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Upscaling the estimation of surface-fire rate of spread in maritime pine (*Pinus pinaster* Ait.) forest

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The prediction of the forward rate of forest fire spread is crucial to fire modeling and fire management. An empirical equation is available to estimate the rate of spread of surface fires in maritime pine stands from local fuel, terrain and weather conditions. However, the equation was primarily developed from experimental small fires under mild weather conditions. The ability to predict the spread rate of wildfires is examined. Underestimation was generalized, with a mean observed-to-predicted spread rate ratio of 2.64, which is proposed to adjust the rate of spread equation for fire-modelling research applications.

Keywords: Fire Behaviour, Fire Modelling, Surface Fire, *Pinus Pinaster*

Introduction

The prediction of forest fire behavior characteristics finds application in several aspects of fire research and fire management. The ability to predict fire spread rate, *i.e.*, the linear rate of advance of the fire front, is at the core of fire behavior prediction systems and makes possible estimating other fire behavior metrics, namely flame length (or height) and fireline intensity. Practical and reliable estimation of fire behavior descriptors is currently restricted to the use of empirical or semi-empirical equations that are developed from or validated with field data (Sullivan 2009).

A comprehensive experimental burning program in northern Portugal resulted in the development of equations that describe fire-spread rate and other fire behavior characteristics in the surface fuel complex of maritime pine (*Pinus pinaster* Aiton 1789) stands (Fernandes et al. 2009). These equations have been integrated in PiroPinus, a spreadsheet application developed to support prescribed burning planning (Fernandes et al. 2012). The forward fire spread rate R (m min^{-1}) is estimated by an equation of the form (eqn. 1):

$$R = aU^b \exp(cS + dMs) FD^e$$

where U is the surface (measured at 1.7-m above ground) in-stand wind speed (km h^{-1}), S is the terrain slope (°), Ms is the moisture content of fine dead surface fuel (%), and FD is the surface fuel depth (m), with parameters a=0.773, b=0.707, c=0.062, d=-0.039 and e=0.188. Eqn. 1 explained 75.3% of the observed variation and predicted R with a mean absolute percent error of 37.1% upon evaluation with an independent data set (Fernandes et al. 2009).

Because the primary objective was to model fire behavior under mild (autumn to spring) weather conditions, the data set used to develop eqn. 1 is dominated by relatively weak (< 6 km h^{-1}) wind speeds and high dead fuel moisture contents (> 15%). Environmental conditions representative of typical wildfire scenarios, namely combinations of dry fuels (Ms<10%) and moderate-to-high wind speeds, and the corresponding higher rates of fire spread are not represented in the data set. It can then be questioned whether the functional relationships in eqn. 1 hold under more extreme fire weather. However, concerns with the small scale of the experiments are probably more relevant regarding the extrapolation of results to high-intensity fires. The experimental setup determines that eqn. 1 describes the spread rate of line-ignited, ~10-m wide fires propagating over a distance of ~10 m, which for radiation-driven fires under calm or weak winds is expected to mirror the spread rate of larger fires (Wotton et al. 1999). Experimental burning programs in grassland, woodland and forest in Australia have shown that the potential rate of forward fire spread increases with head fire width (up to 50-300 m) until reaching an asymptote determined by wind speed (Cheney & Gould 1995, Gould et al. 2003).

Eqn. 1 is now being applied to wildfire scenarios in the context of fire-modeling research (Ascoli et al. 2010, Castedo-Dorado et al. 2012), which departs from the original intended use, *i.e.*, prescribed burning planning. This note examines the ability of the forward fire-spread equation of Fernandes et al. (2009) in predicting wildfire rate of spread in maritime pine forest.

Materials and Methods

Well-documented case studies of wildfire behavior in maritime pine stands were compiled from a review of the peer-reviewed and grey literature. Wildfire selection was dictated by (i) fire type, *i.e.*, crown fires were excluded, and (ii) rate of fire spread and the inputs to eqn. 1 were either available or could be estimated from information in the reports. Fire-spread rate, wind speed and dead fuel moisture content were present in the Australian fire reports; for the Portuguese cases the former was calculated from the mapped fire perimeter and times of arrival, and the latter were derived from weather information using PiroPinus (Fernandes et al. 2012). Terrain slope was reported in all study cases. Fuel depth was obtained from fuel loading as per Fernandes et al. (2002).

