Prediction Contours with Prometheus Based on ROS

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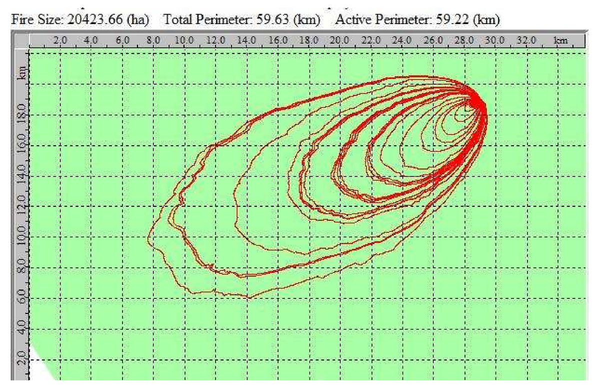
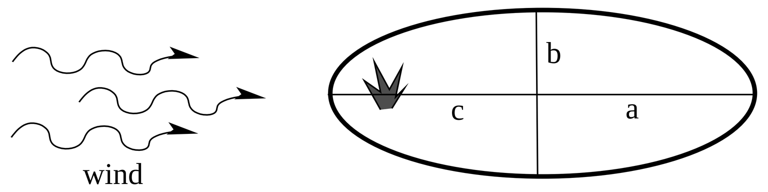
The PROMETHEUS Model

PROMETHEUS is a deterministic fire growth model, developed because of increasing wildfire activity.



Simulated fires begin as small circles representing the fire front at ignition. At subsequent times, the fire front is defined as the envelope of ellipses which correspond to small fires originating from ignition points on the previous fire front.



$$a = \frac{\text{ROS} + \text{BROS}}{2}; \quad b = \text{FROS}; \quad c = \frac{\text{ROS} - \text{BROS}}{2}$$

ROS = rate of spread, BROS (FROS) = back (flank) rate of spread.

Uncertainty in the fire process ⇒ unpredictable effects on the outcome of a fire ⇒ there is a need to incorporate randomness.

Ultimate goal: accurate probability contours

Modelling the Rates of Spread

Factors affecting ROS:

1. fuel type, fuel continuity and moisture content
2. wind speed and direction
3. topography; fires spread faster uphill and cannot cross natural barriers

Imputation of gridded data: ROS values at each grid cell are derived from interpolated weather data from nearby weather stations (temperature, relative humidity, 24-hour precipitation, wind speed and direction), plus topography and fuel maps:

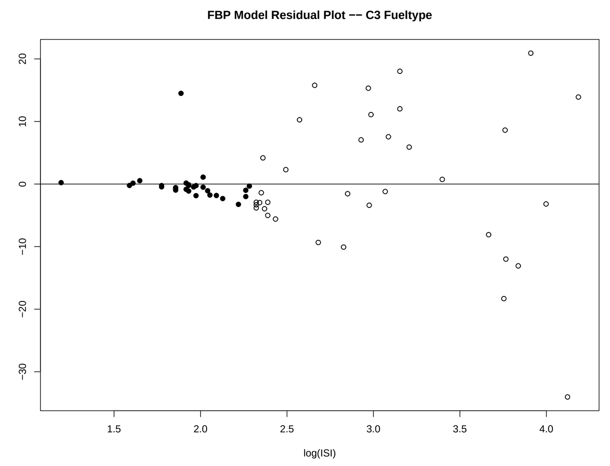
* Fuel moisture (FFMC) is inferred from the weather using an empirical model.
* The wind field (WSV) is generated from a physical model and adjusted for slope.
* Rates of spread are based on data from 240 experimental burns with uniform fuels, wind, moisture content and slope. ROS is closely related to the Rate of Spread Index (RSI) which follows a sigmoidal relation with both wind and moisture:

$$\text{RSI} = \alpha\,(1 - \exp(-\beta \text{ISI}))^{\gamma}$$

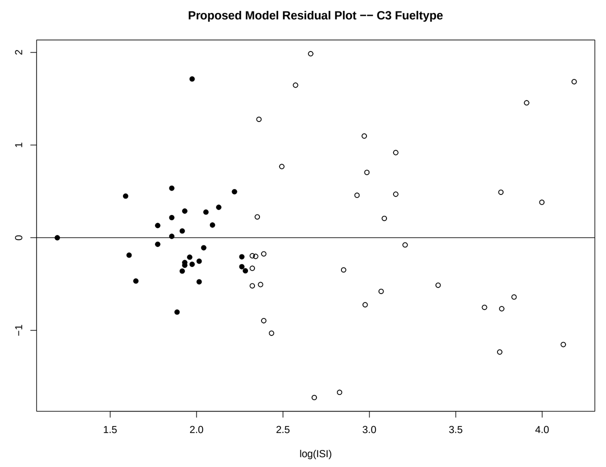
  The α, β and γ parameters have been estimated for several fuel types using nonlinear regression; ISI is the initial spread index which is a function of both wind speed and FFMC (Forestry Canada, 1992).
* BROS and FROS are deduced from similarly obtained empirical relations with wind speed and moisture, but not directly from data.

