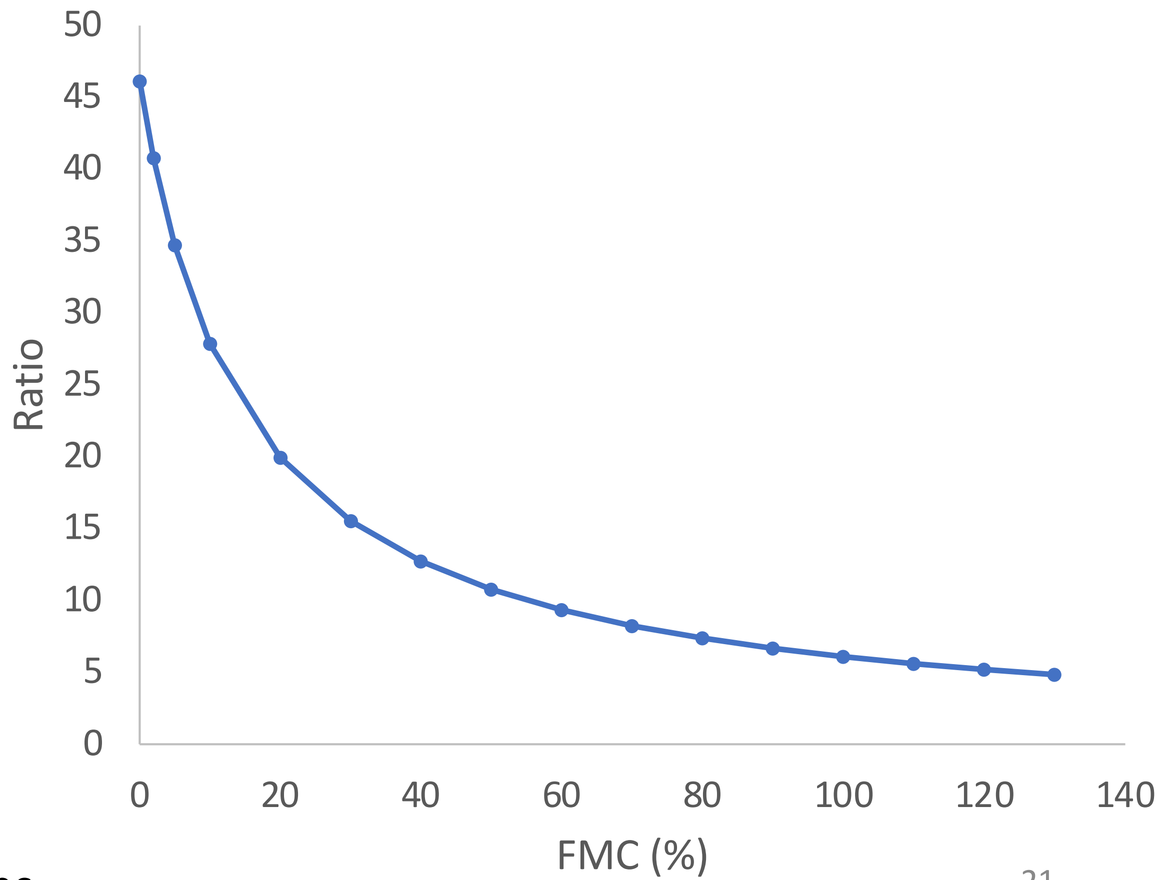
The combustion of 1 g of dry fuel releases 46 times the energy necessary to ignite it !

This ratio drops to 6 when FMC = 100% !

$$\frac{\Delta H_c}{Q_{ig}} = \frac{18000}{390 + 2560\,\frac{FMC}{100}}$$

Theory differs from empirical modelling (previous slide) based on fire data

FMC effects still need investigations



Fuel size

Only fine fuels (< 6 mm) drive fire spread.
Larger elements may burn and contribute to fire intensity and fire emissions

Size is characterized by surface area to volume ratio σ (e.g. σ=4/d for a cylinder of diam. d)

Ignition and spread are faster with thinner fuels, because mass and heat exchanges are faster

But thinner fuels burn out faster as well.

Note : thin dead fuels will dry much faster than thicker ones in warm-dry atmosphere
-> FMC adjusts to weather conditions and frequently reach low values

Typical values of σ :

- Very thin grasses: 20000 m^2/m^3
- Deciduous oak leaves: 10000 m^2/m^3
- Pine needles : 5000 m^2/m^3
- Fine twigs : 500-1000 m^2/m^3
- Branches : 50-100 m^2/m^3

