Introduction to wildland fire physics and behaviour

Jean-Luc Dupuy

Type of models

Many fire behaviour models have been developed over last 60 years, including

1. Empirical models for rate of spread
2. Empirical models for marginal burning
3. Empirical models for crowning activity
4. Empirical models and algorithms for fire growth
5. Semi-empirical models for rate of spread
6. Simplified physics-based models for rate of spread
7. Physics-based transport models for fire behaviour
8. Meso-scale coupled fire-atmosphere models

Fire behaviour models : empirical

Australian Rate of spread models - examples

Grassland (1998)

Inputs:

- Wind speed **U**
- Dead fuel moisture **FMC**
- % dry/green (curing) **C**

Formulation :

$$\mathbf{R = (a+b \,.\, (U - 5)^d) \,.\, f(FMC) \,.\, g(C)}$$

(based on 480 observations)

Heathlands (1998)

Inputs:

- Wind speed **U**
- Height of shrub layer **H**

Formulation :

$$\mathbf{R = a \,.\, U^b \,.\, H^d}$$

(based on 117 field fires and 16 wildfire observations)

European Rate of spread models - examples

Shrubland (Q coccifera garrigue), France (Trabaud 1979)

Inputs :

- Wind speed **U**
- Height of shrub layer **H**
- Live fuel moisture M_v

Formulation :

$$\mathbf{R = a \,.\, U^b \,.\, H^c / M_v^d}$$

(based on 35 experimental fires)

Shrubland fuel types, Portugal (Fernandes 2001)

Inputs:

- Wind speed **U**
- Height of shrub layer **H**
- Dead fuel moisture **FMC**

Formulation :

$$\mathbf{R = a \,.\, U^b \,.\, H^c .\exp(-d.FMC)}$$

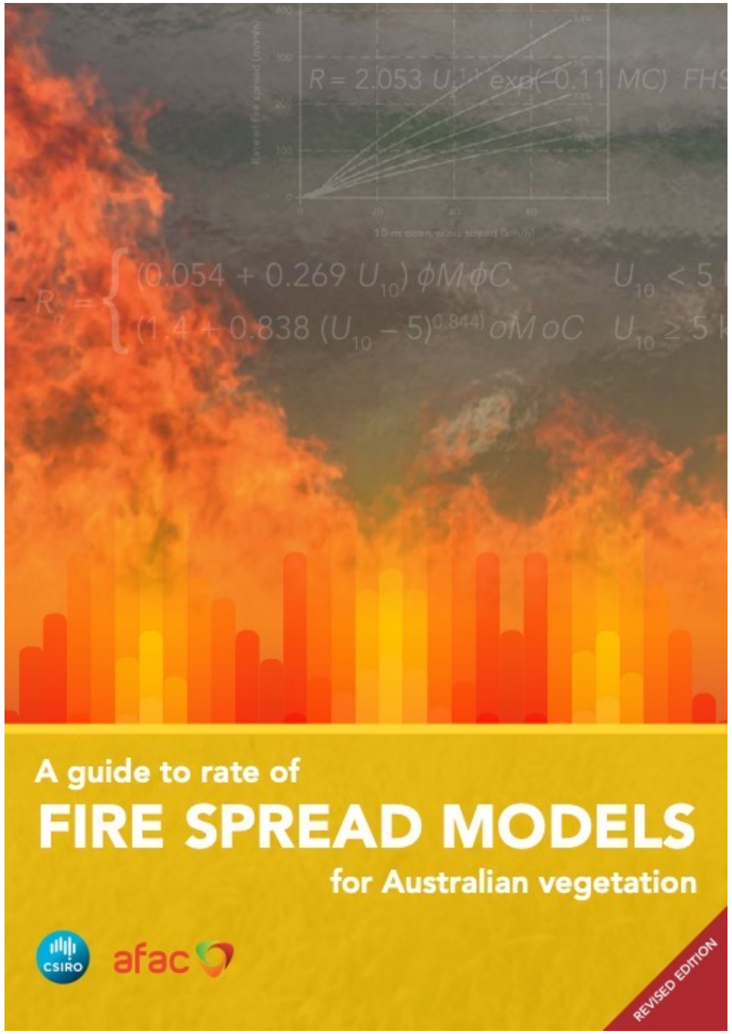
(based on 29 field experimental fires)

Empirical ROS models reviewed by Sullivan 2009

Model	Field or laboratory	Fuel type	FMC function	FMC range (%)	Wind function	Wind speed range ($m\,s^{-1}$)	Add. or Mul.	ROS range ($m\,s^{-1}$)
Empirical			FMC=M					
CFS-accel	Laboratory	Pond./excel.	na	na	$0.74(1-e^{-0.9U})$	0–2.22	na	0.006–0.2
CALM Spinifex	Field	Spinifex	$-82.08M$	12–31	U^2	1.1–10	Add.	0–1.5
CFBP	Field	Forest	$e^{-0.1386M}(1+M^{5.31})$	?	$e^{0.05039U}$	?	Mul.	?
PWSTas	Field	Buttongrass	$e^{-0.0243M}$	8.2–96	$U^{1.312}$	0.2–10	Mul.	?
CALM Mallee	Field	Mallee	$e^{-0.11M_{ld}}$	4–32	$U^{1.05}$	1.5–6.9	Mul.	0.13–6.8
CSIRO Grass	Field	Grass	$e^{-0.108M}$	2.7–12.1	$U^{0.844}$	2.9–7.1	Both	0.29–2.07
Heath	Field	Heath/shrub	na	na	$U^{1.21}$	0.11–10.1	na	0.01–1.00
UdTM Shrub	Field	Heath/shrub	$e^{-0.027M}$	10–40	$e^{0.092U}$	0.28–7.5	Mul.	0.01–0.33
CALM Jarrah I	Laboratory	Litter	$\frac{1}{0.003+0.000922M}$	3–14	$U^{2.22}$	0.0–2.1	Mul.	0.002–0.075
CALM Jarrah II	Field	Forest	$M^{-1.495}$	3–18.6	$U^{2.674}$	0.72–3.33	Mul.	0.003–0.28
UdTM Pinaster	Field	Forest	$e^{-0.035M}$	8–56	$U^{0.868}$	0.3–6.4	Mul.	0.004–0.231
Gorse	Field	Gorse	$-0.0004M$	22–85	na	<1.4	na	0.004–0.039
Maquis	Field	Maquis	na	15.3–27.7	$0.495U$	0.02–0.25	na	0.01–0.15
Helsinki	Field	Moss	na	7–94	$e^{2.286U}$	0.1–1.6	na	0–0.057
CSIRO Forest	Field	Forest	$M^{-1.495}$	5.6–9.6	$U^{0.904}$	1.56–4.58	Both	0–0.38
Quasi-empirical								
TRW	Laboratory	Match splints	na	na	$U^{0.5}$	0–4.7	na	0–0.007
NBRU	Laboratory	Match splints	na	na	U^3	0–9	na	0.004–0.38
USFS	Laboratory	Needles/excel.	$\frac{e^{-4.05M}}{(700+2260M)}$	2–33	$U^{0.91}$	0–3.1	Mul.	0–0.23
Coimbra	Laboratory	Needles	na	10–15	na	?	na	?
Nelson	Laboratory/field	Birch sticks	na	na	$U^{1.51}$	0.0–3.66	na	<0.271

Australian emprirical models

Many other models have been produced for a variety of Australian vegetation covers, including forests and plantations



A guide to rate of

FIRE SPREAD MODELS

for Australian vegetation

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Australian emprirical models

Model	Inputs (units)	Output (units)	Equations	Common name
Southern grasslands				
McArthur (1966a, 1973b)	10-m open wind speed (km/h) Air temperature (°C) Relative humidity (%) Curing level (%)	*R* (km/h)	3.1 3.2	Mk 3/4 Grassland Fire Danger Meter
McArthur (1977)	10-m open wind speed (km/h) Dead fuel moisture content (%) Curing level (%) Fuel load (t/ha)	*R* (km/h)	3.3	Mk 5 Grassland Fire Danger Meter
Cheney *et al.* (1998)	10-m open wind speed (km/h) Dead fuel moisture content (%) Curing level (%)	*R* (km/h)	3.5 3.6 3.10 3.11	CSIRO Grassland Fire Spread Meter
Grasslands - Hummock spinifex				
Griffin and Allan (1984)	2-m wind speed (m/s) Air temperature (°C) Relative humidity (%) MC (%) live and dead Spinifex cover (%) Bare ground cover (%) Patchiness	*R* (m/s)	3.12 3.13 3.14	Central Australia spinifex model
Burrows *et al.* (1991)	2-m wind speed (km/h) MC (%) live and dead Fuel load (t/ha) Air temperature (°C)	*R* (m/h)	3.15	Spinifex model
Burrows *et al.* (2009)	2-m wind speed (km/h) MC (%) live and dead Fuel load (t/ha) or Fuel cover (%) and height (cm)	Likelihood of fire spread *R* (m/h)	3.16 3.17 3.18 3.19 3.20	WA spinifex model

