Automated Wildfire Forecasting in the Continental US

Funded by California Energy Commission (CEC# EPC-18-026) and
US National Institute of Standards and Technology (70NANB20H118)

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NIST National Institute of Standards and Technology U.S. Department of Commerce

State of California Energy Commission

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PYREGENCE™ Consortium Working Groups

Spatial Informatics Group — PRINCIPAL INVESTIGATOR (PI) & PROJECT MANAGER (PM)

WG1	WG2	WG3	WG4
UCAR	Berkeley University of California	REAX Engineering	University of California Merced
EXTREME WEATHER	FIRE BEHAVIOR	SHORT TERM FORECAST (Pyrecast)	LONG TERM FORECAST
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Outline

- Part 1 – Pyrecast intro & usage
- Part 2 – Under the hood
- Discussion / Q&A

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Part 1:

Pyrecast intro & usage

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Part 2:

Under
the hood

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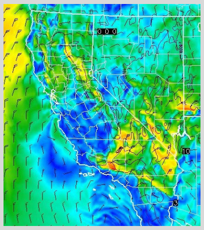
Automated Real Time Fire Forecasting

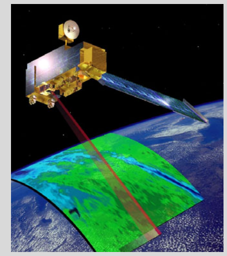


Weather forecast

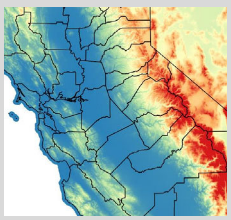
$$\frac{\partial \phi}{\partial t} + U_x \frac{\partial \phi}{\partial x} + U_y \frac{\partial \phi}{\partial y} = 0$$

$$U^*_{x,||} = \frac{b^2 \sin(\omega)}{\sqrt{a^2 \cos^2(\omega) + b^2 \sin^2(\omega)}}$$

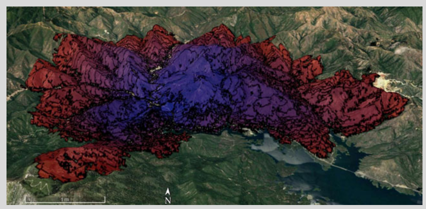
ELMFIRE/GRIDFIRE



Real-time fire location data



Fuel & topography



Fire spread forecast

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Fuel & Topography Inputs

	Source	Coverage	Resolution	Native quantities	Derived quantities
Fuel & Topo	Pyrologix CA 2022 Fuelscape*	CA	30 m	Surface fuel model, canopy base height, canopy bulk density, canopy cover, canopy height	Wind adjustment factor
	LANDFIRE 2020 Update (LF 2.2.0)†	CONUS	30 m		
	California Forest Observatory 2020 / 2022	CA	10 m		
	Center for Ecosystem Climate Solutions 2021	CA	10 m		

* Default in CA

† Default outside of CA

Canopy cover (LANDFIRE 2.2.0)

Canopy Cover (CFO 2020)

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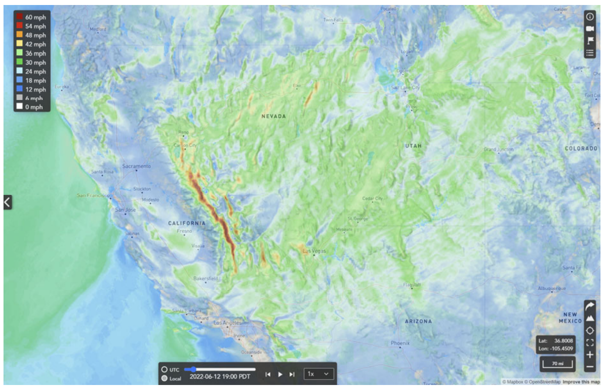
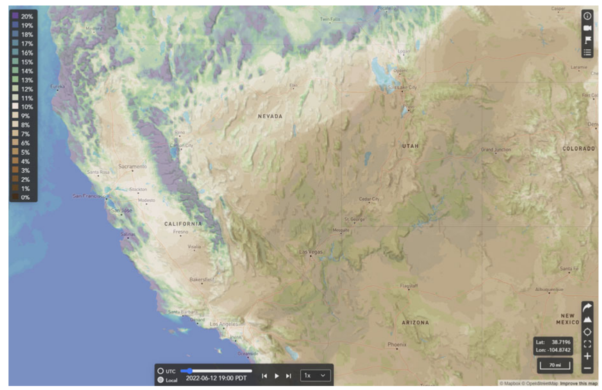
Weather Inputs