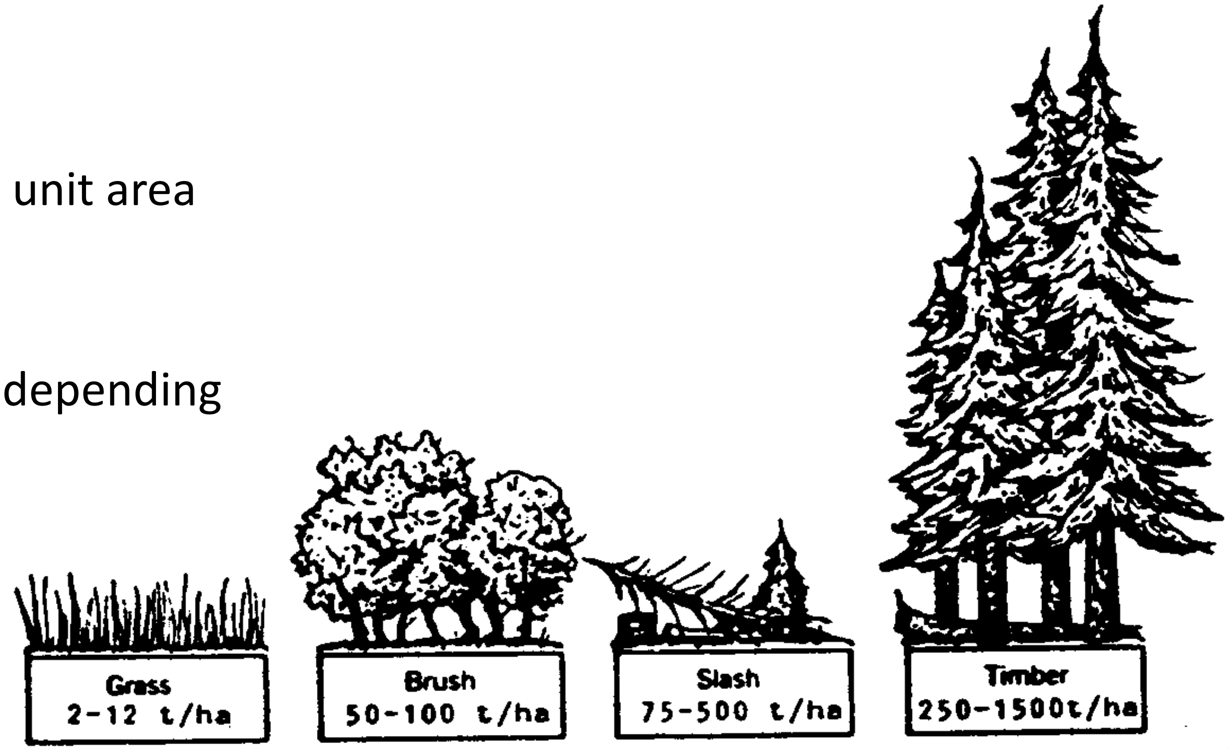
Fuel load

The amount of fuel elements per unit area
(1 kg/m^2 = 10 t /ha)

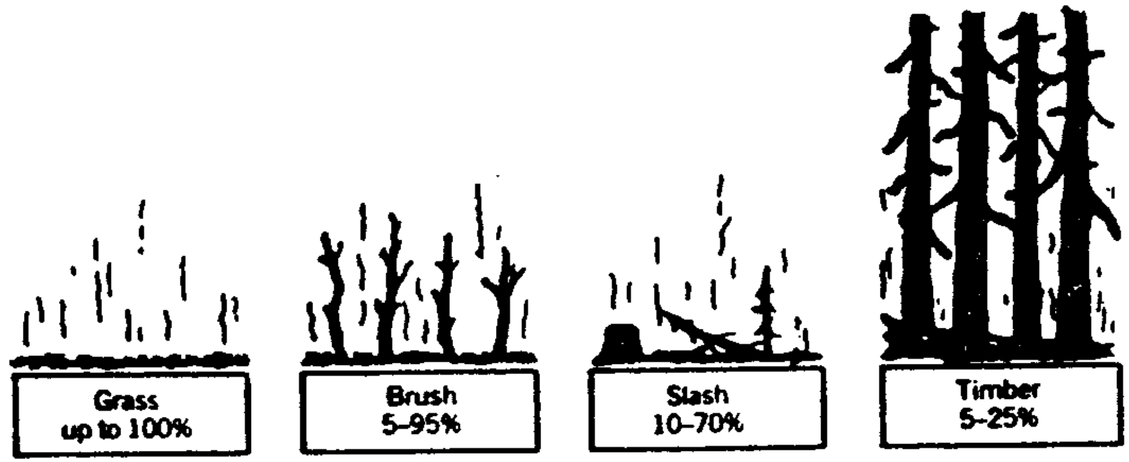
Fuel consumption may vary a lot depending on fuel and weather conditions

Relatively small effect on ROS

Effect on fire intensity and emissions



Available aerial biomass (not fuel)



Biomass consumption

Fuel load

Aerial biomass in Mediterranean plant communities (from Trabaud, 1977)

Dense pine stand (trees):

160 t/ha, foliage 15 t/ha

Open pine stand (trees):

22 t/ha, foliage 3.4 t/ha

Kermès oak guarrigue :

24 t/ha, foliage 5 t/ha de feuillage

Sparse Kermès oak garrigue:

13 t/ha, foliage 4 t/ha de feuillage

Pine needle fuel bed

5 à 15 t/ha

Fuel structure

The spatial arrangement of fuel elements, at multiple scales (shoot to stand to landscape)

Horizontal continuity favors fire spread over landscape
Vertical continuity in forests favors crowning

In detail, these effects are difficult to predict

Horizontally and vertically discontinuous

Fire spread is highly unlikely

Horizontally and vertically continuous

Fire spread is certain in relatively dry and windy conditions

Fuel structure

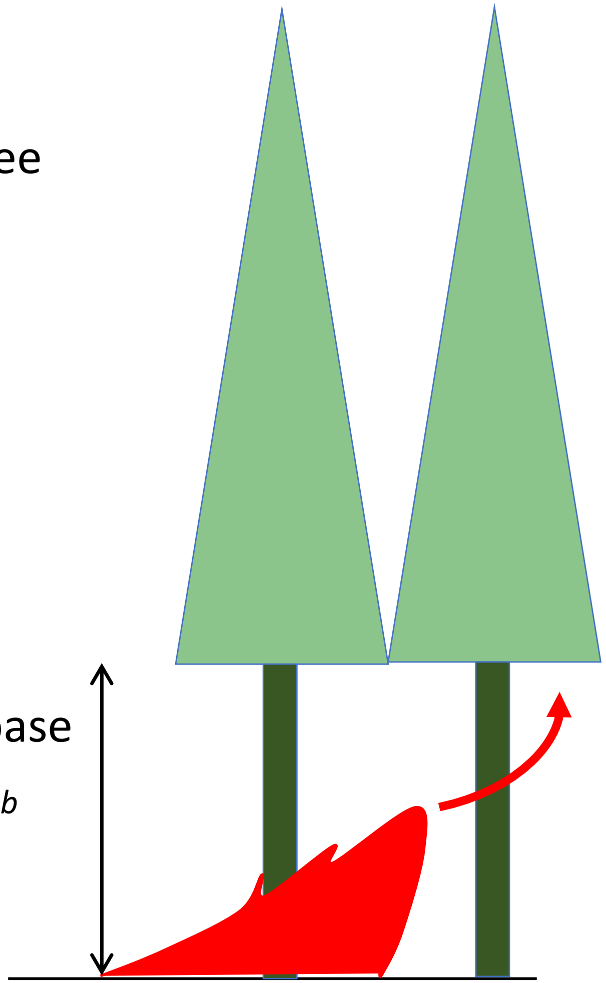
The role of vertical structure in crown fire initiation, here the crown base height h_b

Van Wagner (1973) proposed a criterion for crown fire initiation based on theory and some fire experiments

The minimal surface fire intensity leading to ignition of tree crowns is : $I_0 = (C\ hb\ Qi_g)^{3/2}$

Hence, the minimal intensity increases as $hb^{\ 3/2}$

Q_{ig} is the heat of igntion of the crown foliage, which depends on its moisture content



Fuel structure

For forest fires, it is important to anticipate :

- when surface fires are susceptible to ignite crown fuels
- whether fire will burn trees independently (torching) or in a continuous fire front

That crowning potential depends on weather/fuel moisture conditions but also on the fuel structure at scale of the canopy layer