Model	Inputs (units)	Output (units)	Equations	Common name
Grasslands - Tropical savannas				
Cheney *et al.* (1998)	10-m open wind speed (km/h) Dead fuel moisture content (%) Curing level (%) Overstorey type	*R* (km/h)	3.5 3.6 3.10 3.11	CSIRO Fire Spread Meter for Northern Australia
Shrublands – Buttongrass moorlands				
Marsden-Smedley and Catchpole (1995a)	2-m wind speed (km/h) Dead fuel moisture content (%) Fuel age (years)	*R* (m/min)	4.1	Buttongrass model
Shrublands heathlands				
Catchpole *et al.* (1998)	2-m wind speed (m/s) Fuel height (m)	*R* (m/s)	4.4	Heathland model
Anderson *et al.* (2015)	10-m wind speed (km/h) Dead fuel moisture content (%) Fuel height (m)	*R* (m/min)	4.5	Heathland model
Shrublands Mallee-heath				
McCaw (1995)	2-m wind speed (m/s) Dead fuel moisture content (%)	*R* (m/s)	4.7	WA mallee model
Cruz *et al.* (2010)	10-m open wind speed (km/h) Dead fuel moisture content (%) Near-surface Fuel Percent cover Score (PCS) Elevated Fuel Hazard Score (FHS) Overstorey Height (m)	Likelihood of fire spread Likelihood of crown fire spread *R* (m/min)	4.8 4.10 4.11 4.12 4.13	SA heath SA mallee-heath
Cruz *et al.* (2013)	10-m open wind speed (km/h) Dead fuel moisture content (%) Overstorey Cover (%) Overstorey Height (m)	Likelihood of fire spread Likelihood of crown fire spread *R* (m/min)	4.14 4.16 4.17 4.18 4.19	Mallee-heath

Fire behaviour models : empirical

Australian emprirical models

Model	Inputs (units)	Output (units)	Equations	Common name
Dry eucalypt forests – prescribed burning				
McArthur (1962)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/min)	5.1 5.2 5.3 5.4	Leaflet 80; Control Burning Guide
Sneeuwjagt and Peet (1985)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/h)	5.9 5.10 5.11 5.12 - 5.17	Red Book; Forest Fire Behaviour Tables
Cheney *et al.* (1992)	2-m wind speed (km/h) Dead fuel moisture content (%) Near-surface fuel height (m)	*R* (m/min)	5.18	Young Regrowth Forest Burning Guide
Dry eucalypt forests – wildfire				
McArthur (1967, 1973a)	10-m open wind speed (km/h) Air temperature (°C) Relative humidity (%) Drought factor KBDI (mm) Time since rain (days) Rainfall (mm) Last rain amount (mm) Available litter fuel load (t/ha)	*R* (km/h)	5.19 5.20 5.27	Mk 5 Forest Fire Danger Meter
Cheney *et al.* (2012)	10-m open wind speed (km/h) Dead fuel moisture content (%) Surface Fuel Hazard Score (FHS) Near-surface (Fuel Hazard Score (FHS) Near-surface fuel height (cm) Fuel Hazard Rating (FHR)	*R* (m/h)	5.28 5.29 5.31	Dry Eucalypt Forest Fire model Vesta model

Model	Inputs (units)	Output (units)	Equations	Common name
Wet eucalypt forests – prescribed burning				
Sneeuwjagt and Peet (1985)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/h)	6.1 6.2 6.3 6.4 6.9	Red Book; Forest Fire Behaviour Tables
Pine plantations – prescribed burning				
Byrne (1980); Hunt and Crock (1987)	10-m open wind speed (km/h) Relative humidity (%) Available understorey fuel load (t/ha)	*R* (m/h)	7.1	Prescribed burning guide Mk 3
Sneeuwjagt and Peet (1985)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/h)	See 5.9 - 5.17 7.2 7.3	Red Book; Forest Fire Behaviour Tables
Pine plantations – wildfire				
Cruz *et al.* (2008)	10-m open wind speed (km/h) Air temperature (°C) Fine dead fuel moisture content (%) Live foliar moisture content (%) Fuel strata gap (m) Surface fuel model Canopy bulk density (kg/m^3) Stand height (m) Stand density (trees/ha)	*R* (m/min) Fire type		PPPY – Pine Plantation Pyrometrics

Generic ROS models for grassland and shrubland

Grassland (Cheney et al 1998)

when $U_{10} < 5$ km h^{-1}

$$R_n = [0.054 + 0.269\, U_{10}] \,.\, \phi M \,.\phi C$$
$$R_{cu} = [0.054 + 0.209\, U_{10}] \,.\phi M \,.\phi$$

when $U_{10} > 5$ km h^{-1}

$$R_n = [1.4 + 0.838\,(U_{10} - 5)^{.844}] \,.\, \phi M \,.\, \phi C$$

$$R_{cu} = [1.1 + 0.715\,(U_{10} - 5)^{.844}] \,.\phi M \,.\phi C$$

where

R_n = quasi-steady rate of spread in undisturbed natural pastures (km h^{-1}).

R_{cu} = quasi-steady rate of spread in cut, grazed, or par tially trampled pastures (km h^{-1})

U_{10} = 10 m wind speed in the open (km h^{-1}) application bounds (0-80 km h^{-1}).

ϕM = moisture coefficient (equations 14, 15, 16)

ϕC = curing coefficient (equation 17)

Dead fuel moisture coefficient

$\phi M = \exp(-0.108\, M_f)$ if $M_f < 12\%$ (14)

$\phi M = 0.684 - 0.0342\, M_f$ if $M_f > 12\%$, $U_{10} <$ 10 km h^{-1} (15)

$\phi M = 0.547 - 0.0228\, M_f$ if $M_f > 12\%$, $U_{10} >$ 10 km h^{-1} (16)

where M_f = dead fuel moisture content (%): application bounds 2 - 24%.

Curring coefficient

$\phi C = 1.120/[1 + 59.2 \exp(-0.124\,(C-50))]$ (17)

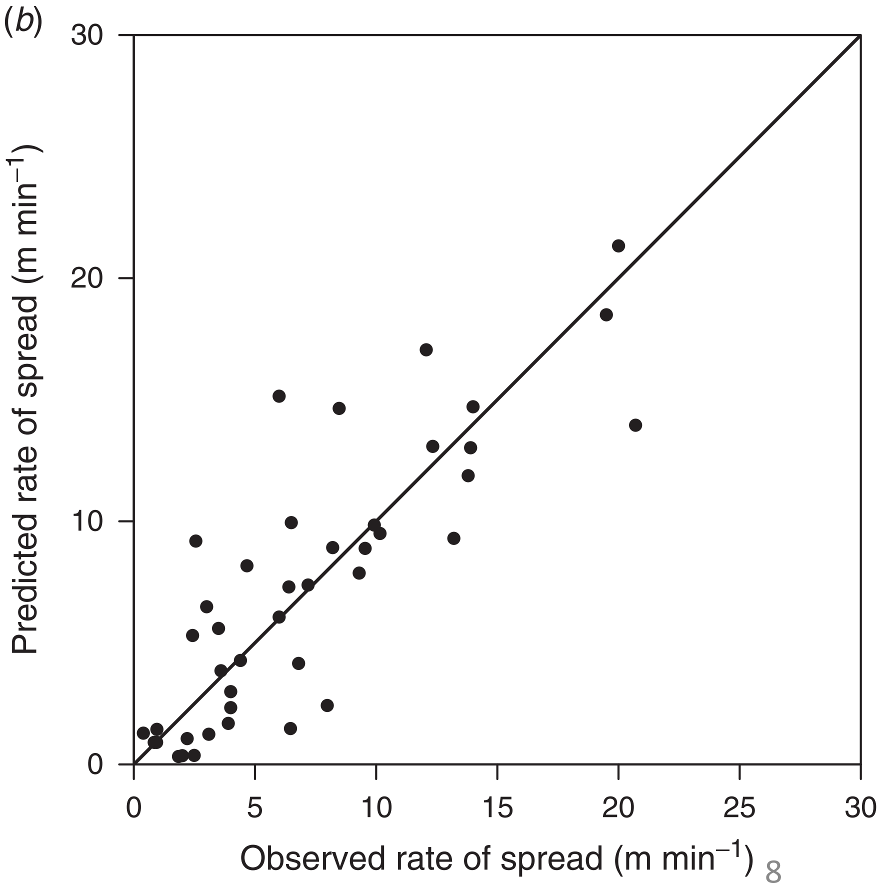
where C is the degree of grass curing (%): application bounds 50 - 100%.