	Model	Resolution		Forecast duration	Cycles / day	Native quantities	Derived quantities
		Spatial	Temporal				
Weather	High Resolution Rapid Refresh (HRRR)	3 km	1 hr	2 day	4	Relative humidity, temperature, precipitation, solar fluxes, wind speed, wind direction, wind gust	Fosberg Fire Weather Index, Hot Dry Windy Index, dead fuel moisture by size class, NFDRS indices
	North American Mesoscale Model (NAM)	3 km	1 hr	2.5 day	4		
	Global Forecast System (GFS)	0.125 º	1-3 hr	16 day	4		
	Real Time Mesoscale Analysis (RTMA)	2.5 km	hourly	Real time	-	Same as above	Live fuel moisture (herbaceus & woody)



Wind gust (native quantity)



Fine dead fuel moisture (derived quantity)

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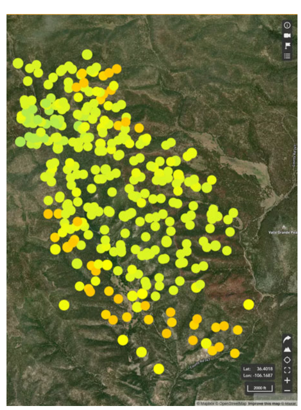
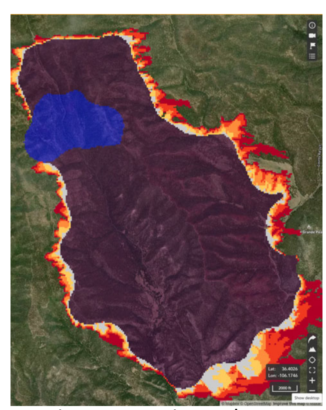
Near Real-time Fire Inputs

	Data source	Resolution		Native quantities	Derived quantities
		Spatial	Temporal		
Near real time fire	CALFIRE incidents feed	-	Real-time	Named fire locations	Fire progression polygons
	NIFC large fires feed	-	Daily		
	NASA FIRMS - Terra/Aqua - MODIS	1 km	12 hr	Satellite-based hot spots	
	NASA FIRMS - Suomi NPP / NOAA 20 - VIIRS	375 m	12 hr		
	Wildland Fire Interagency Geospatial Services (WFIGS) perimeters	~30 m	1-2 days	Fire perimeter polygons	

WFIGS perimeter



Satellite hot spots



Fire progression polygon

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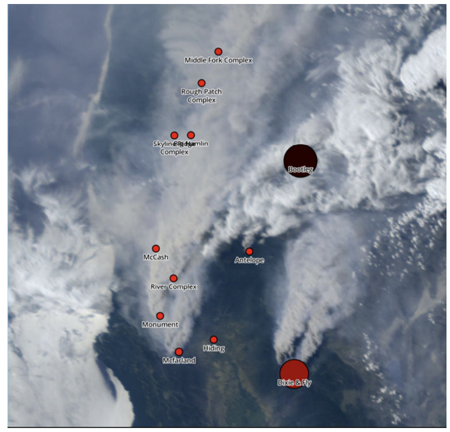
Real-time Situational Awareness