Torching

Active crown fire

Scott and Reinhardt 2001

Fuel structure

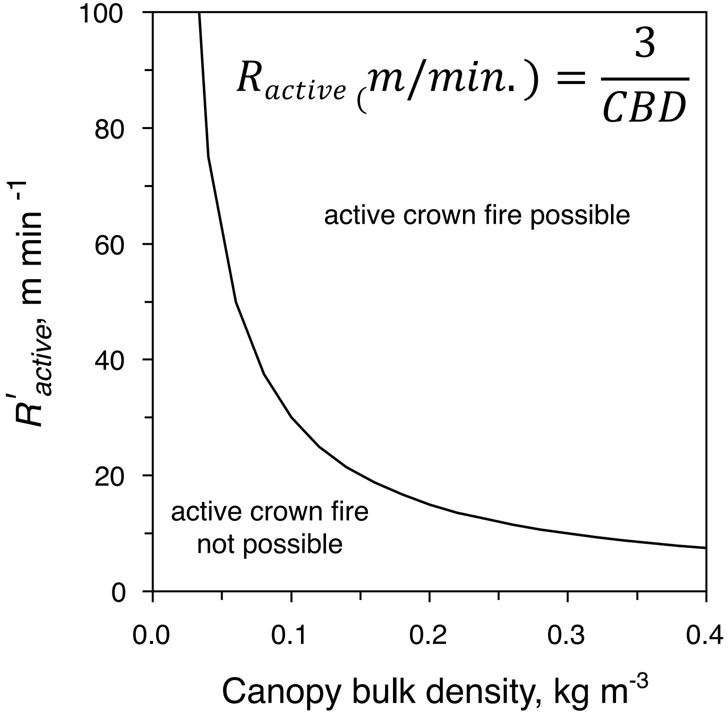
Van Wagner (1977) also derived a criterion for active crown fire spread, assuming that enough canopy fuel must "feed" the fire front for the fire to spread as an active crown fire :

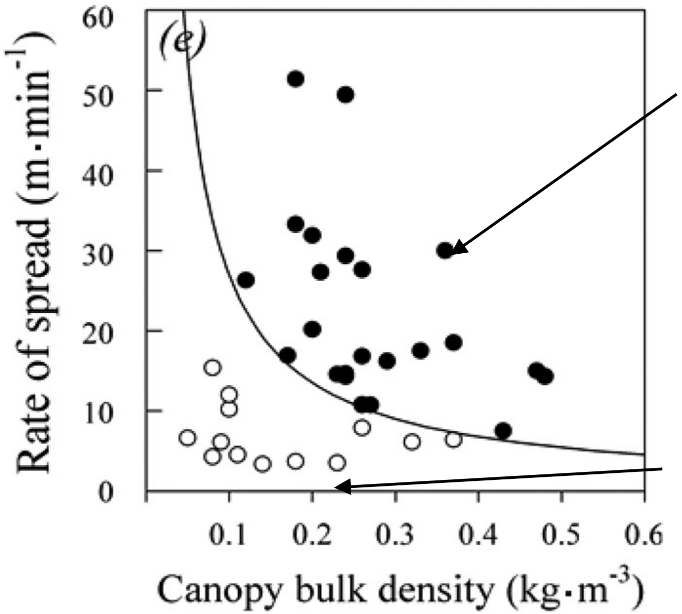
$$S = Ractive\ CBD \approx 0.05\ kg\ m^{-2} s^{-1}$$

Canopy bulk density (kg/m^3)

Minimum ROS of active fire (m/s)

Scott and Reinhardt 2001





Active crown fire

37 experimental crown fires

Non Active crown fire

Cruz et al 2005

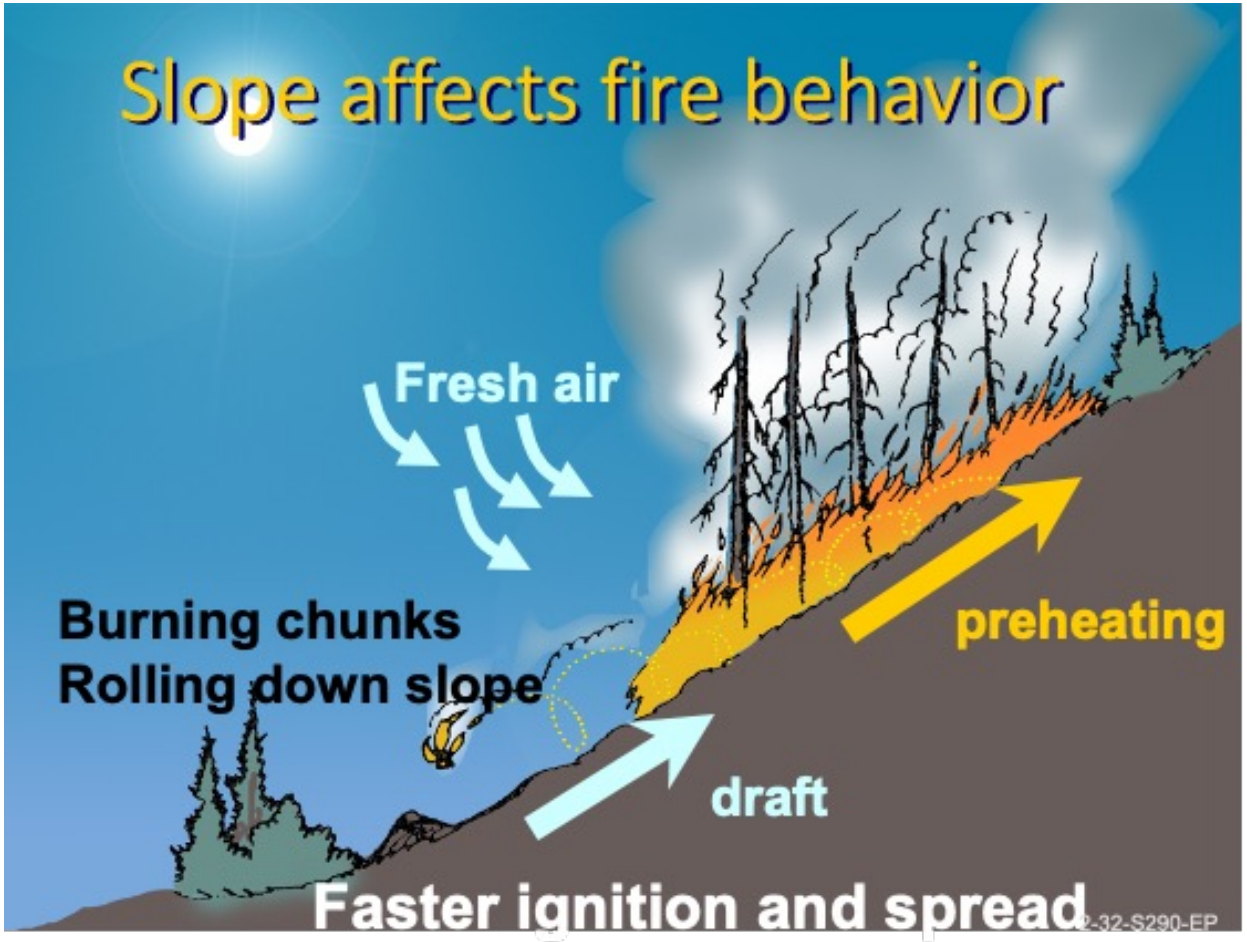
That criterion, among others, is used to model the crown fire potential