Generic ROS models for grassland and shrubland

Shrubland (Anderson et al 2015)

$$R = \begin{cases} [R_0 + 0.2(a(5w_f)^b - R_0)U_{10}]h^c \exp(-k_d M_d), U_{10} < 5 \\ a(w_f U_{10})^b h^c \exp(-k_d M_d), U_{10} \geq 5 \end{cases}$$

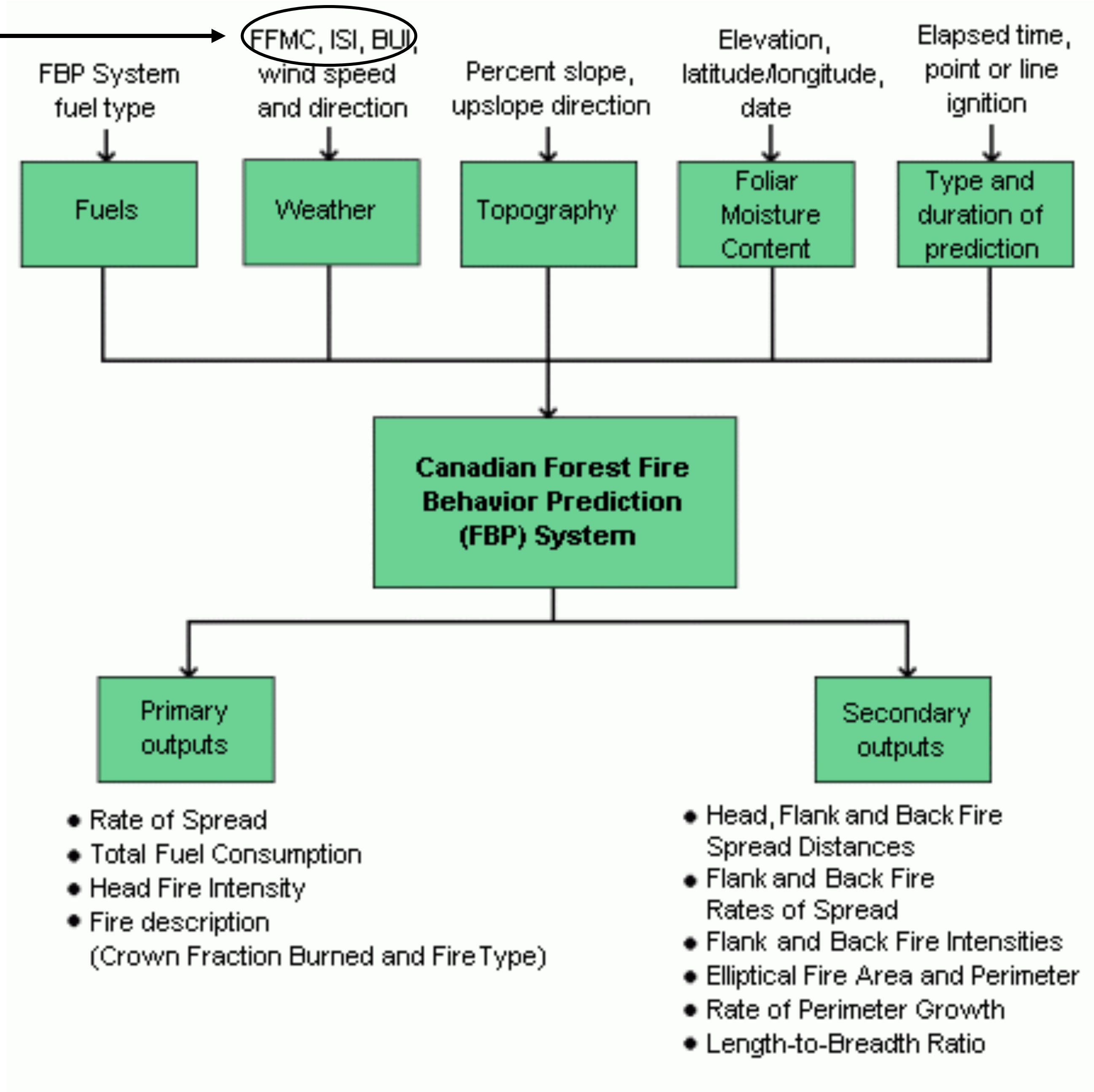
U_{10} 10 m – wind speed
M_d dead fuel moisture content
w_f is a wind reduction factor,
0.67 for shrublands and 0.35 for woodlands



Fire behaviour models : empirical

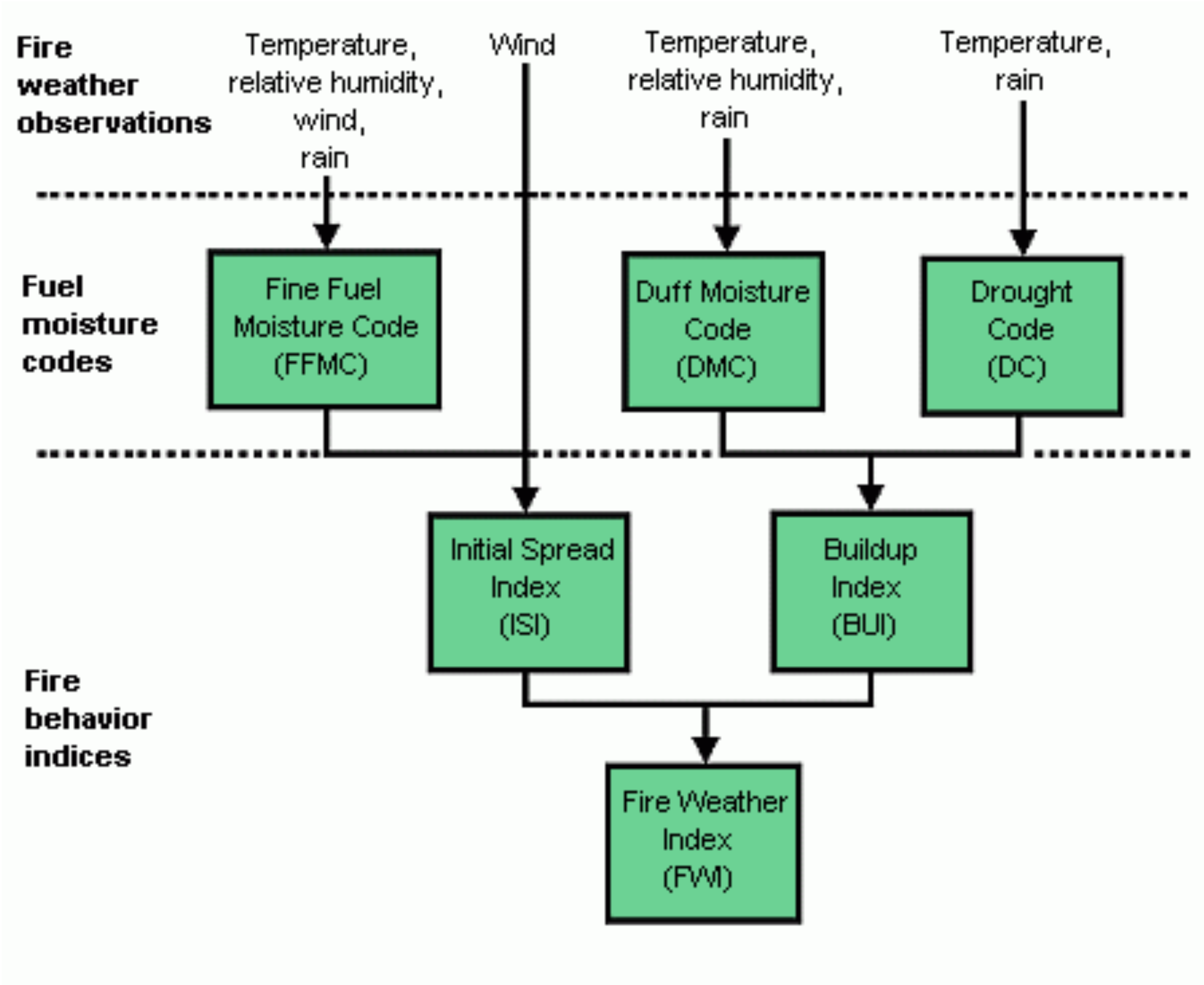
The Canadian Fire Behaviour Prediction System (1992)