Rate of fire spread was estimated with eqn. 1 for the prevailing wildfire conditions. Deviation of predictions from the observed values was assessed by the absolute percent error (*APE*, Willmott 1982 - eqn. 2):

$$APE = \frac{|y_i - \hat{y}_i|}{y_i} \cdot 100$$

where y_i and $\hat{y}_i$ are the observed and the predicted fire-spread rates, respectively. Prediction accuracy was additionally expressed by the ratio of observed-to-predicted rate of fire spread. Linear and non-linear least squares regression was used to relate observed and predicted rates of fire spread.

Results and Discussion

The analysis considered six study cases (Tab. 1 and Tab. 2), two in Portugal and four in Australia, of which one corresponded to the experimental burning of three 1.3-ha plots (Burrows et al. 1988). Comparison between observed and predicted fire-spread rates is likely to be affected by substantial variation in terrain slope and wind direction.

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Tab. 1 - Case studies of surface-fire spread data in maritime pine stands. (W): wildfire; (E): experimental fire. Fire danger rating based on Sneeuwjagt & Peet (1985) and Palheiro et al. (2006), respectively for Australia and Portugal.

Data source	Data type	Location	Date	Fire danger rating	Observation time (hours)	Fire size (ha)
McArthur (1965)	W	Gnangara, Western Australia	January 22, 1962	Extreme	1150-1700	50
Macedo & Sardinha (1987)	W	Praia da Raínha, Portugal	May 12, 1984	Very High	1400-1700	850
Burrows et al. (1988)	E	Mullalyup, Western Australia	December 10, 1986	Very High	1030-1430	1.3
Smith (1992)	W	Myalup, Western Australia	April 21, 1991	Extreme	1245-1400	260
Burrows et al. (2000)	W	Gnangara, Western Australia	December 30, 1994	Extreme	1400-1930	850
Ferreira & Galante (2003)	W	Mata Nacional de Leiria, Portugal	August 2, 2003	Very High	1500-1900	2578

Tab. 2 - Surface-fire spread data in maritime pine stands collected in the literature. (R): rate of fire spread; (APE): absolute % error; (U): in-stand wind speed at 1.5-2 m; (S): terrain slope; (M_S): moisture content of fine dead surface fuels; (FD): fuel depth.

Data source	U (km h^{-1})	S (°)	M_S (%)	FD (cm)	R (m min^{-1}) Pred.	R (m min^{-1}) Obs.	APE (%)
McArthur (1965)	4	0	5	12	2.7	3.7	27
Macedo & Sardinha (1987)	8	11	7	70	11.5	13.8	16.7
Burrows et al. (1988)	3.4	0	10.9	5	1.6	3	46.7
Smith (1992)	11	0	7	8	4.7	21.8	78.4
Burrows et al. (2000)	8.3	0	4.9	5	3.4	14.9	77.2
Ferreira & Galante (2003)	3	5	11	5	3.3	7.9	58.2

However, this is not a relevant concern in this study, as slope was a minor fire-spread factor (Tab. 2) and maps in the reports portrayed wildfires of regular shapes, with high length-to-breadth ratio. Additionally, observation periods were relatively short (Tab. 1), minimizing variation in the fire environment and in fire behavior. Portuguese fires burned in litter-shrubs fuel complexes, while the Australian cases respect to litter. Fire spread rate was in all cases underpredicted, with a mean absolute percent error of 50.7% (Tab. 2 and Fig. 1). Underprediction varied by a factor of 1.2 to 4.6, averaging 2.64. The two fastest spreading wildfires were driven by a combination of relatively high wind speed and relatively low fuel moisture content and exhibited the highest ratios of observed-to-predicted spread rate (4.6 in Smith 1992; 4.4 in Burrows et al. 2000). The fire-spread rate in Burrows et al. (1988) was underestimated by a factor of 1.8, which seems high given the moderate burning conditions. However, Burrows et al. (1988) fires were carried out in an unthinned stand with vertical fuel continuity and comprised short-lived periods of crowning during which rate of spread increased 2 to 5 times.