Topography effects on fire spread

Two main mechanisms of effects :

1- Terrain slope affects heat transfer and has a direct effect on fire spread

2- Terrain features (valleys, canyon, ridges, slopes) influence the local winds that drive fires



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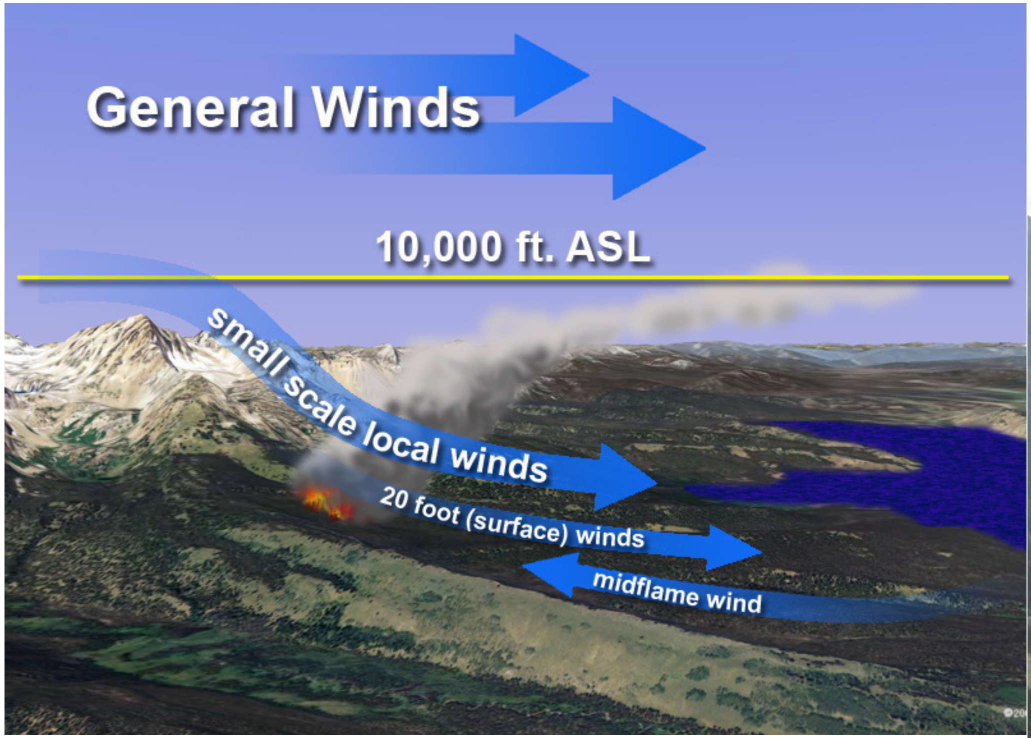


Photographs taken by Stephen Wilkes (NSW Rural Fire Service Air Observer).

Topography effects on fire spread

Slope effect

Rule of thumb of Australian fire-fighters:
ROS doubles for every 10° increase in slope

Bushfire,slope 40°

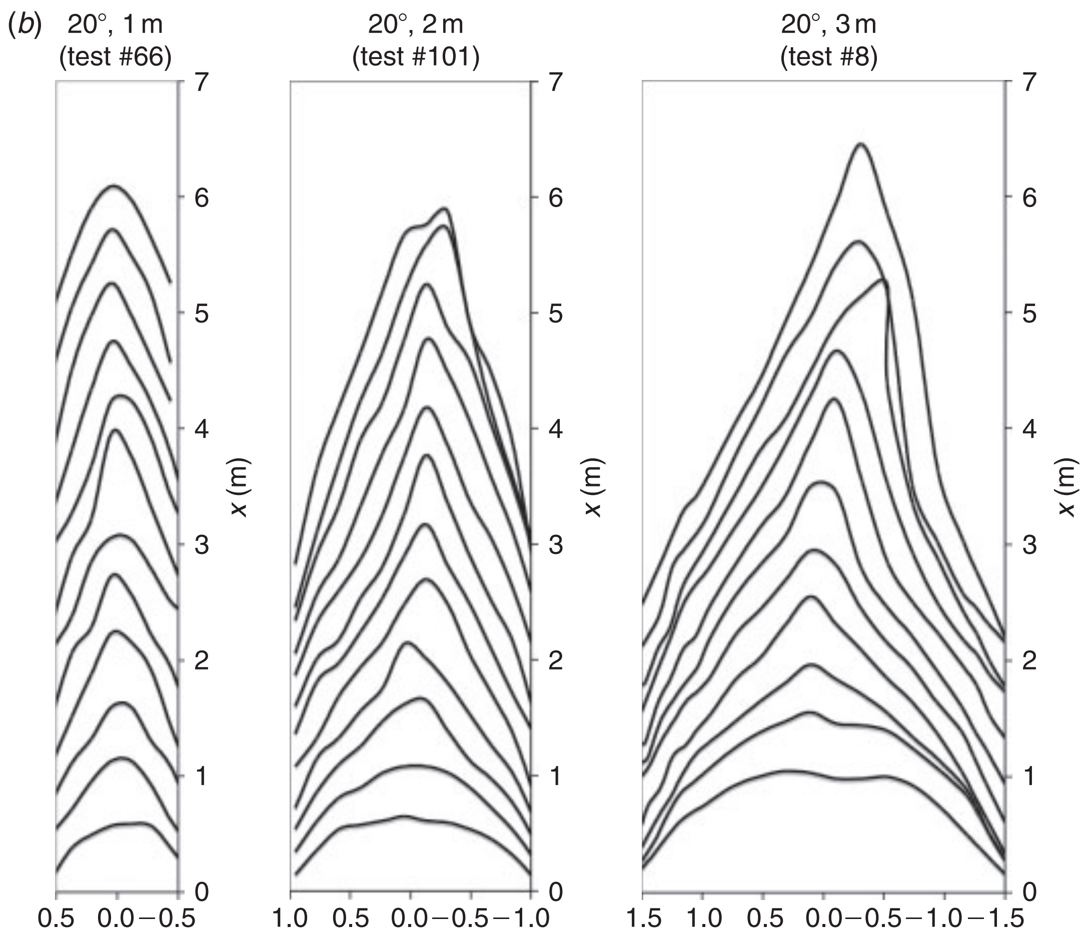
Bushfire, slope 30°

Photographs taken by Stephen Wilkes (NSW Rural Fire Service Air Observer).