Alert Wildfire camera feeds



GOES-16 Imagery

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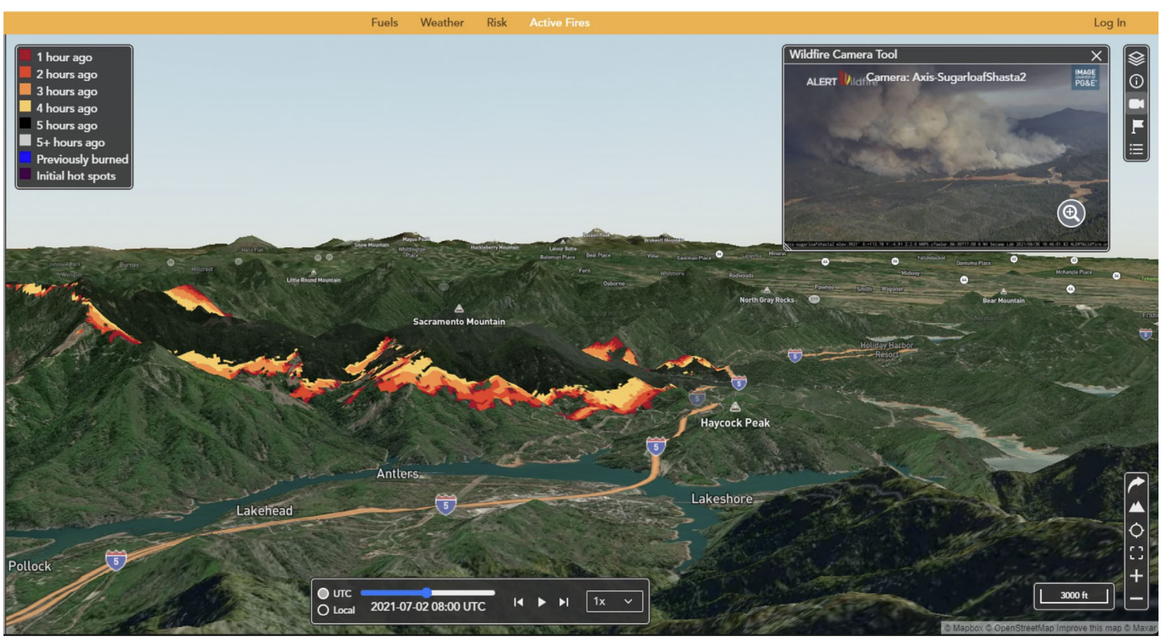
Real-time Situational Awareness



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Computational Models

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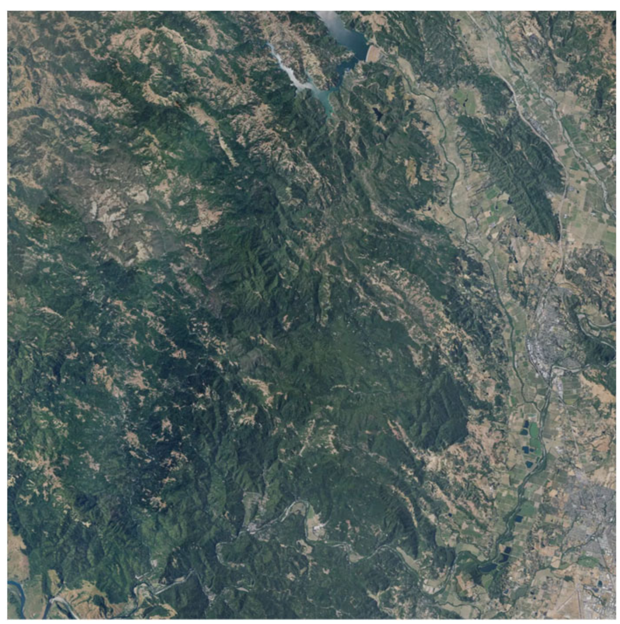
Ensemble Fire Forecasts