A Deficiency in the Current Model for ROS

* The empirical relation between ROS and ISI has a noise component which could be used to model the uncertainty in ROS.
* The variance of the noise component can be obtained as a by-product of the nonlinear least-squares estimation of the ROS-ISI relation — provided that *the noise variance is constant.*
* A scatter plot of the residuals after fitting the published relation for the C3 fuel type appears in the figure below.
* The noise variance is increasing with ISI; the fitted model is not optimal, and the noise variance cannot be calculated from this model.
* An alternative model is needed.



A New Model for ROS



* The figure above displays a scatter plot of residuals from a weighted least-squares fit of the model:

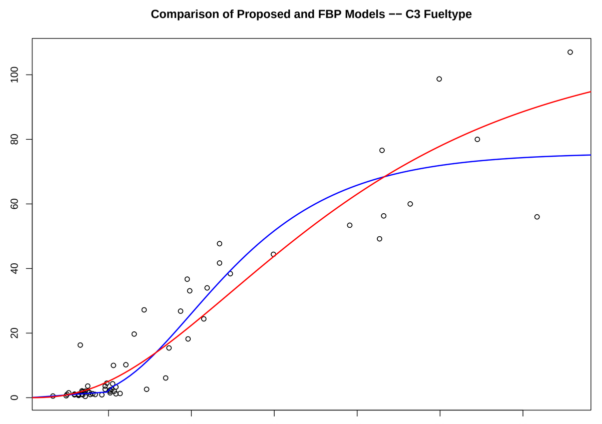
$$\frac{1}{\textbf{ROS}} = A\,(1 - \exp(-\beta \textbf{ISI}))^{C} + \varepsilon, \qquad \log(\textbf{ISI}) < 2.3 \text{ (low ISI)}$$

$$\sqrt{\textbf{ROS}} = \alpha\,(1 - \exp(-\beta \textbf{ISI}))^{\gamma} + 2\varepsilon, \qquad \log(\textbf{ISI}) \geq 2.3 \text{ (higher ISI)}$$

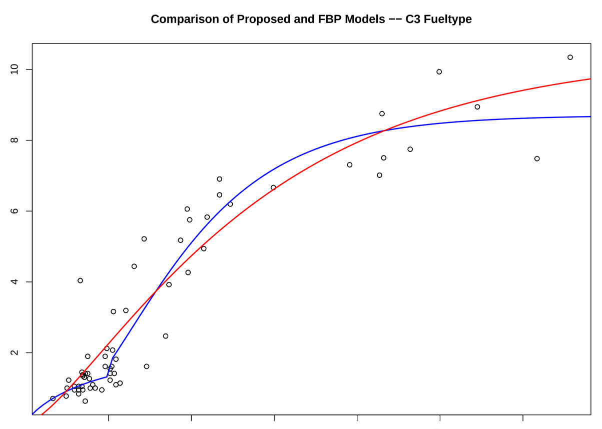
  ε is noise with mean 0 and standard deviation σ.
* Parameter estimates: $\widehat{\alpha} = 8.710$; $\widehat{\beta} = .09758$; $\hat{\gamma} = 3.485$; $\widehat{A} = 0.275$; $\widehat{C} = -1.539$.
* The solid black dots represent fires burning under low ISI conditions; effectively surface fires (S).
* The open circles represent fires burning under higher ISI conditions; mostly crown fires (C).
* Two regimes of approximately constant variability: ROS for crown fires has a standard deviation which is very nearly twice the standard deviation for surface fires: $\widehat{\sigma}_S = 0.507$; $\widehat{\sigma}_C = 1.02$.

Comparison of the Two Models

* The plot below displays the original empirical relation between ROS and ISI for the C3 fuel type (red) and the proposed relation (blue).

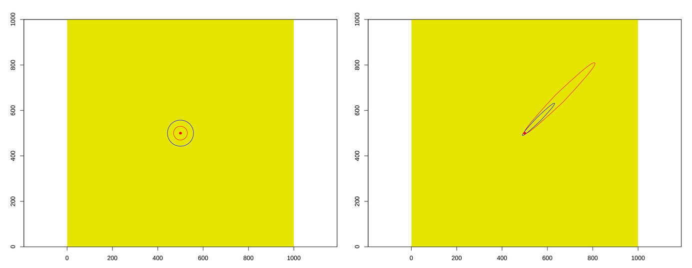


* Transforming to the square root scale on the vertical axis allows one to see a marked transition from surface to crown fire behaviour.