Topography effects on fire spread

Slope effect

Fire lines in upslope fires (3 fire widths : 1, 2 and 3m)



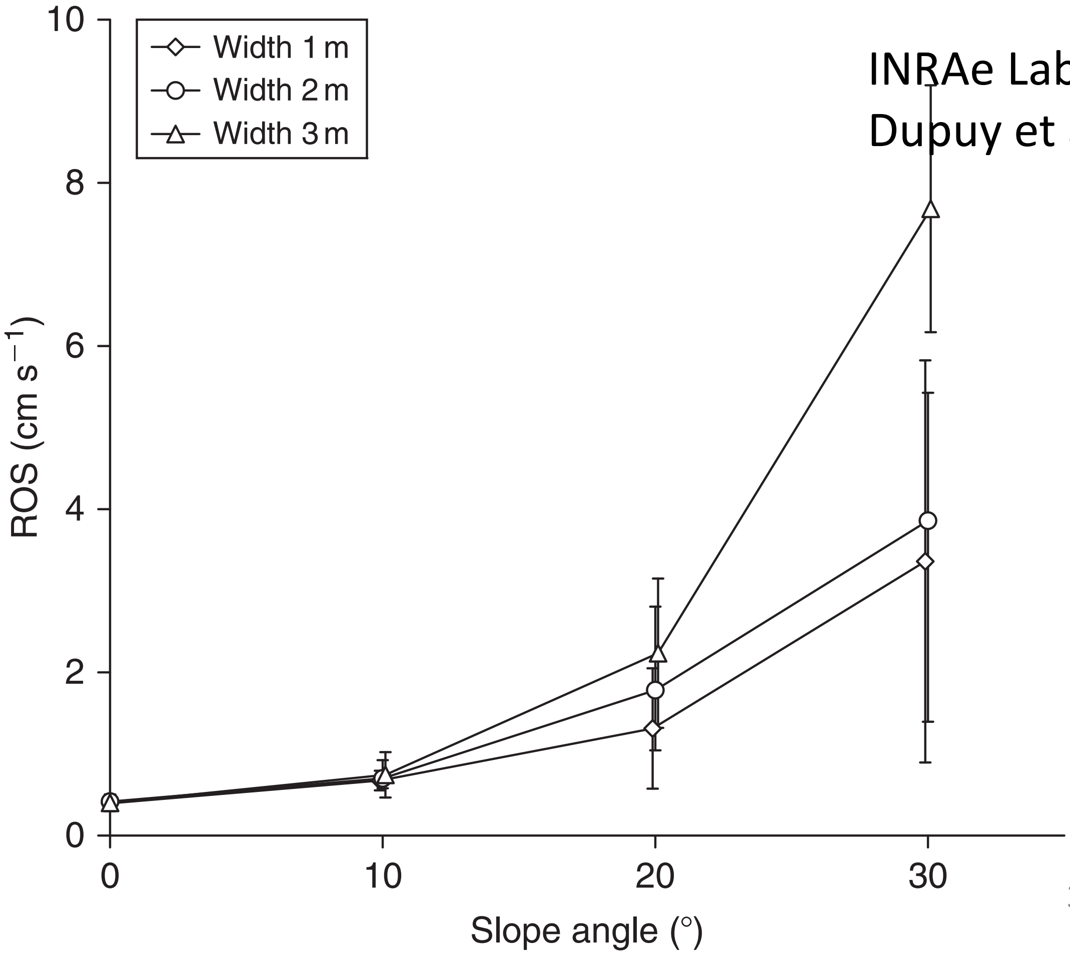
INRAe Lab
Dupuy et al 2012

Topography effects on fire spread

Slope effect

Rate of spread as function of slope angle

Fire width influences the increase of ROS with slope angle



INRAe Lab
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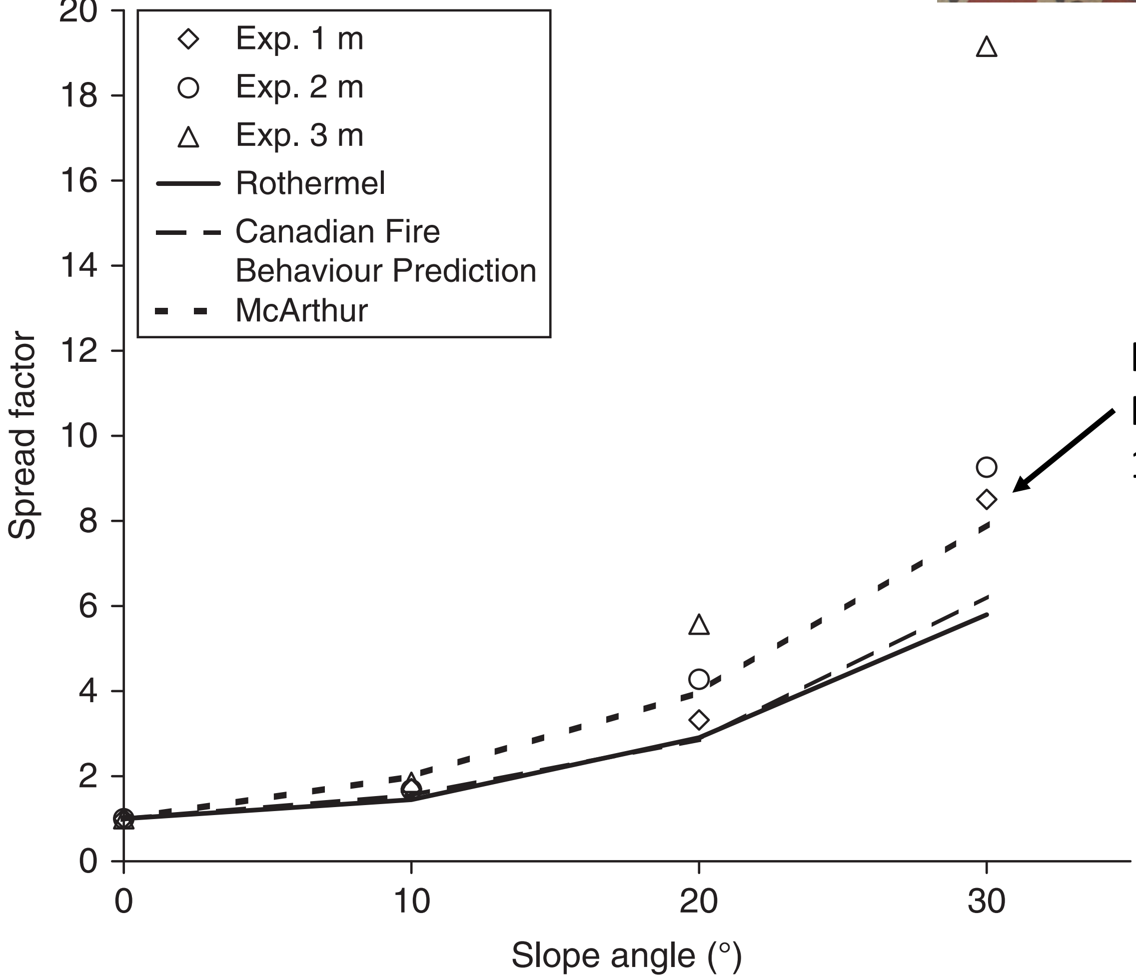
Topography effects on fire spread