- Multiple simulations are run with model inputs perturbed from baseline values, *e.g.*
  - Wind speed and direction
  - Fuel moistures
  - Spotting parameters
- Animation to the right is a series of 24-hour fire spread forecasts condensed to 2 seconds
- Fires size percentiles are determined from modeled fire area at end of forecast period



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ELMFIRE

- Eulerian Level Set Method for Fire Spread
- https://github.com/lautenberger/elmfire
- https://elmfire.io

Fire Safety Journal 62 (2013) 289–298

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Wildland fire modeling with an Eulerian level set method and automated calibration

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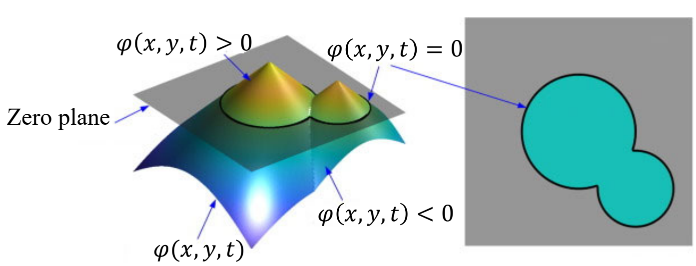
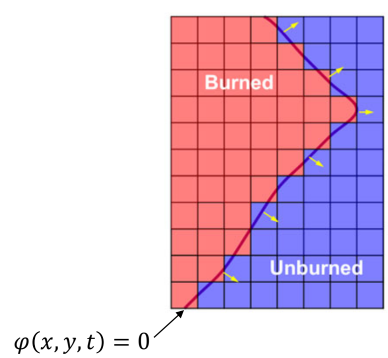
Eulerian Level Set Method

- Level set methods are a class of numerical techniques to track surfaces, shapes, or interfaces
- Eulerian: fixed frame of reference such as a grid
- Eulerian level set methods work by solving a partial differential equation (PDE) for the dependent variable ϕ
- ϕ has no physical meaning except when $\phi = 0$, which is the interface being tracked
- In ELMFIRE, $\phi = 0$ is the contour that separates unburned from burned or burning fuel





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Eulerian Level Set Method

- ϕ field is calculated by numerically integrating a hyperbolic PDE of the form:

$$\frac{\partial \phi}{\partial t} + U_x \frac{\partial \phi}{\partial x} + U_y \frac{\partial \phi}{\partial y} = 0$$

- U_x and U_y are calculated using the Rothermel model and Huygens principle – more later
- Fire front spreads only in direction perpendicular to itself as given by the unit normal vector $\hat{n}$:

$$|\nabla \phi| = \sqrt{\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2}$$

$$\hat{n} = \frac{1}{|\nabla \phi|}\left(\frac{\partial \phi}{\partial x}\hat{i} + \frac{\partial \phi}{\partial y}\hat{j}\right) = n_x \hat{i} + n_y \hat{j}$$

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Rothermel Surface Spread Model (1972)

- For ~50 years, has been used to calculate surface fire spread rate in the US. Used by all 2D operational fire spread models in the US

$$V_s = \frac{I_R \xi (1 + \varphi_w + \varphi_s)}{\rho_b \varepsilon Q_{ig}}$$

V_s: Surface fire spread rate (m/s)

I_R: Reaction intensity (kW/m^2)

ξ: Propagating flux ratio (-)

ϕ_w: Wind coefficient (-)

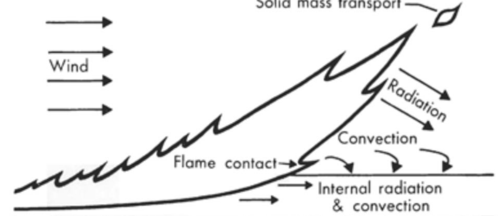
ϕ_s: Slope coefficient (-)

ρ_b: Bulk density (kg/m^3)

ε: Heating number (-)

Q_{ig}: heat of preignition (kJ/kg)

Figure 3.--Schematic of wind-driven fire.