Canadian Fire Weather Index (FWI) System



The Fire Weather Index (FWI) System

It is a widely used fire danger (not fire beahviour) prediction system



The Canadian Fire Behaviour Prediction System (1992)

Rate of spread prediction

Inputs:

- Fuel types (currently 16 types)
- Wind and fuel moisture through the ISI

Formulation :

One equation for eah fuel type (500 fire experiments) :

$$\mathbf{R = a \,.\, [1 - exp(-b \,.\, ISI)^{c}]}$$

Terrain slope effect : an empirical law to correct for slope

C1 – Spruce-Lichen Woodland

C3 – Mature Jack or Lodgepole Pine

C6 – Conifer plantation

S2 – White Spruce – Balsam Slash

M1 – Boreal Mixedwood-Leafless

M4 – Dead Balsam Fir Mixedwood

Fire behaviour models : semi-empirical

The Rothermel model (1972) – USDA Forest Service

The model is based on an energy balance for fuel bed pre-heating (Frandsen 1971), parameterized from laboratory experiments .

When fire approaches at rate *R*, a fuel elementary volume ΔV receives heat from flames and hot embers in the form of horizontal and vertical 'propagating fluxes' ***J,*** leading to its ignition:

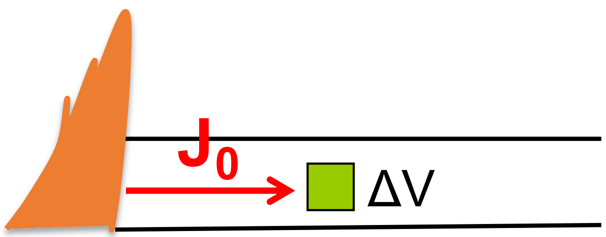
$$R\,\rho_e Q_{ig} = J = J_0 + J_v$$

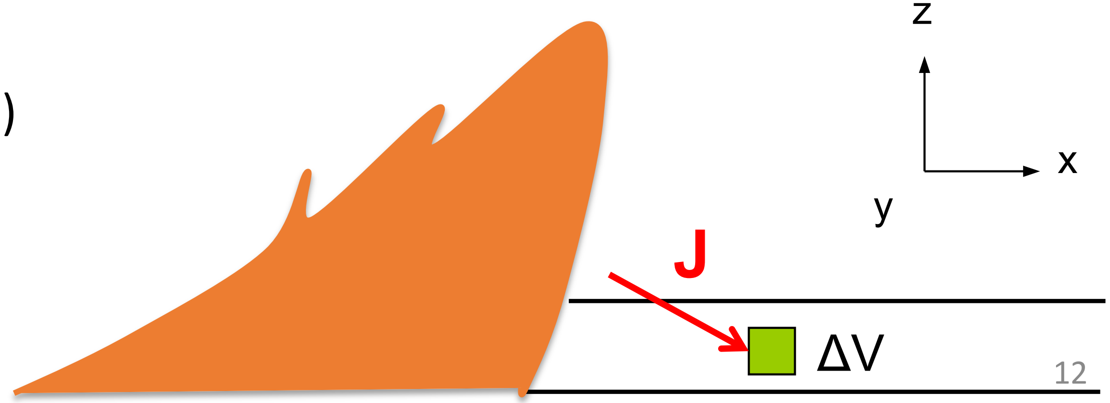
- $R\,\rho_e Q_{ig}$: Preheating heat flux (kW/m²)
- J_0: Horizontal propagating flux (kW/m²)
- J_v: Vertical propagating flux (kW/m²)

$\rho_e = \varepsilon\,\rho_b$ is the mass of fuel bed effectively burned per unit volume (ρ_b bulk density of the fuel bed kg/m³)

Q_{ig} is heat of ignition kg/m³

No wind, no slope ($J \approx J_0$)





The Rothermel model (1972)

No slope, no wind

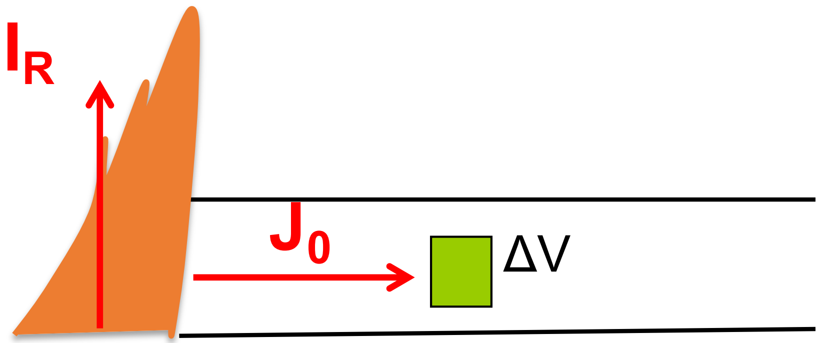
The 'propagating flux' J_0 is assumed proportional to the heat flux released by the combustion of a unit area of fuel bed, called the reaction intensity (this is different from fireline intensity)

$$I_R = \frac{\Delta H_c \, wa}{\tau} \quad (\mathrm{kW/m^2})$$

ΔH_c is the low heat of combustion of the fuel (kJ/kg)

w_a is the fuel load consumed (kg/m²)

τ is a characteristic time of fuel combustion (s)



The Rothermel model (1972)

No slope, no wind conditions

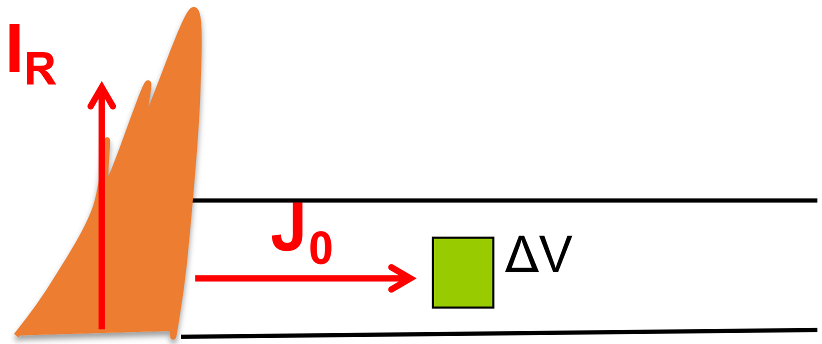
The 'propagating flux' J_0 is assumed proportional to the heat flux released by the combustion of a unit area of fuel bed, called the reaction intensity (this is different from fireline intensity)

$$I_R = \frac{\Delta H_c \, wa}{\tau}$$

ΔH_c is the low of combustion of the fuel (kJ/kg)

w_a is the available fuel load (kg/m^2)

τ is a characteristic time of fuel combustion (s)



The 'propagating flux' J_0 then writes

$$J_0 = \xi \; IR$$

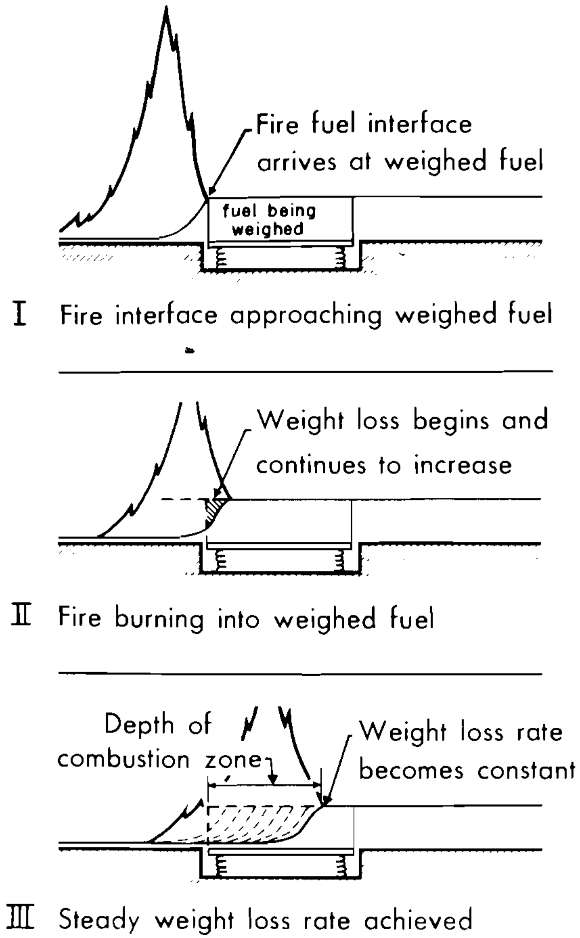
The Rothermel model (1972)

No slope, no wind conditions

The reaction intensity and the 'propagation flux' are then estimated from independent measurements in fire experiments.