Slope effect

Spread factor as function of slope angle
(ROS normalized to 1 at 0°)



INRAe Lab
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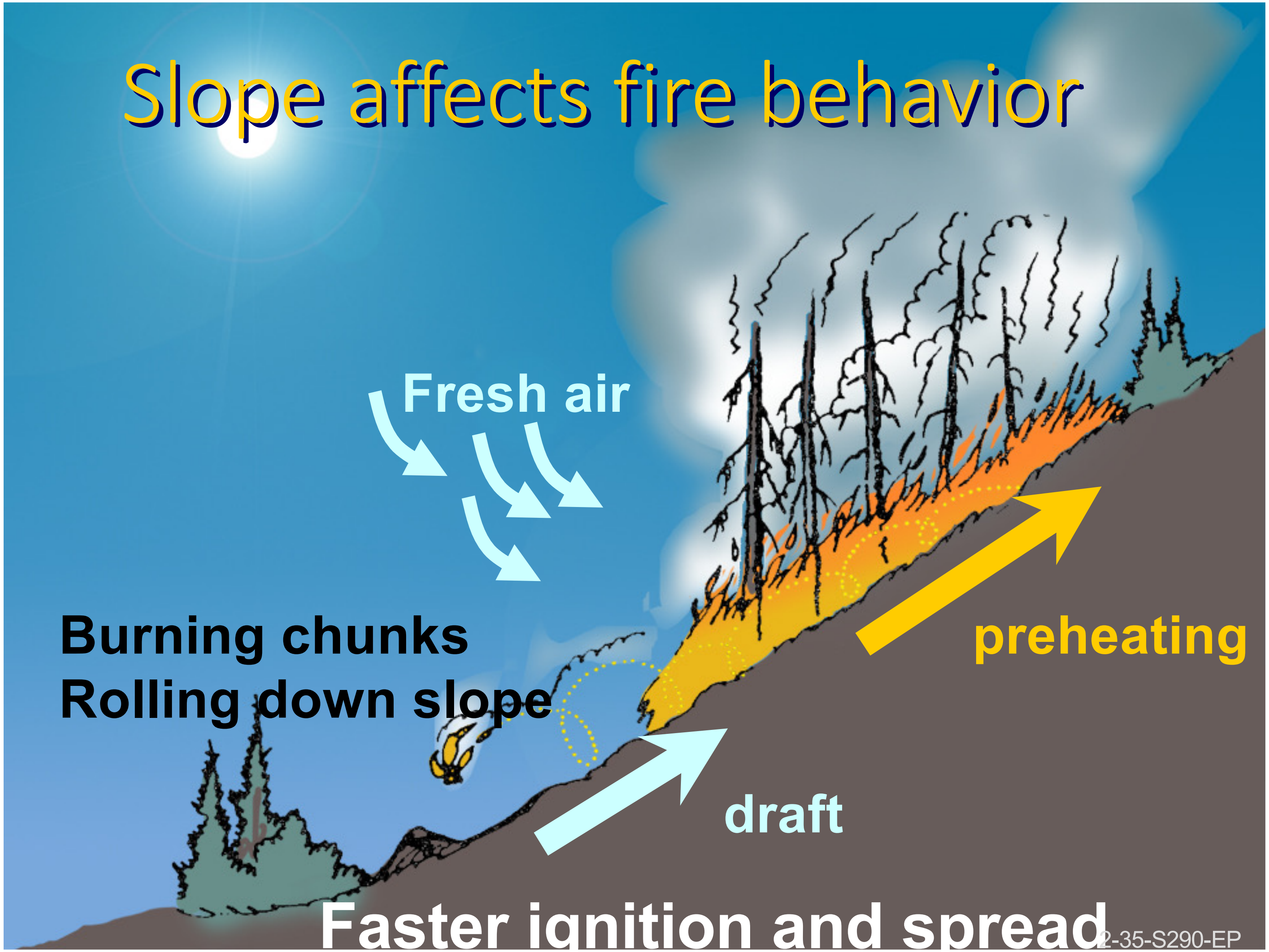
Topography effects on fire spread