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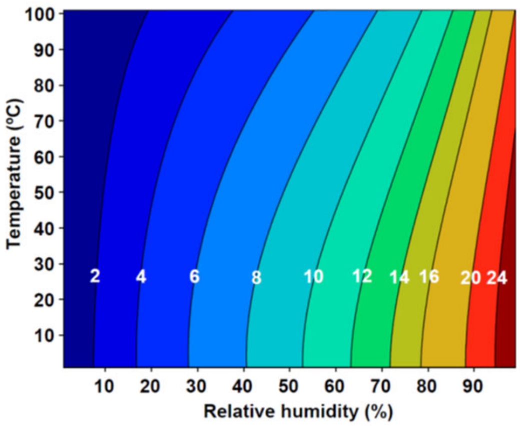
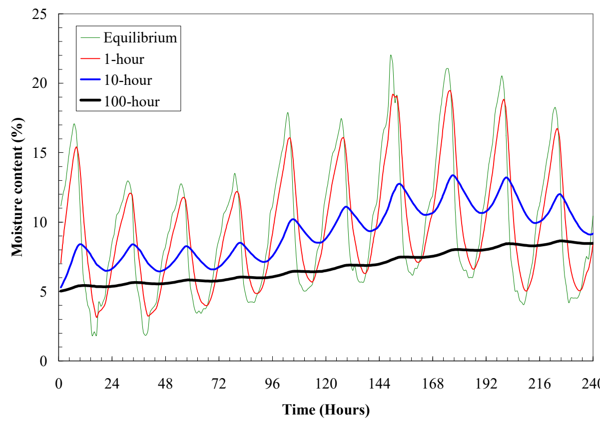
Dead Fuel Moisture

- In the case of no precipitation, for simplicity:

$$\frac{dM}{dt} = \frac{M_{eq} - M}{\tau_c}$$





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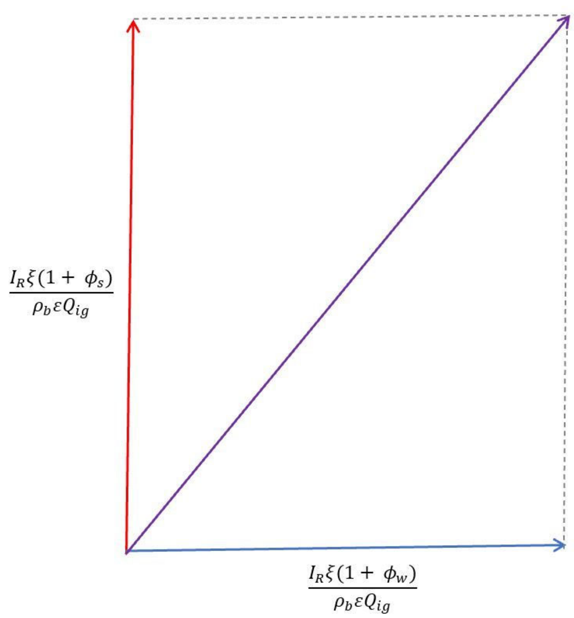
Vectoring the Rothermel Model

- Rothermel model gives spread rate only in direction of maximum spread, which is a function of the relative magnitudes of ϕ_s and ϕ_w
- Example for cross slope wind with wind out of West blowing across fireline on a South facing slope shown to right



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Elliptical Dimensions

- Since Rothermel only gives spread rate in the direction of maximum spread, mathematical properties of ellipses are used to infer spread rate in other directions
- This is called Huygens principle, originally applied to light propagation
- Every point along the fireline behaves as an independent elliptical wavelet

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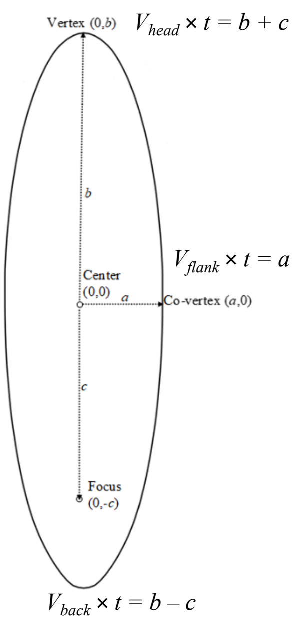
Elliptical Dimensions