- Reaction intensity estimated from mass loss measurement on spreading fire
  Note : reaction inetensity is decomposed in several terms, not detailed here
- Propagation flux known from ROS (R) and fuel consumption (ε) measurements :

$$J_0 = R\varepsilon\rho_b Q_{ig}$$

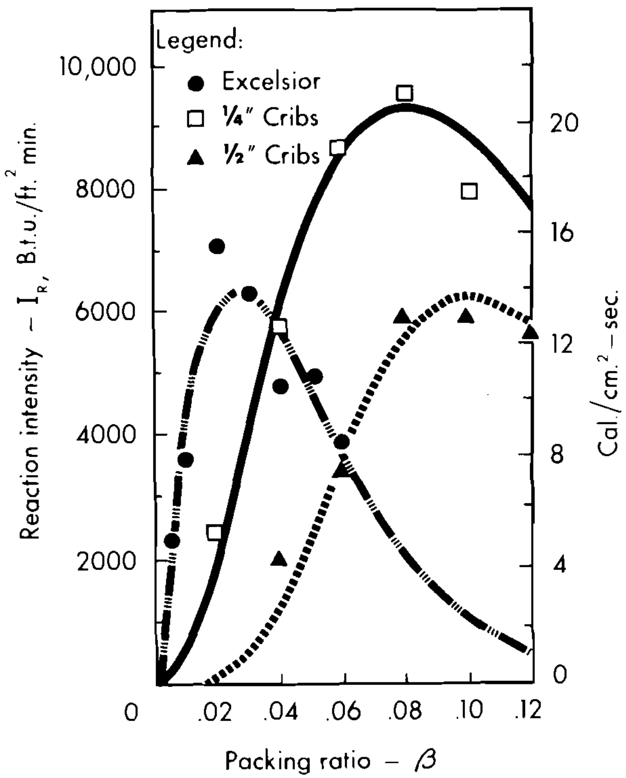


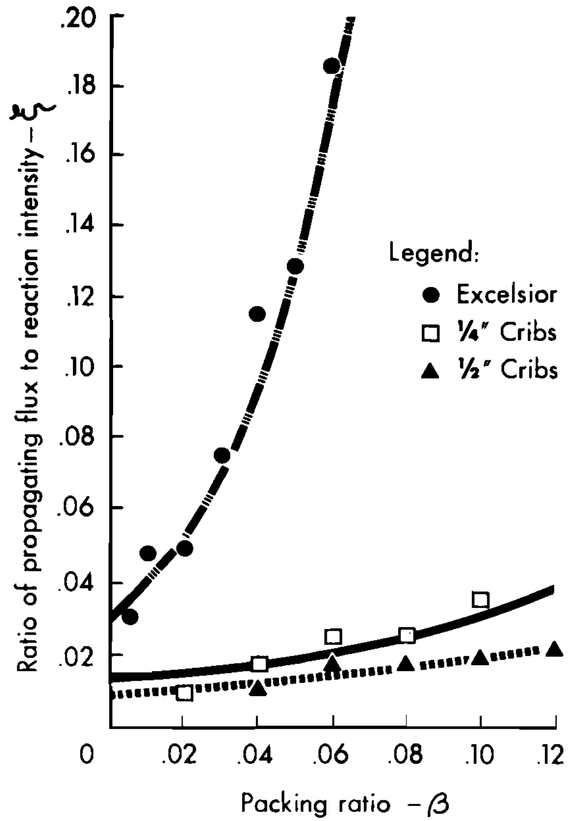
The Rothermel model (1972)

No slope, no wind conditions

The terms of the model are fitted to fuel bed parameters :

- **σ** the surface to volume ratio of fuel elements (m^{-1})
- ***β*** the packing ratio of the fuel bed (=ρ_b/ρ)
- **δ** the fuel bed depth (m)
- **M** fuel moisture content





The Rothermel model (1972)

Wind and slope effects

The propagating flux is written as : $J = J_0 + Jv = J_0\,(1 + \phi_W + \phi_S)$

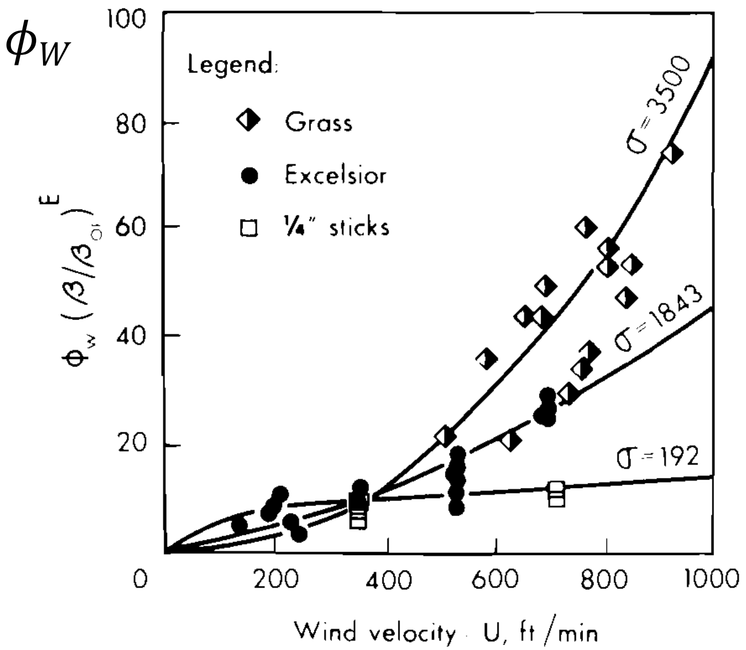
Coefficients estimated from specific fire experiments in wind tunnel and on tilted bench

No wind, no slope propagating flux

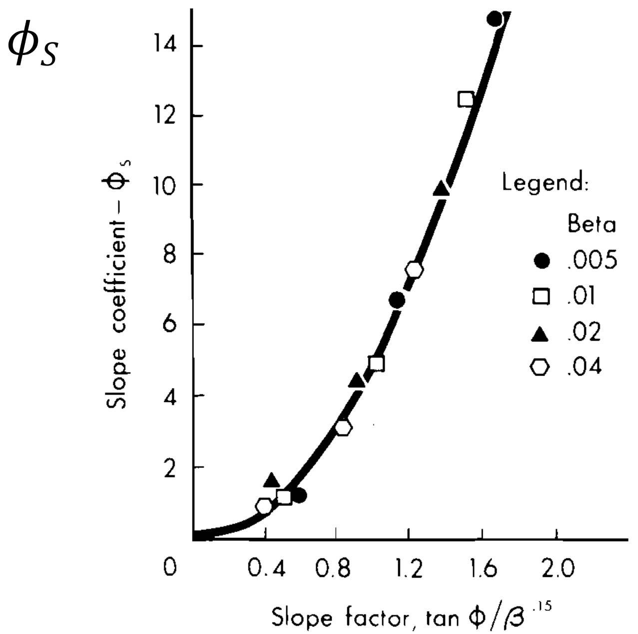
Wind coeff.