Topography effects on fire spread

Narrow canyon

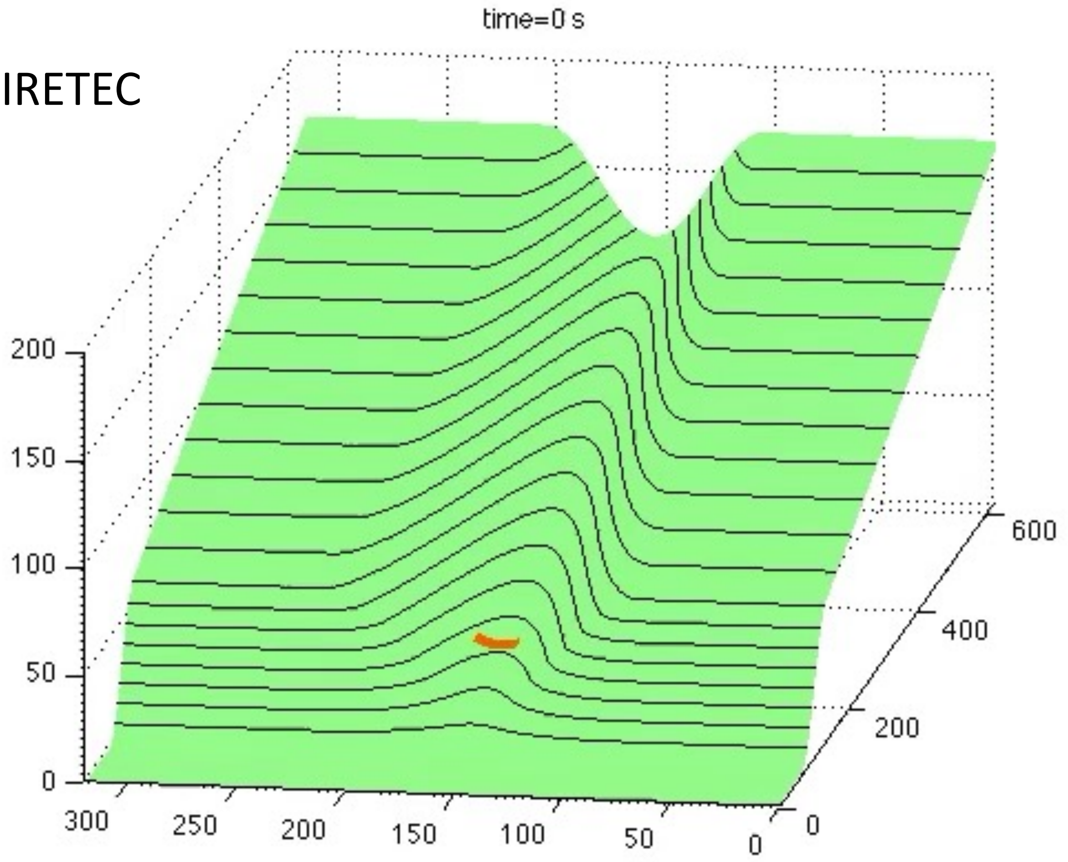
Fires starting in steep narrow canyons can easily spread to fuels on the opposite side due to upslope air movement

Topography effects on fire spread

Narrow canyon

Fires starting in steep narrow canyons can easily spread to fuels on the opposite side due to upslope air movement