The underestimation of wildfire rate of spread by eqn. 1 is likely an outcome of the combination of insufficient fire width and mild fire weather in the experimental fires, as mentioned before. Fernandes et al. (2009) discussed that while the quantitative effect of slope in eqn. 1 is remarkably similar to other studies, a value of *b* as low as 0.7 is seldom reported in the literature. Fernandes et al. (2009) attributed this to the dominance of moist fuels (hence decreased convective heat output) and weak winds in the experimental data set. The observed rate of fire spread in flat terrain (slope ≤ 5°, one fire excluded) is best related to the predicted value by means of an exponential function, which accounts for 86% of the existing variation (Fig. 1). This non-linear behavior implies that underestimation increases more than proportionally as fire weather conditions worsen, but note that a linear regression would fit the data nearly as well ($r^2 = 0.82$). The ratio of observed-to-predicted fire-spread rate increases with wind speed ($r = 0.9$; $p = 0.027$). Likewise, eqn. 1 might underestimate the damping effect of fuel moisture, but its relationship with the ratio of observed-to-predicted rate of fire spread is not statistically significant ($r = -0.35$; $p = 0.566$). Results suggest an actual steeper response of fire-spread rate to increasingly higher wind speeds, with $b>1$, although the number of observations is too meager to warrant a re-examination of the functional relationships in eqn. 1.

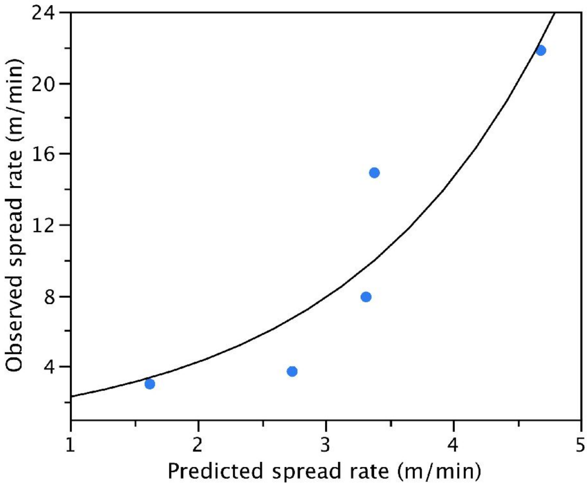

Fig. 1 - Plot of observed versus predicted fire-spread rates in flat (slope ≤ 5°) terrain (data in Tab. 2). The fitted equation: $y = 1.2208\ e^{0.6201\ x}$ accounts for 86% of the variability of observed fire-spread rate.

The results indicate that by setting a=2.041 (the product of 0.773 and 2.64) eqn. 1 can be extended to fully developed wildfires under windier and drier conditions than those present in the experimental database. Similarly, Australian fire-spread models for eucalypt forest underestimated the rate of spread of large (ignition line = 120 m) experimental fires by a factor of 2 to 3 (McCaw et al. 2008). Nonetheless, as data in Smith (1992) and Burrows et al. (2000) show, the 2.64 upscaling factor can still underestimate the rate of spread of surface fires in maritime pine stands. Note, however, that this concern is relevant only in tall, thinned and high-pruned stands carrying low-to-moderate fuel loadings (*e.g.*, Burrows et al. 2000). Under most other circumstances transition to crown fire will occur upon reaching substantially lower rates of spread, *e.g.*, Fernandes et al. (2004); more open stands will also experience higher wind speeds and lower fuel moisture contents.

Conclusion

PiroPinus provides estimates of fire behavior characteristics and fire effects for maritime pine stands in a user-friendly manner. A substantial advantage in relation to the options available is the ability to account for site-specific fuel and stand conditions (Fernandes et al. 2012). PiroPinus is fully compatible and can be linked with empirical models of crown fire initiation and spread, increasing the interest of its use in fire simulation modeling. While an *interim* adjustment factor for the spread rate of high-intensity wildfires is proposed here, future research should endeavor to develop a robust alternative to eqn. 1 with a wider scope of application.

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