Slope coeff.

$$\phi_w = CU^B(\beta/\beta_{op})^{-E}$$



$$\phi_s = 5.275\beta^{-.3}(\tan\phi)^2$$

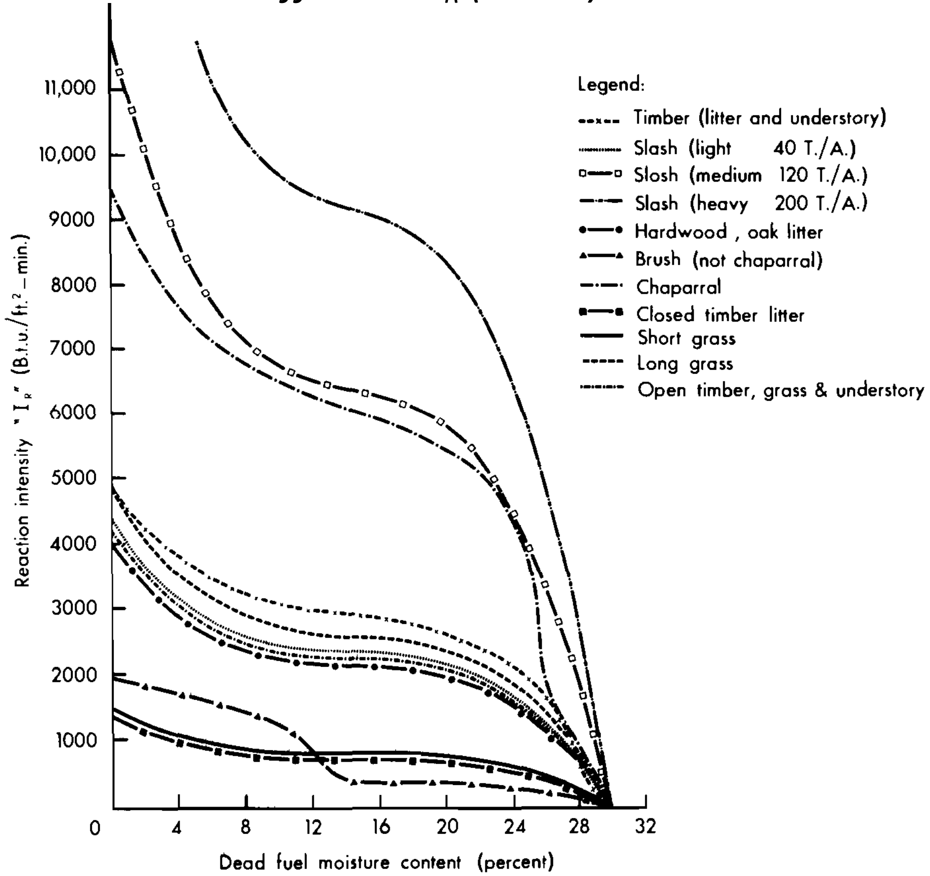


The Rothermel model (1972)

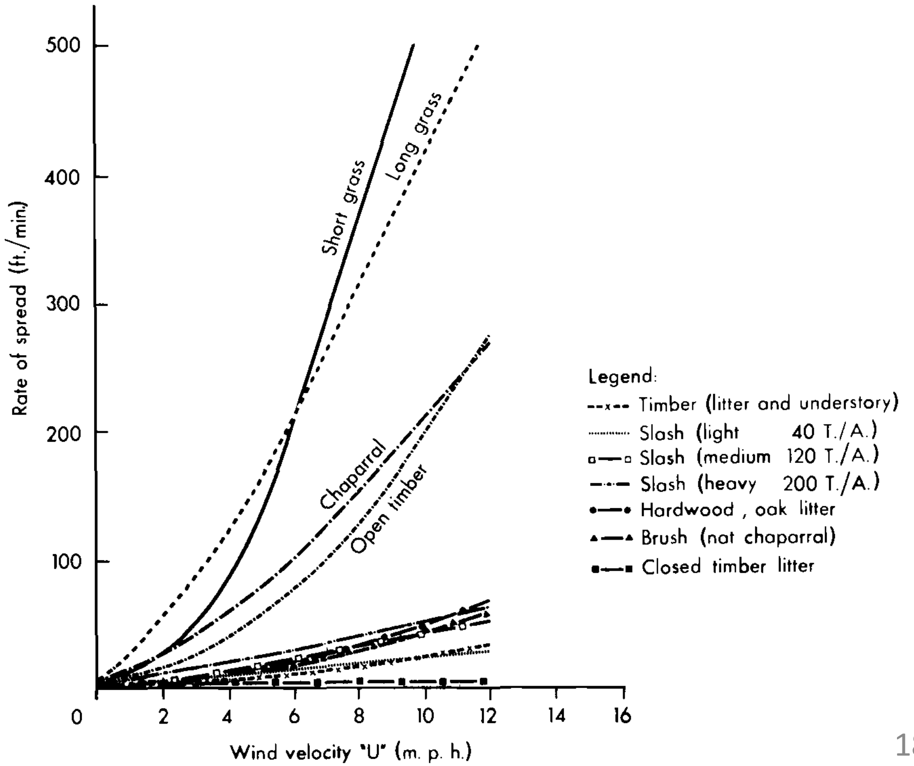
Final model formulation $$R = \frac{\xi \, IR \, (1 + \phi_W + \phi_S)}{\rho_b \, \varepsilon \, Qig}$$

The formulation was extended to a mixture of fuels, so the model can simulate effects in different fuel types

Dead FMC effect on I_R (and R) :



Wind effect on R :



The Rothermel model (1972)

This model is the most widely used fire behaviour model worldwide. It is intended for the prediction of surface fire rate of spread.

It has been embedded in a number of fire prediction systems, in particular in North-America:

BEHAVE, FLAMAP, FARSITE, …

Fuel models have been built for operational use in US (and elsewhere) : a set of fuel structure parameters ($\boldsymbol{\sigma}$, $\boldsymbol{\beta}$, $\boldsymbol{\delta}$) is attribued to each fuel type.

Its relative simplicity and full parameterization allowed this wide success.

The model outputs must be controlled against fire observations, and fuel models may need to be adjusted, depending on the context of application.

Physics-based model : what is it ?

Basically, it is a set of mathematical equations describing the major fire processes and their interactions in both time and space.

It is based on the conservation laws of physics for mass, momentum and energy.
Well known examples of such equations are models for weather forecasts.

For wildfires, these equations describe :

- the atmospheric processes in interaction with the fire and the vegetation: wind flow and fire-induced flow
- the thermal degradation and combustion of fuel
- the heat transfer between flames, embers and the fuels

To date two models have been developed that are operational at stand to landscape scales:
- FIRETEC (Los Alamos National Laboratory, USA ; co-developed with INRAe 10-15 years ago)
- WFDS (Wildland Fire Dynamics Simulator, an extension of the FDS from the NIST, USA
More 'research' models have been produced as well (e.g. FIRESTAR, University of Marseille)

Physics-based transport model : what is it ?

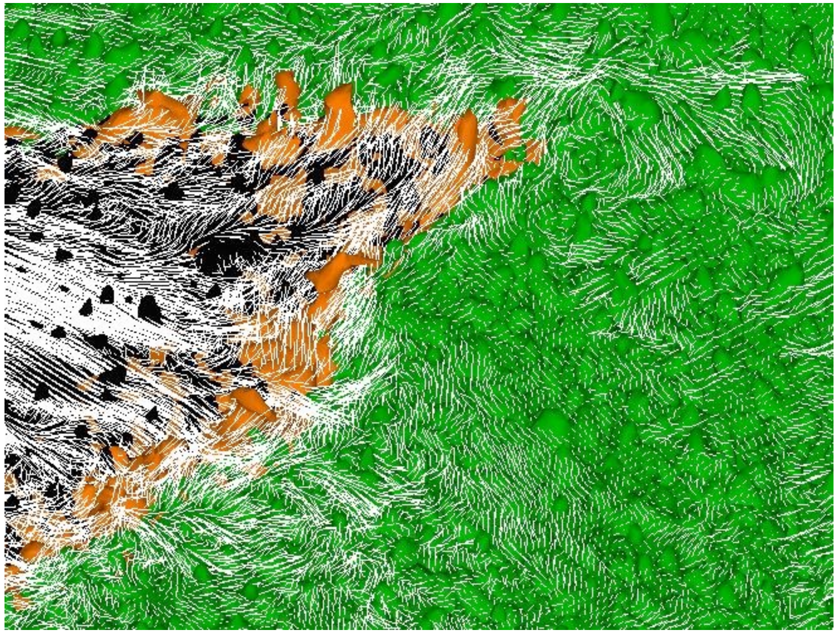
These equations must be solved numerically in time and space thanks to (high-performance) computers.

For this, time and space are discretized in time steps and spatial cells organized according to a grid geometry (grid cells).