Length to width ratio

$$\frac{L}{W} = \min\left[0.936 \times \exp\left(0.2566 U_{mf}\right) + 0.461 \times \exp\left(-0.1548 U_{mf}\right) - 0.397, 8\right]$$

or

$$\frac{L}{W} = 1 + 0.125 u_{H+20}$$

Backing and flanking spread rates

$$\frac{V_{head}}{V_{back}} = \frac{b+c}{b-c} = \frac{\frac{L}{W} + \sqrt{\left(\frac{L}{W}\right)^2 - 1}}{\frac{L}{W} - \sqrt{\left(\frac{L}{W}\right)^2 - 1}}$$

$$V_{flank} = \frac{1}{2}\frac{V_{head} + V_{back}}{L/W}$$

For algebraic convenience

$$A = \frac{1}{2}\frac{V_{head} + V_{back}}{L/W} \qquad B = \frac{1}{2}\left(V_{head} + V_{back}\right) \qquad C = \frac{1}{2}\left(V_{head} - V_{back}\right)$$

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Elliptical Dimensions

$\omega = \theta_n - \theta_{DMS}$	Difference between angle normal to fire front and direction of maximum spread
$U_{x,\|\|} = \frac{B^2 \sin(\omega)}{\sqrt{A^2\cos^2(\omega) + B^2\sin^2(\omega)}}$ $U_{y,\|\|} = \frac{A^2 \cos(\omega)}{\sqrt{A^2\cos^2(\omega) + B^2\sin^2(\omega)}} + C$	*x* and *y* components of velocity in orthogonal coordinate system with *y*-axis aligned with direction of maximum spread
x and *y* components of velocity after solid body rotation to north-up *y*-axis $U_x = U_{y,\|\|} \times \sin(\theta_{DMS}) + U_{x,\|\|} \times \cos(\theta_{DMS})$ $U_y = U_{y,\|\|} \times \cos(\theta_{DMS}) - U_{x,\|\|} \times \sin(\theta_{DMS})$	

$$\frac{\partial\phi}{\partial t} + U_x\frac{\partial\phi}{\partial x} + U_y\frac{\partial\phi}{\partial y} = 0$$

Level set equation

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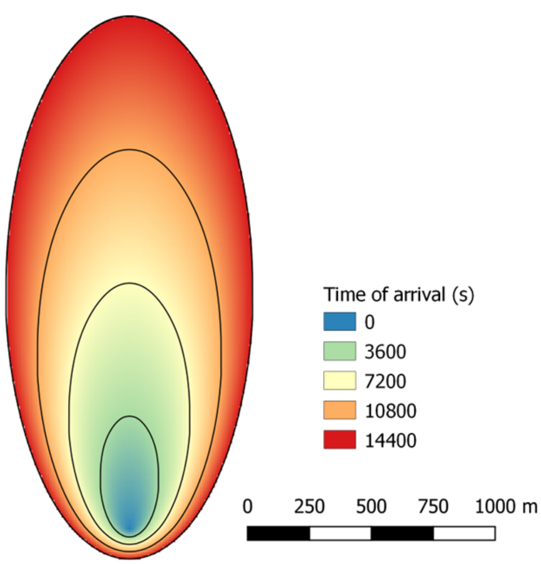
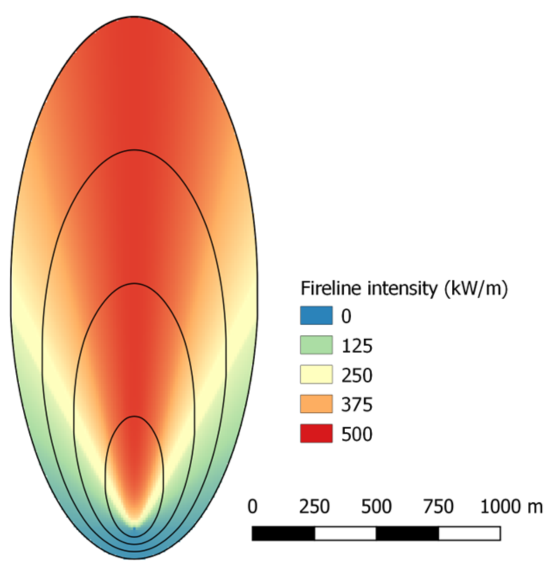
Elliptical Dimensions