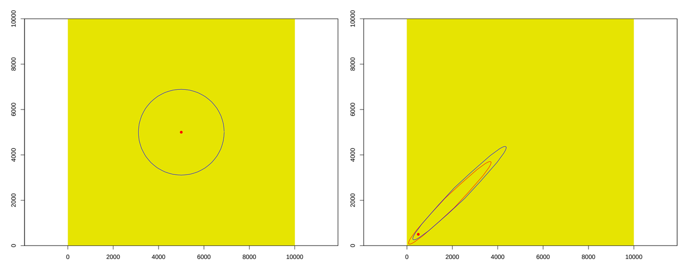


Effects on Prometheus Behaviour

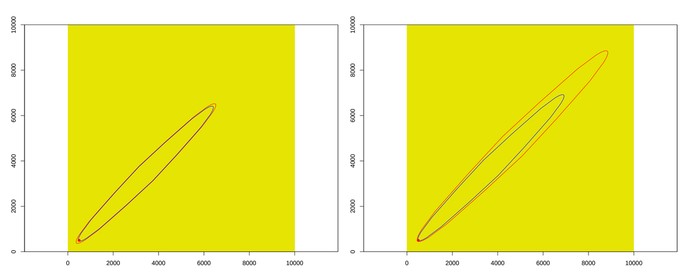
* Prometheus output below is based on homogeneous C3 fuel conditions and constant weather. The version of Prometheus used is under development in R (Garcia et al, 2008, R Core Team, 2010).
* Displayed fire fronts correspond to 3 hours after ignition (red curve = original model; blue curve = proposed model).



Above left panel: Wind Speed = 0 km/h; FFMC = 90.
Right panel: Wind Speed = 20 km/h; Wind direction: NE; FFMC = 90.



Above left panel: Wind Speed = 0 km/h; FFMC = 100.
Right panel: Wind Speed = 10 km/h; Wind direction: NE; FFMC = 100.



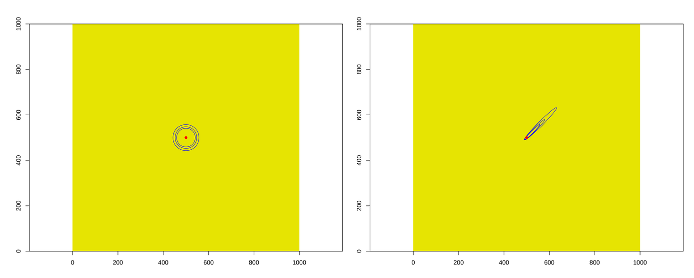
Above left panel: Wind Speed = 20 km/h; Wind direction: NE; FFMC = 100.
Right panel: Wind Speed = 30 km/h; Wind direction: NE; FFMC = 100.

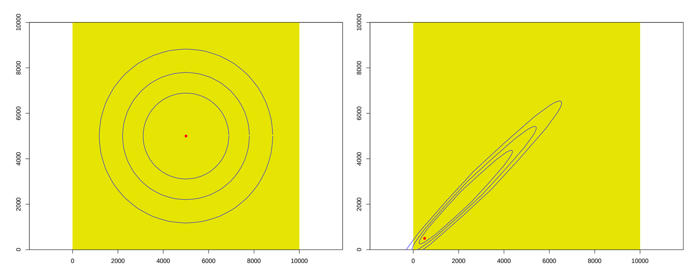
Probability Contours for Prometheus

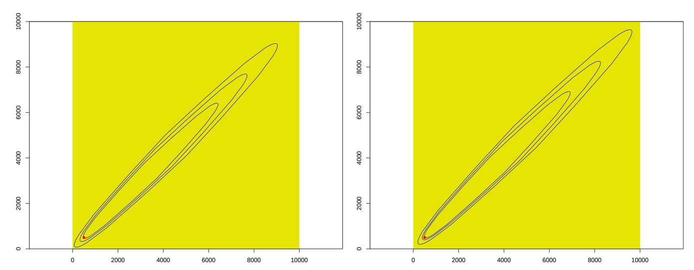
* The pth probability contour contains the fire with probability p, assuming that weather conditions are constant and known precisely.
* The rate of spread corresponding to the pth probability contour is $\textbf{ROS}_p$ in

$$\frac{1}{\textbf{ROS}_p} = A\,(1 - \exp(-\beta \textbf{ISI}))^{C} + z_p \sigma_S, \qquad \log(\textbf{ISI}) < 2.3 \text{ (low ISI)}$$

$$\sqrt{\textbf{ROS}_p} = \alpha\,(1 - \exp(-\beta \textbf{ISI}))^{\gamma} + z_p \sigma_C, \qquad \log(\textbf{ISI}) \geq 2.3 \text{ (higher ISI)}$$







* The 50th, 80th and 95th probability contours are plotted above, for the wind and moisture conditions considered earlier.

Next Steps

* ROS models with uncertainty estimates will be developed for other FBP fuel types.
* Weather forecast uncertainty and weather variability will be incorporated using a block bootstrap.
* Adjustments for topography can also be made.
* Rigourous testing on archived fires is required before this approach can be implemented.

References

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2. Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire behaviour Prediction System. Forestry Canada, Ottawa, Ontario. Information Report ST-X-3.
3. R Development Core Team (2010). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL `http://www.R-project.org`.

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