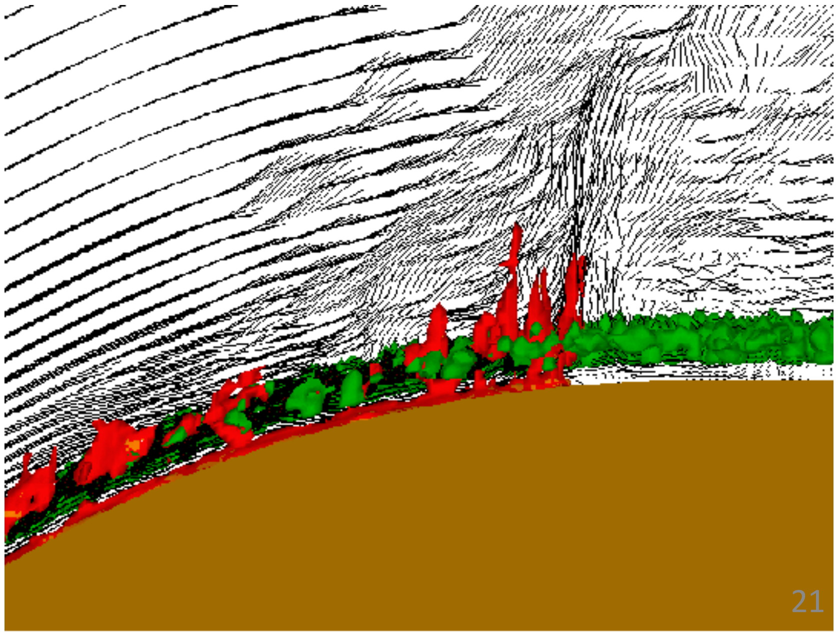
In each grid cell, the time evolution of the following state variables is computed :

temperature, mass density, chemical species, flow velocity.

Top view of a simulated grass fire (FIRETEC)

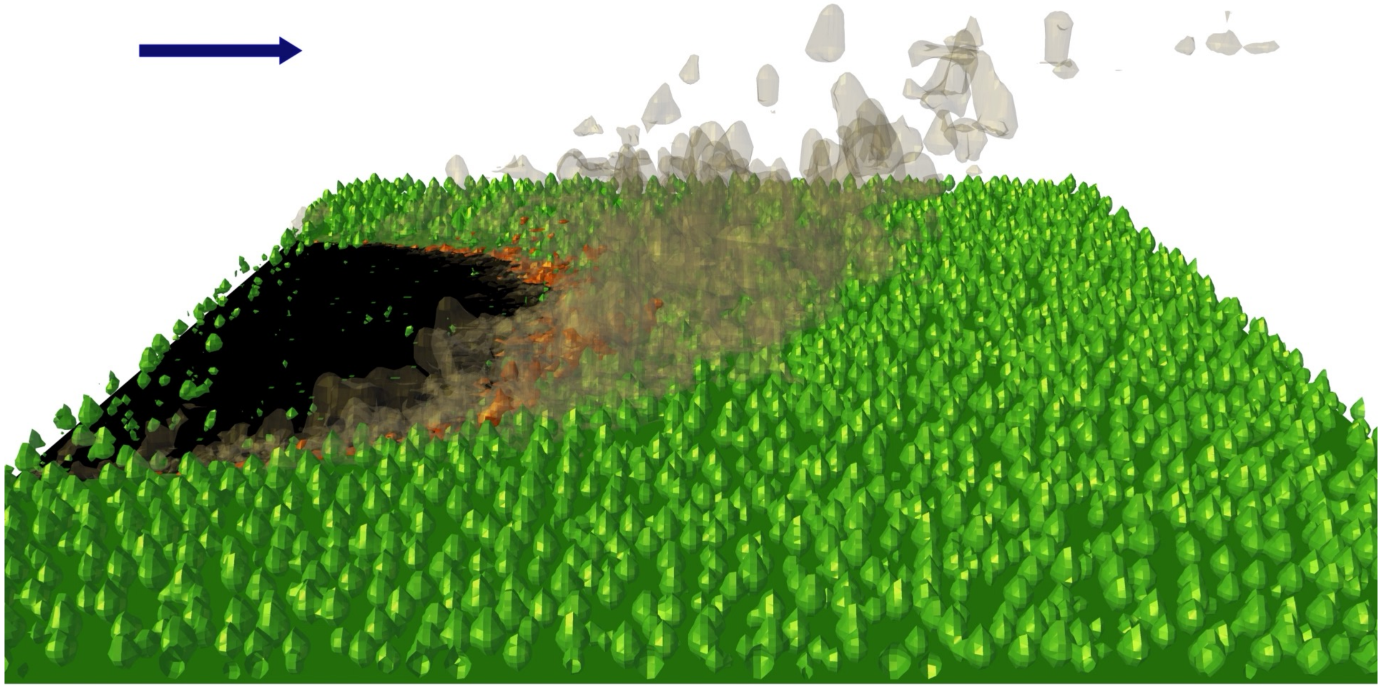


Side view of a simulated forest fire (FIRETEC)



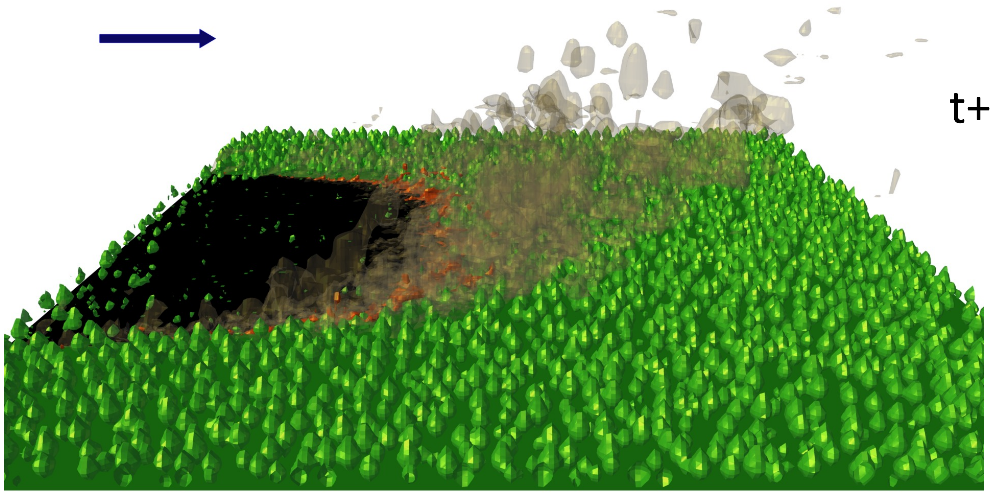
Example of the FIRETEC model

Spatial resolution : *2 to 10 m* grid cells (usually 2 m)
Spatial domains : *300 to 3000 m en (x,y), 600 à 1500 m (z)*