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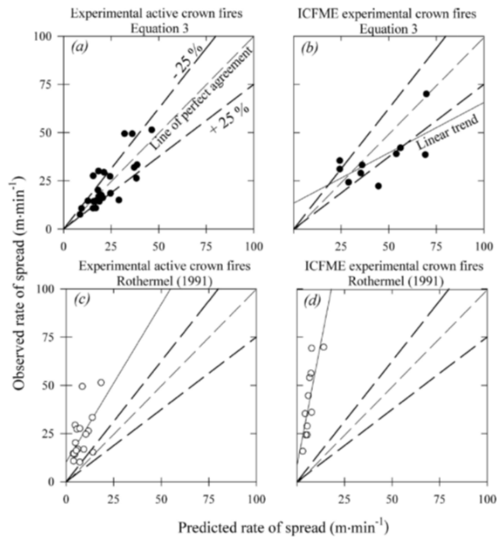
Crown Fire Initiation & Spread Rate

Van Wagner crown fire initiation criterion with spread rate calculated by Cruz *et al*. [1]. Provides better agreement with observed crown fire spread rates than Rothermel 1991 [2].

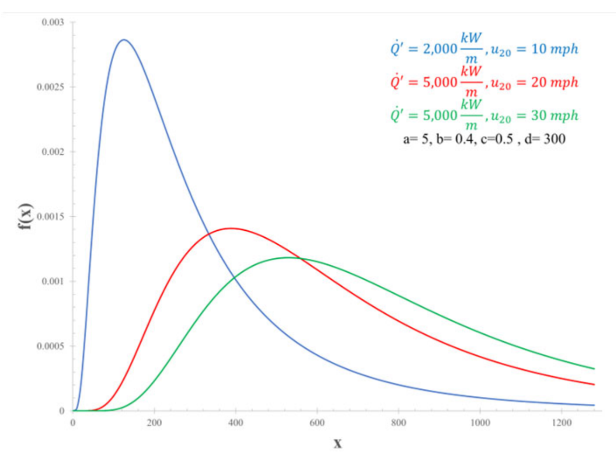
$$V_C = 11.02U_{10}^{0.9} \times \text{CBD}^{0.19} \times \exp(-0.17M_1)$$



1. Cruz, M.G., Alexander, M.E., Wakimoto, R.H., "Development and testing of models for predicting crown fire rate of spread in conifer forest stands," *Canadian Journal of Forest Research* **35**: 1626-1639 (2005).
2. Rothermel, R.C., "Predicting Behavior and Size of Crown Fires in the Northern Rocky Mountains," United States Department of Agriculture Forest Service, Intermountain Research Station, *Research Paper Int-438*, January 1991.

Spotting

Lognormal distribution per Sardoy *et al*. "Numerical study of ground-level distribution of firebrands generated by line fires," *Combustion and Flame* **154**: 478-488 (2008).



$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x}\exp\left(-\frac{1}{2}\left(\frac{ln\, x-\mu}{\sigma}\right)^2\right)$$

$$\mu = ln\left(\frac{m^2}{\sqrt{v+m^2}}\right)$$

$$v = m \times d$$

$$m = a \times \dot{Q}'^{b} \times u_{20}^{c}$$

$$\sigma = \sqrt{ln\left(1+\frac{v}{m^2}\right)}$$

Discussion / Q&A

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