Simulation with the FIRETEC model



Topography effects on fire spread

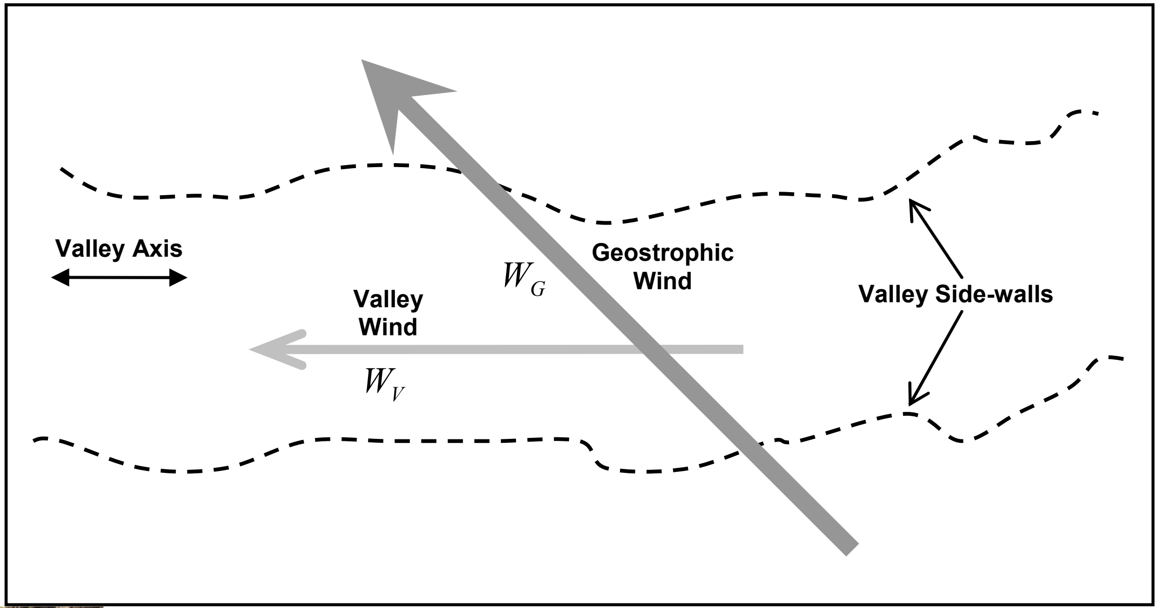
Narrow canyon

Ridges may offer a good place to assist in containing a fire

Topography effects on fire spread

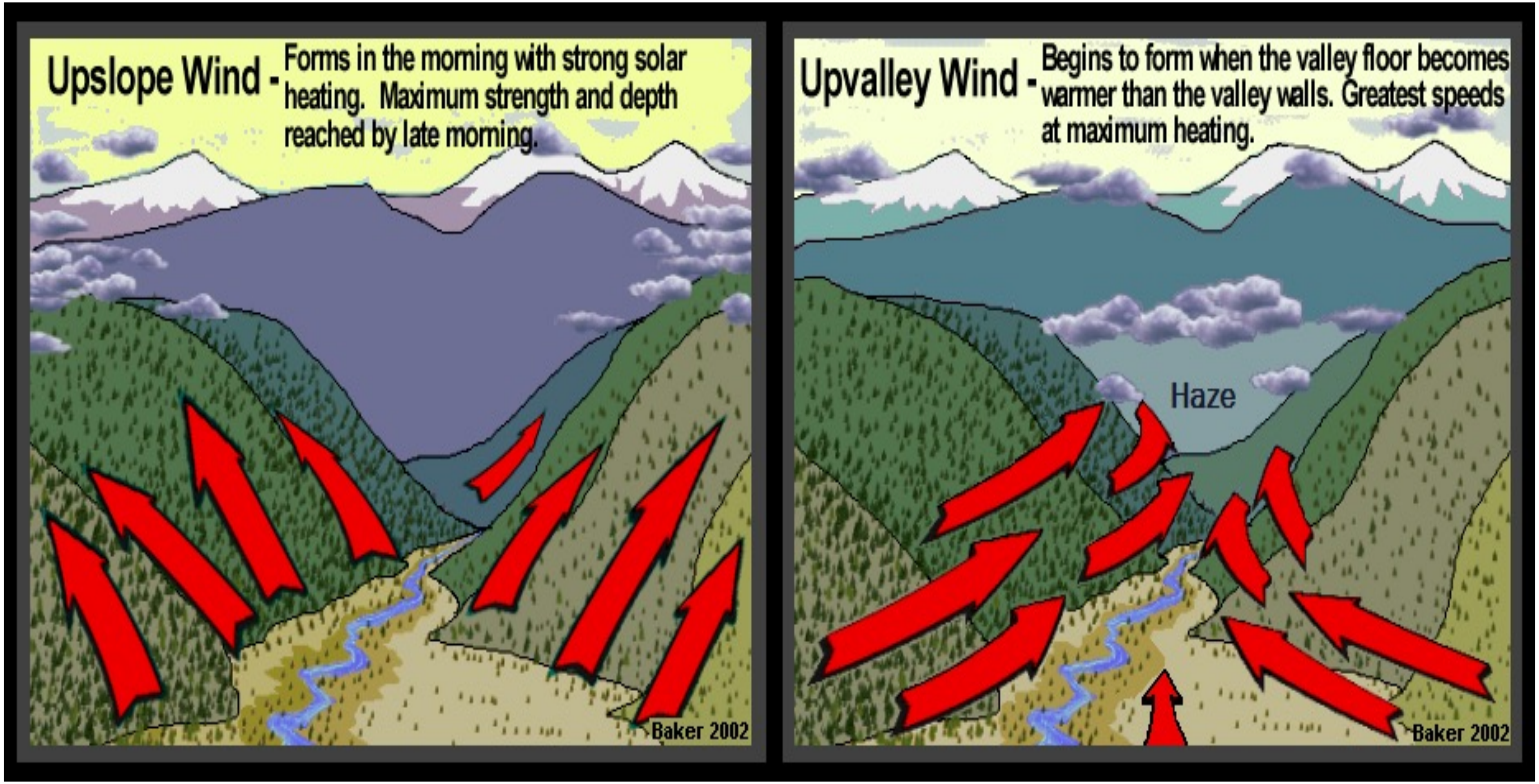
Wind channeling in a valley

Fire in a wide canyon can be heavily influenced by wind. Prevailing wind direction can be altered by the direction of the canyon.



Topography effects on fire spread

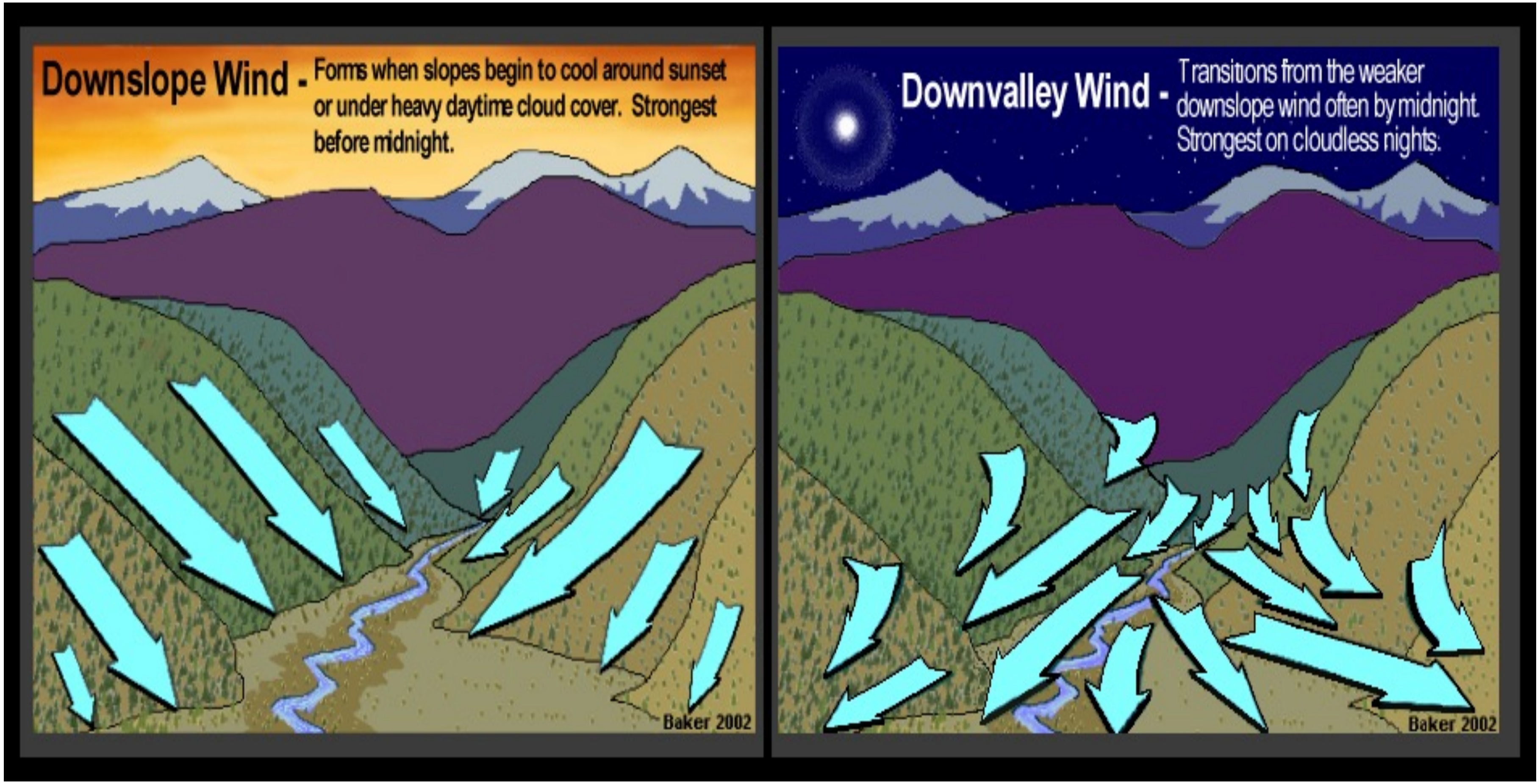
Local winds in valleys



Early to Mid-Morning- 3 to 8 mph | **Late Morning and Afternoon- 10 to 15 mph**

Topography effects on fire spread

Local winds in valleys



Late Afternoon and Evening- 2 to 5 mph

Late Evening and Overnight- 5 to 10 mph

Topography effects on fire spread

Chimney effect