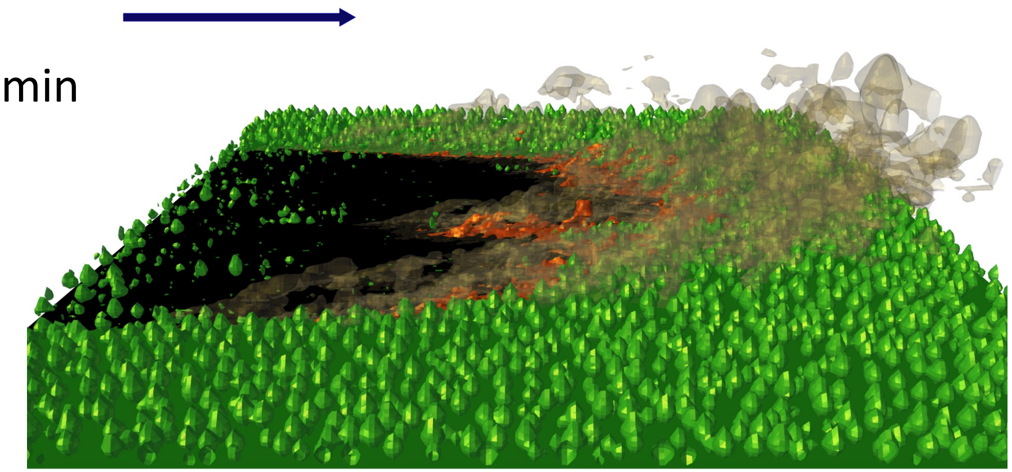


Example of the FIRETEC model

Wind effect



t+5min

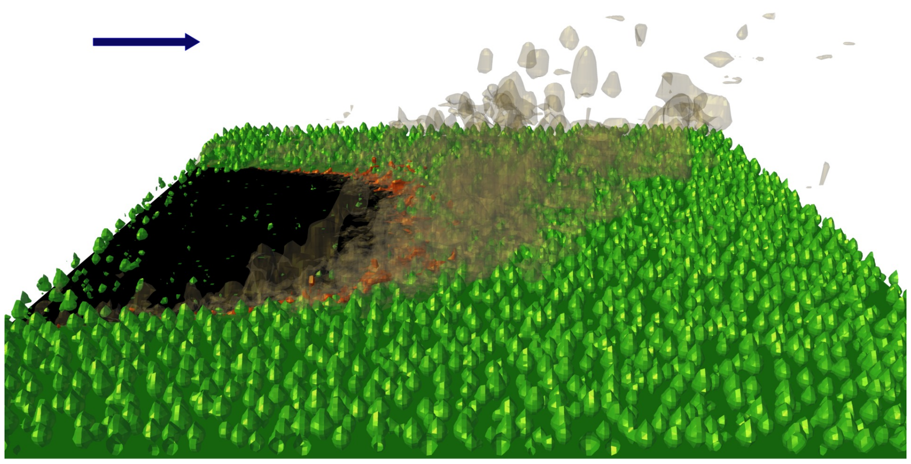


Wind 25 km/h

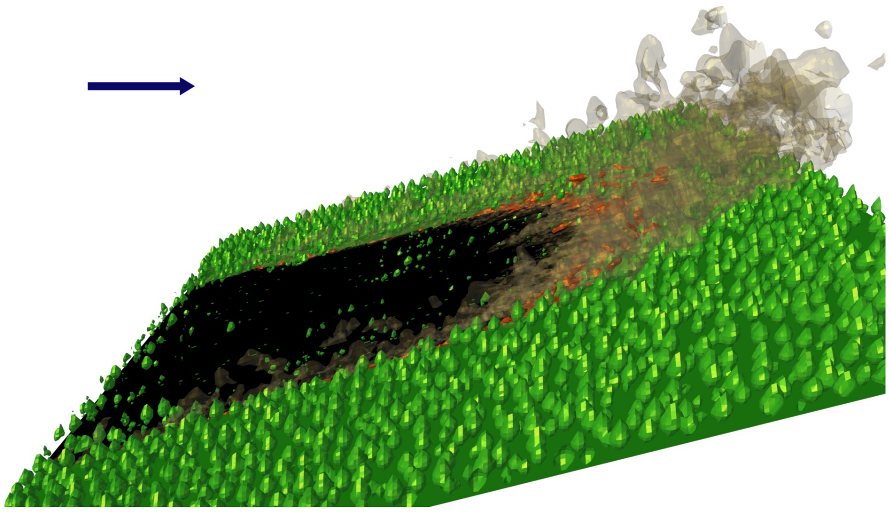
Wind 50 km/h

Example of the FIRETEC model

Slope effect



t+5min

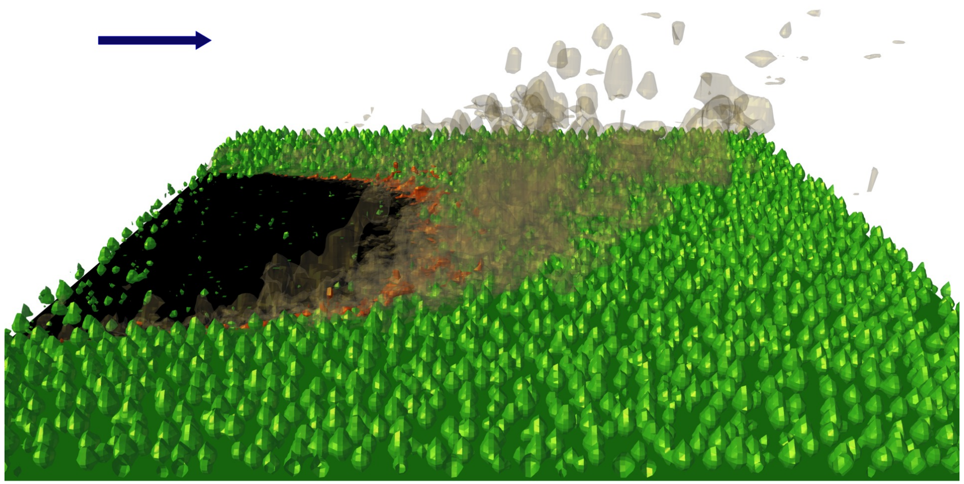


No slope

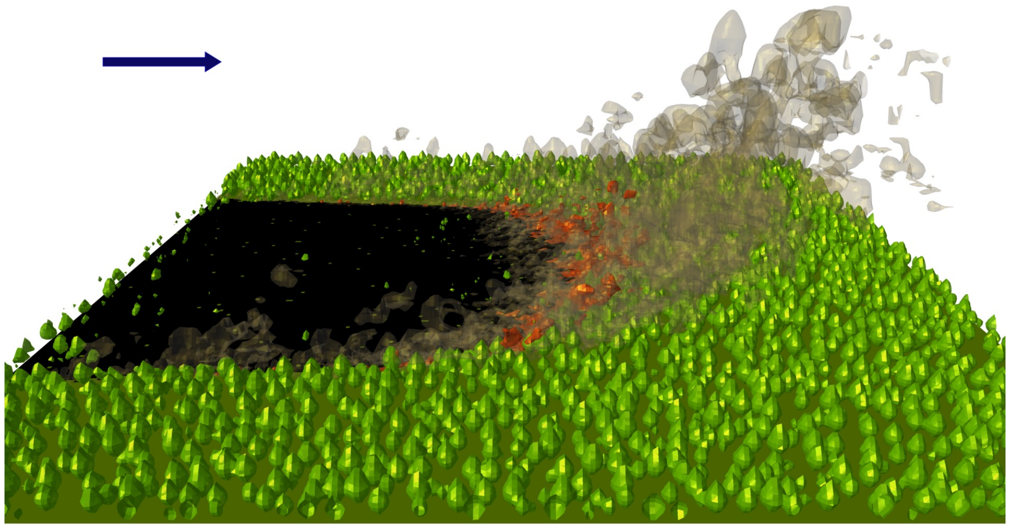
Slope 30%

Example of the FIRETEC model

Fuel moisture effect



Beginning of summer:
Pines 100 %, Shrubs 70 %



End of summer:
Pines 90%, Shrubs 56 %

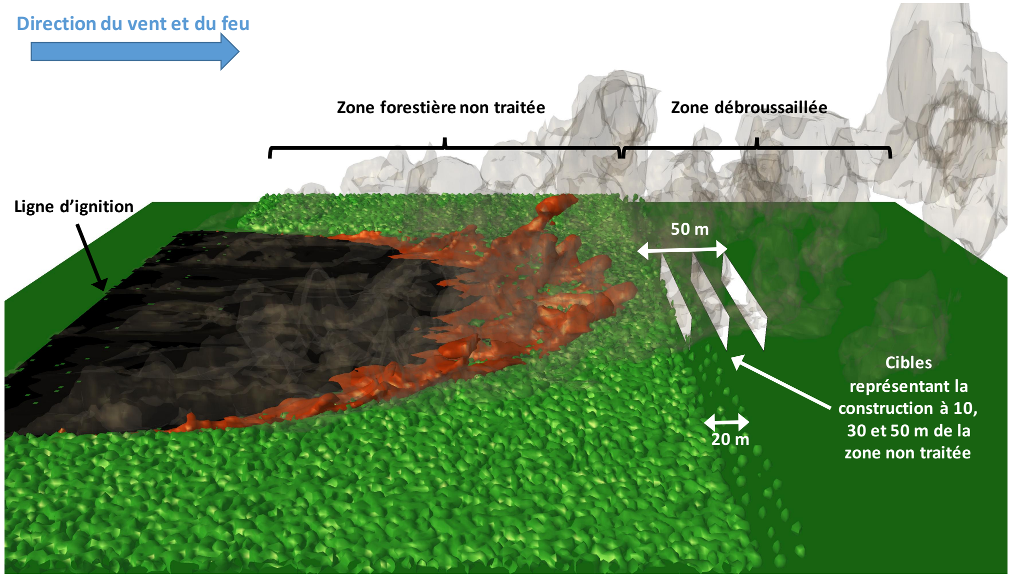
Fire behaviour models : physics-based

Example of the FIRETEC model

Fuel treatment depth needed to reduce heat fluxes in wildland-urban interface

Radiative fluxes and temperatures (1 min time-averaged)

	Flat terrain		Slope 30%	
	Radiative flux (kW/m^2)	Temperature (°C)	Radiative flux (kW/m^2)	Temperature (°C)
10 m	22-28	329-422	30-39	280-336
30 m	8.3-9.2	110-143	12-13.2	105-120
50 m	5.4-5.9	59-70	8-9.1	68-78



Example of the FIRETEC model

Movies showing several FIRETEC studies